levitate

Converting impacts of connected and automated vehicles to monetary terms

Deliverable D3.3 – WP3 –PU

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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 connected and automated transport systems, maximise the benefits and utilise the technologies to achieve societal objectives.

Connected and automated transport systems (CATS) 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 tool** to enable city and other authorities to forecast impacts of CATS.
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 CATS 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 CATS** over the short, medium and long term for a range of use cases.

Executive summary

The objective of this deliverable is to provide monetary valuations of potential impacts of connected and automated vehicles. These valuations are intended for use in cost-benefit analyses of policy interventions designed to ensure that connected and automated vehicles are introduced in a way that maximises their societal benefits.

In previous deliverables, the potential impacts of connected and automated vehicles were identified and classified (deliverable D3.1) and methods for predicting and quantifying the impacts were surveyed (deliverable D3.2). A total of 33 potential impacts were identified. Impacts were classified as direct, systemic and wider. Direct impacts are noticed by each road user on each trip. Systemic impacts are changes in the transport system, such as changes in traffic volume and congestion or the modal split of travel. Wider impacts occur both inside the transport system and in other sectors of society. These impacts include, for example, changes in the number of accidents and air pollution.

To convert an impact to monetary terms, the impact must be quantified in units that lend themselves to monetary valuation. A majority of the potential impacts of connected and automated vehicles can be stated in numerical terms allowing monetary valuation. A survey was made of valuation studies. It was found that monetary valuations are available at a European level for the following potential impacts of connected and automated vehicles:

1. Changes in travel demand (traffic volume)
2. Congestion
3. Travel time
4. Accidents
5. Air pollution

Changes in traffic volume are valued by means of the change in consumer surplus associated with the changes. The term consumer surplus refers to the net benefits consumers obtain from consuming a commodity, i.e. the area under a demand curve between its left origin and its intersection with the price curve, see the illustration in Figure ES 1.

The rectangle shows what consumers pay (price per unit · number of units bought). The area between the demand curve and the rectangle shows the consumer surplus. In studies of travel demand (traffic volume), demand is usually modelled as a function of the generalised costs of travel. The generalised costs of travel is the sum of all sacrifices made when travelling, converted to monetary terms. This includes the capital cost of the vehicle, its operation costs, the internal cost of accidents and the costs of travel time.

It is proposed that a schedule of monetary valuations should satisfy three criteria:

1. The valuations should refer to final outcomes of a causal process.
2. The valuations should avoid double counting.
3. The valuations should be exhaustive.

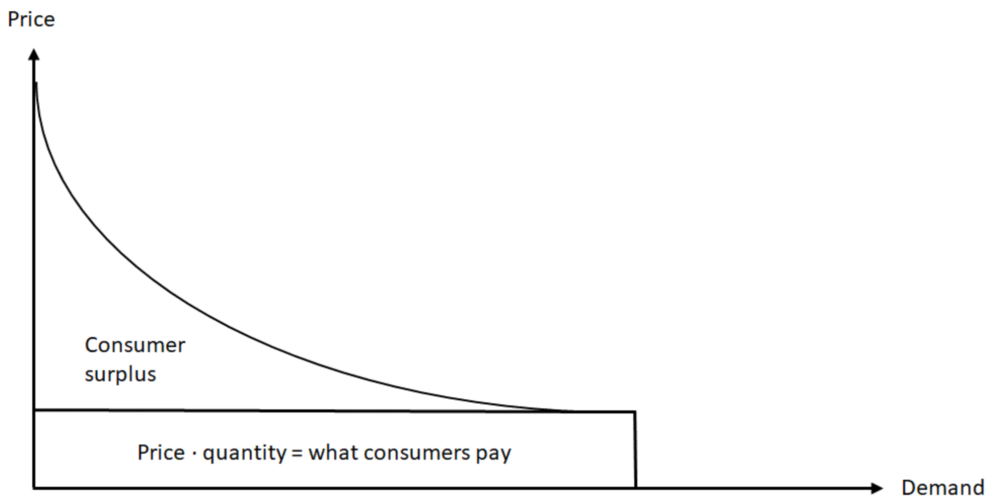

Figure ES 1: Illustration of the concept of consumer surplus

The first criterion is particularly relevant for air pollution. The list of impacts related to air pollution can be viewed as a causal chain involving the following steps:

Propulsion energy → Energy efficiency → Vehicle emissions → Air pollution → Public health

The monetary valuations refer to changes in public health, i.e. to the effects of air pollution on mortality and morbidity. However, to make the valuations easy to apply, they are stated per unit of emissions, specified according to the type of chemical emitted. These valuations can be applied to vehicle emissions factors (emissions in grams per kilometre of driving) in order to estimate the monetary value of changes in air pollution.

The second criterion is particularly relevant to accidents, since part of the cost of accidents is internal and therefore part of the generalised costs of travel. To avoid double counting, the cost of accidents was divided into internal and external costs. The internal costs reflect the benefits of improved safety to occupants of connected and automated vehicles. The external costs reflect the benefits of improved safety for other road users (pedestrians, cyclists, moped riders, motorcycle riders, users of other non-automated vehicles).

The third criterion refers to whether monetary valuations include all potential impacts of connected and automated vehicles, or if there are impacts for which no monetary valuation exists. If there are impacts without monetary valuations, a cost-benefit analysis will be incomplete and may give biased results by not including all relevant impacts. While most of the potential impacts of connected and automated vehicles can be valued in monetary terms, three potentially important impacts do not easily lend themselves to monetary valuation:

1. Loss of trust in automation technology
2. Changes in inequality in transport
3. Changes in land use

As far as loss of trust in automation technology, with an attendant loss of transport relying on this technology is concerned, one may perhaps derive a rough monetary estimate of its value by applying the utility functions proposed in prospect theory, a psychological model of decision-making developed by Kahneman and Tversky (see references). However, quite strong assumptions must be made to apply prospect theory.

Inequality in transport can be measured numerically by e.g. the Gini-index or the Palma-index (these measure degree of inequality). Changes in the degree of inequality may therefore be quantified. One possible basis for evaluating whether changes in inequality are good or bad, is to apply the difference principle of fair distribution proposed by John Rawls (see references).

Changes in land use can be stated in terms of sustainability indicators referring to, for example, energy use, modal split of travel or human health, by relating these indicators to changes in land use parameters such as population density per square kilometre, mean commuting distance, or volume of car travel. The changes can thus be quantified and the evaluation of whether they are good or bad may be based on changes in the sustainability indicators.

The monetary valuations proposed in this deliverable have been standardised to Euros in 2020-prices. For accidents and travel time, valuations are available for every European country. The values proposed in this deliverable are average values for all European countries.

It is proposed to convert all valuations to rates per vehicle kilometre of travel. This is the most convenient unit for analysis when there is a need for estimating the generalised costs of travel. An illustration is given of how to estimate the generalised costs of travel and change in consumer surplus associated with vehicle automation. The main purpose of the illustration is to explain the logic and steps of analysis; the numerical values used should therefore only be interpreted as illustrative.

1 Introduction and objective

This deliverable describes how impacts of connected and automated vehicles can be converted to monetary terms. For the sake of completeness, an overview of potential impacts of connected and automated vehicles is given initially. Impacts that can be quantified are identified. In subsequent chapters, the possibilities of converting impacts to monetary terms is discussed. The purpose of doing so is to include the impacts in cost-benefit analyses of connected and automated vehicles. This introductory chapter defines the objectives of the deliverable.

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 connected and automated transport systems (CATS) 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 CATS** over the short, medium and long term for a range of use cases, operational design domains and environments and an **extensive range of mobility, environmental, safety, economic and societal indicators**. A series of case studies will be conducted to validate the methodologies and to demonstrate the system.

4. To incorporate the methods within a **new web-based policy support tool** to enable city and other authorities to forecast impacts of CATS on urban areas. The methods developed within Levitate will be available within a tool box 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 CATS measures that will result in their desired policy objectives.

1.2 Work package 3 and objectives of this deliverable

This deliverable contributes to the second and third objectives. Developing methods for assessing and predicting the impacts of CATS consists of the following main stages:

1. Identification and classification of impacts of connected and automated transport systems

2. Description and measurement of impacts of connected and automated transport systems
3. Development of methods for backcasting and forecasting of impacts of connected and automated transport systems
4. Evaluation of comparability and amenability to monetary valuation of impacts of connected and automated transport systems
5. Developing methods for analysing costs and benefits of connected and automated transport systems

Deliverable D3.1 provided a taxonomy of potential impacts of connected and automated transport systems (CATS) and briefly discussed how to measure the impacts. Deliverable D3.2 gave an overview of methods that can be used to predict and quantify potential impacts of connected and automated vehicles. This deliverable refers to point 4 on the list above: the comparability and amenability to monetary valuation of impacts of connected and automated transport systems. The main objectives of the deliverable are:

1. To discuss which of the potential impacts of connected and automated vehicles that can be converted to monetary terms
2. To recommend monetary values for use in cost-benefit analysis for those impacts that can be given a monetary valuation
3. To discuss how to ensure that potential impacts that cannot be expressed in monetary terms will be included in wider assessments of societal impacts of connected and automated transport systems

Based on these objectives, the main research questions asked in this deliverable are:

1. Which of the potential impacts of connected and automated transport systems can be converted to monetary terms by relying on currently available valuation studies?
2. Is it possible to recommend a set of state-of-the-art monetary valuations of impacts of connected and automated transport systems?
3. How can impacts that at present cannot be valued in monetary terms best be included in a wider assessment of societal impacts of connected and automated transport systems?

The possibilities of converting impacts to monetary terms will be assessed by relying on available valuation studies found in the literature. This means that Levitate will not conduct new valuation studies. Studies designed to obtain monetary valuations of impacts for which there are no previous valuation studies is a major undertaking and there is no guarantee that meaningful results will be obtained. Historically, studies of the monetary value of goods without market prices started with those goods that were the easiest to study. Travel time was regarded as a comparatively easy item; hence the history of assigning monetary values to travel time savings goes back at least 50 years. The next impact to be studied was life and limb, which turned out to be considerably more difficult than travel time. Next followed pollution, which was even more complex than life and limb.

It is important to note that monetary valuations are still not available for all potential impacts of connected and automated transport systems. Important impacts, like inequality and equity issues, remain outside the domain of monetary valuations. It is hoped that the transition to automated transport will make access to it more equal and more fairly distributed. Yet, the fairness of a distribution is not an impact that easily, if at all, lends itself to monetary valuation. The challenge is to set up a system for assessing impacts which ensures that the non-monetary impacts are not forgotten or underestimated, simply because they do not appear on the list of monetised impacts.

Initially, to keep the deliverable self-contained, the list of potential impacts identified in deliverables D3.1 and D3.2 will be repeated.

2 Potential impacts of connected and automated transport systems

Potential impacts of connected and automated transport systems (CATS) were identified in Deliverable 3.1 of Levitate. For the sake of completeness, these impacts are also listed here. Impacts that can be quantified are identified. As a rule, an impact needs to be quantified in order to assign a monetary value to it. A list is made of impacts for which monetary valuations will be sought.

2.1 Potential impacts

Table 1 lists the potential impacts of CATS as identified in deliverable D3.1. A distinction is made between direct, systemic and wider impacts. The classification of impacts into these categories is discussed in deliverable D3.2.

A total of 33 impacts are listed. Some of the impacts are the same, but listed both at the micro level and the macro level. The direct impacts are impacts that are noticed by each road user on each trip, i.e. these are impacts at the micro level. Obviously, these impacts will vary from person to person. Levitate does not aim to describe variations between individuals with respect to impacts of CATS. However, all of these impacts have their counterparts at the systemic and wider levels of impacts.

Thus, changes in travel time are closely related to changes in road capacity and congestion. Change in travel comfort is related to trust in technology. Valuation of travel time is related to optimisation of route choice. Vehicle operation cost is related to vehicle utilisation rate. Vehicle ownership cost is related to vehicle ownership rate. Access to travel is correlated with amount of travel and inequality in transport. Individual route choice is related to optimisation of route choice.

Most of the studies that try to estimate and quantify impacts of CATS do so at the aggregate level. However, estimating aggregate impacts will capture the typical impacts at the individual level, at least average impacts.

In deliverable D3.2 studies attempting to quantify the potential impacts of CATS were reviewed. Based on that review, Table 2 lists impacts that can be quantified. For all impacts that can be quantified, it is relevant to ask whether a monetary valuation of them can be obtained.

Table 1: Potential impacts of connected and automated transport systems

Impact	Description of impact
	Direct impacts
Travel time	Duration of a trip between a given origin and a given destination
Travel comfort	Subjective rating of the level of comfort on a given trip
Valuation of time	Willingness to pay for reduced travel time
Vehicle operating cost	Direct outlays for operating a vehicle per kilometre of travel
Vehicle ownership cost	The cost of buying and keeping a vehicle
Access to travel	The opportunity of taking a trip whenever and wherever wanted
Route choice (individual)	Technology to support the best choice of route on a given trip
	Systemic impacts
Amount of travel	Vehicle kilometres or person kilometres of travel per year in an area
Road capacity	The maximum number of vehicles that can pass a section of road per unit of time
Congestion	Delays to traffic as a result of high traffic volume
Infrastructure wear	The rate per unit of time at which a road is worn down
Infrastructure design	Equipping roads with technology for vehicle-to-infrastructure communication
Modal split of travel	The distribution of trips between modes of transport
Optimisation of route choice	Direction of vehicles to routes that minimise overall generalised cost of travel for traffic as a total
Vehicle ownership rate	Percent of households owning 0, 1, 2 etc vehicles
Shared mobility	Sharing a vehicle with others on a trip-by-trip basis
Vehicle utilisation rate	Share of time a vehicle is in motion (not parked); cabin factor (share of seats in use)
Parking space	Size of areas designated for parking
Traffic data generation	The availability of detailed trip data for transport planning

Table 1: Potential impacts of connected and automated transport systems

Wider impacts	
Trust in technology	Share of population indicating high trust in automation technology
Road safety	The number and severity of accidents
Propulsion energy	Source of energy used to move vehicles (fossil fuel or electric)
Energy efficiency	Rate at which propulsion energy is converted to movement; rate of loss due to conversion of energy to heat or noise rather than movement
Vehicle emissions	Emissions in micrograms per kilometre per vehicle (by chemical)
Air pollution	Concentration of pollutants per cubic metre of air
Noise pollution	Number of individuals exposed to noise above a certain threshold
Public health	Incidence of morbidity and mortality; subjectively rated health state
Employment	Changes in number of people employed in given occupations
Geographic accessibility	Time used to reach a given destination from different origins
Inequality in transport	Statistics indicating skewness in the distribution of travel behaviour between groups according to social status
Commuting distances	Length of trips to and from work
Land use	Density of land use for given purposes (residential, industrial, etc.)
Public finances	Income and expenses of the public sector

2.2 Quantified impacts

Table 2 lists impacts of CATS that can be quantified based on studies reviewed in deliverable D3.2. It is clear that nearly all potential impacts of CATS can be quantified. In a few cases, a widely accepted scale for quantifying impacts does not exist. However, if quantifying an impact is a requirement for assigning a monetary value to it, it is clear that most impacts of CATS may in principle be converted to monetary terms.

Table 2: Possibility of quantifying impacts of connected and automated transport systems

Impact	Possibility of quantifying impact
	Direct impacts
Travel time	Can be quantified
Travel comfort	In principle possible to quantify, but no commonly accepted scale exists
Valuation of time	Willingness to pay for reduced travel time; is quantified
Vehicle operating cost	Direct outlays for operating a vehicle per kilometre of travel; is quantified
Vehicle ownership cost	The cost of buying and keeping a vehicle; is quantified
Access to travel	In principle possible to quantify, but no commonly accepted scale exists
Route choice (individual)	Characteristics like the number of alternative routes and their length and duration can be quantified
	Systemic impacts
Amount of travel	Vehicle kilometres or person kilometres of travel; is quantified
Road capacity	The maximum number of vehicles that can pass a section of road per unit of time; is quantified
Congestion	Delays to traffic as a result of high traffic volume; is quantified
Infrastructure wear	Aspects like rut depth and roughness index can be quantified
Infrastructure design	Equipping roads with technology for vehicle-to-infrastructure communication; costs can be quantified
Modal split of travel	The distribution of trips between modes of transport; is quantified
Optimisation of route choice	Direction of vehicles to routes that minimise overall generalised cost of travel for traffic as a total; can be quantified
Vehicle ownership rate	Percent of households owning 0, 1, 2 etc vehicles; is quantified
Shared mobility	Sharing a vehicle with others on a trip-by-trip basis; can be quantified
Vehicle utilisation rate	Share of time a vehicle is in motion (not parked); cabin factor (share of seats in use); are quantified
Parking space	Can be quantified
Traffic data generation	Amount of data can be quantified

Table 2: Possibility of quantifying impacts of connected and automated transport systems

Wider impacts	
Trust in technology	Can be quantified
Road safety	Can be quantified
Propulsion energy	Source of energy used to move vehicles; is not a quantitative variable
Energy efficiency	Can be quantified
Vehicle emissions	Can be quantified
Air pollution	Can be quantified
Noise pollution	Can be quantified
Public health	Can be quantified
Employment	Can be quantified
Geographic accessibility	Can be quantified
Inequality in transport	Can be quantified
Commuting distances	Can be quantified
Land use	Can be quantified
Public finances	Can be quantified

3 Monetary valuation of impacts of connected and automated transport systems

This chapter first discusses general issues related to the monetary valuation of impacts of connected and automated transport systems. The relevant schedule of monetary valuations is defined. A survey is made of available monetary valuations conforming to this schedule. The applicability of these valuations to analyses of the impacts of connected and automated transport systems is discussed. The next chapter proposes recommended valuations.

3.1 Issues related to monetary valuations

Monetary valuations of non-market goods may serve many purposes. Depending on the intended use of the valuations, analytic choices are made when developing the valuations. Some of these analytic choices and some of the uses of monetary valuations are briefly discussed below to provide guidelines for surveying the literature on monetary valuations of potential impacts of connected and automated transport systems. The main issues to be discussed are:

1. What are the main purposes of monetary valuations of various types of goods?
2. Which of these purposes are relevant for assessing the impacts of connected and automated transport systems?
3. How can a comprehensive set of valuations based on harmonised methods be obtained?

Monetary valuations of various types of goods can serve many purposes. Historically, studies of willingness-to-pay for a product or service originated in market research. The main purpose was to find out whether a business could make a profit by launching a new product or service. To help decide this, the business needed an estimate of how well the product or service was likely to sell at different prices. The question these early studies sought to answer was: Will this product or service be sufficiently demanded at a price of X to make it worthwhile for business A to offer the service or product at that price?

It was soon discovered that the same kind of study could help governments decide whether to make investments that would produce non-market goods like savings in travel time, safer roads or a cleaner environment. These goods are not traded in markets in the same sense as products or services like cars or meals in restaurants. It is nevertheless costly to produce the goods and governments wanted to allocate resources in a way that produced the largest benefits.

Today, the main application for monetary valuations of non-market goods is in cost-benefit analyses of public projects, in which the basic question is: do the benefits of the project exceed its costs? This is also the intended application of the monetary valuations of potential impacts of connected and automated vehicles. These valuations are intended for use in cost-benefit analysis of policies influencing the introduction and use of connected and automated vehicles.

However, the introduction of connected and automated vehicles differs from public investment projects. Connected and automated vehicles are private goods with a known market price. The basic question may therefore appear to be the same as that asked in market research: Should car manufacturers offer connected and automated vehicles at a given price? To answer this question, studies of the willingness-to-pay for connected and automated vehicles are needed.

The problem addressed in LEVITATE is a different one. LEVITATE adopts a societal perspective on the introduction of connected and automated vehicles, in which the main problem is how public policies can be formulated and implemented so as to maximise the benefits to society of introducing connected and automated vehicles. According to this perspective and research objective, it is not obvious that leaving the introduction of connected and automated vehicles entirely to the market mechanism will produce the largest societal benefits.

The main societal benefits of connected and automated vehicles; see e.g. Elvik et al. 2020 (Deliverable D3.2 of LEVITATE), are increased road capacity, less congestion, shorter travel time, fewer accidents and less emissions. These are the impacts that need monetary valuations.

As noted by Elvik et al. (2020), the fact that connected and automated cars may reduce the costs of travel, by having lower operating costs than a manual car and by shortening travel time, may induce more travel. This is a rebound, or feedback impact, that may reduce the societal benefits in terms of shorter travel time and less accidents and pollution. From a road user perspective, however, having greater opportunities for travel at a given cost is a benefit.

According to economic theory, trips are not made if their benefits to the traveller are smaller than their cost (to the traveller). Induced travel is a shift of the demand curve brought about by a reduction of the generalised costs of travel. For travellers as consumers, cheaper travel is a good and makes more travel possible for a given sum of money. This is clearly a benefit; it enlarges the consumer surplus of travel. From a societal perspective, induced travel is an ambiguous good. What makes it ambiguous from a societal perspective, is that it also increases the external impacts of car use. As an example, if kilometres driven by car increases, there will be a smaller reduction of accidents than if kilometres driven by cars does not increase. This holds at least as long as the accident rate per kilometre driven is not zero, which it will not be even if all cars are connected and automated. How should this be handled in the monetary valuation of the impacts of connected and automated vehicles?

The monetary valuation of any impact of connected and automated cars should refer to the final net impacts of the cars. It is what the impacts are after market equilibrium has been attained that counts. If induced travel demand fills up all of the increased road capacity, there will be no travel time savings, and this benefit of connected and automated cars thus becomes zero. But would there still be a gain in consumer surplus? Yes, in the sense that more trips than before can be taken within a given time period. Whether there will still be a societal gain is less obvious, as external congestion costs will increase, since more people are now spending time in a queue than before.

In short, the societal benefits of connected and automated vehicles are the net changes in travel time, accidents and pollution of car use associated with their introduction. Societal interest in promoting the use of connected and automated vehicles consists only of these benefits. If connected and automated vehicles are no safer, no less noisy, no cleaner, etc. than current motor vehicles, they do not bring about any societal benefits. In the societal perspective, it is by and large irrelevant how much car owners have to pay to buy connected and automated vehicles.

The words “by and large” were inserted because exceptions to the rule can be imagined. If connected and automated vehicles become very expensive, but are expected to bring about huge benefits, a case can be made for subsidising them in order to realise these benefits. Therefore, one cannot completely ignore studies of the willingness-to-pay for automation technology and what these studies tell us about the likely demand for connected and automated vehicles.

The rebound impacts in terms of increased travel demand are unwanted from a societal perspective, as increased travel demand will increase the external impacts of car use and thus reduce societal benefits. The more traffic increases, the smaller will be the reduction of travel time, accidents, pollution, and so on. There is, in that sense, a conflict of interest between society at large and car users as a group. Car users as a group gain from increased travel and their benefit equals the increase of consumers’ surplus. Society, on the other hand, loses because the external impacts are greater than they would have been without the increase in traffic volume. From a societal perspective, the best estimate of benefits is once more the net impacts, i.e. the increase in consumers’ surplus associated with induced travel demand, plus the net changes in travel time, accidents and pollution.

The above discussion can be summarised as follows with respect to the three questions asked at the beginning of this section:

1. The monetary valuations of impacts of connected and automated vehicles should represent the societal benefits of their introduction. These benefits consist primarily of a net reduction of negative external impacts of motor vehicle use, in terms of congestion, accidents and pollution. Benefits to car users in terms of induced travel are also part of the societal benefit.
2. The main application of monetary valuations of impacts of connected and automated vehicles is cost-benefit analyses adopting a societal perspective. These analyses will be applied to policy options for regulating the introduction and use of connected and automated vehicles in order to maximise their societal benefits.
3. Monetary valuations which are consistent with this application should be based on studies of willingness-to-pay. Impacts included in a schedule of monetary valuations should be final and exhaustive (i.e. all relevant impacts should be included), but not involve double counting.

A schedule of monetary valuations, as mentioned in point 3, is a list of impacts with their valuations. The impacts included on such a list should be final and exhaustive and avoid double counting. Final means that the impacts are the end point of a causal chain. Thus, air pollution is a causal chain with many stages such as the production of polluting substances, the dispersion of these substances in air, the inhalation of the substances by humans, and changes in morbidity and mortality attributable to polluting substances. Monetary valuations should refer to the final impacts, morbidity and mortality.

An impact is relevant if connected and automated vehicles may influence it and if preferences are attached to it. Thus, fear of cyber attacks is relevant if it makes travel by automated vehicles uncomfortable and generates a desire for eliminating or reducing the risk of cyber attacks.

Double counting is to include the same impact twice. It would, for example, be double counting to add a valuation of travel time savings to a reduction of the generalised costs of travel, as the valuation of travel time is part of the generalised costs of travel and therefore already accounted for.

3.2 A schedule of monetary valuations of potential impacts

The most likely impacts of connected and automated vehicles for which a monetary valuation is needed include:

1. Changes in road capacity resulting in changes in congestion and travel time.
2. Changes in the cost of ownership and use of motor vehicles.
3. Changes in traffic volume, resulting from increased traffic volume induced by a reduction of the generalised costs of travel.
4. Changes, most likely a reduction, in the number of accidents.
5. Changes, most likely a reduction, in vehicle emissions and air pollution.

The societal benefit of a more efficient utilisation of road capacity is, all else equal, a reduction of congestion, which takes the form of a reduction of travel time for a given trip. However, savings of travel time is not the only benefit of less congestion, as fuel consumption, at least for vehicles running on fossil fuel, depends on speed and increases at low and highly variable speed, which is typical of congested traffic.

Historical experience, as discussed in deliverable D3.2 (Elvik et al. 2020), shows that an increase in road capacity is likely to induce increased travel demand. This is because savings in travel time reduce the generalised costs of travel, of which travel time is an important part. The generalised cost of travel is the monetary value of the sum of all sacrifices made by travelling. For travel by car, these include vehicle operating costs, the costs of travel time and the internal part of accident costs. Vehicle operating cost includes not just the variable costs incurred on a trip, but also vehicle ownership costs converted to a depreciation rate per kilometre driven.

The generalised cost of travel is a very comprehensive concept and essentially includes everything except the external costs of travel, i.e. the costs that travellers do not take into account when travelling. This includes external costs of congestion, external accident costs and the full costs of noise and air pollution, assuming that the latter two items do not influence individual travel behaviour.

It is important to be very specific about what is included in the generalised cost of travel in order to avoid double counting of impacts. The concept is, ultimately, subjective like so many other concepts in modern economic theory. It refers to what a traveller takes into account, and that may vary between individuals. Thus, if someone who buys an electric car states that one of the reasons for doing so was to reduce global warming, then global warming is part of the generalised cost of travel for this individual. A person who chooses a car based on its performance in pedestrian impact tests in Euro NCAP may reasonably be viewed as including some of the costs of pedestrian impacts in his or her generalised costs of travel.

It is impossible to know precisely what goes into the generalised cost of travel for each individual. This gives analysts great freedom in specifying what they, for analytic purposes, include in the concept. The main guideline is to define the components of valuation in such a way that the valuations applied to impacts in any cost-benefit analyses are: (1) exhaustive (includes all impacts), (2) not involves double counting (includes each impact only once), (3) refer to end-point net impacts (final outcomes when all intermediate effects have reached equilibrium). To clarify this guideline, it is instructive to discuss an example.

Table 3 shows estimated impacts of connected and automated vehicles in an urban traffic environment, estimated by applying dose-response curves developed in deliverable D3.2 (Elvik et al. 2020).

Table 3: Summary of estimated net impacts of connected and automated vehicles in urban areas. Relative changes from a baseline 0% market penetration.

Market penetration of automated vehicles (%)	Traffic volume	Travel time	Air pollution	Number of accidents
0	100.0	100.0	100.0	100.0
10	102.4	99.3	98.4	103.8
20	104.8	98.6	96.9	100.6
30	107.2	97.8	95.4	97.4
40	109.8	97.1	94.0	94.0
50	112.4	96.3	92.7	90.6
60	115.0	95.6	91.5	87.2
70	117.7	95.0	90.4	83.7
80	120.5	94.2	89.4	80.1
90	123.3	93.5	88.6	76.5
100	126.2	92.8	87.7	72.8

Traffic volume is expected to increase. This is the result of reduced generalised costs of travel. The relevant monetary valuation of this impact is the increase in consumer surplus associated with the increase in travel demand. But how can we know what the generalised costs of travel were initially, and how can we know how much they have been reduced? Table 3 only shows the final net impacts. A growth in traffic volume of about 25% can arise from a wide range of changes in the generalised cost of travel.

The size of the change in the generalised cost of travel producing an increase in traffic volume of about 25% depends on the elasticity of travel demand with respect to the generalised cost of travel. If, for example elasiticity is -0.5, a 50% reduction of the generalised cost of travel would be associated with an increase of 25% in travel demand. Estimates of the elasticity of travel demand with respect to the generalised costs of travel vary (Litman 2019). If an elasticity of -1.0 is assumed, a 25% reduction of the generalised cost of travel would be sufficient to induce an increase of 25% in travel demand. The assumption made about the elasticity of travel demand with respect to the generalised costs of travel is decisive for the estimate of these costs and for the size the benefits in terms of increased consumer surplus. A simple illustration can show this.

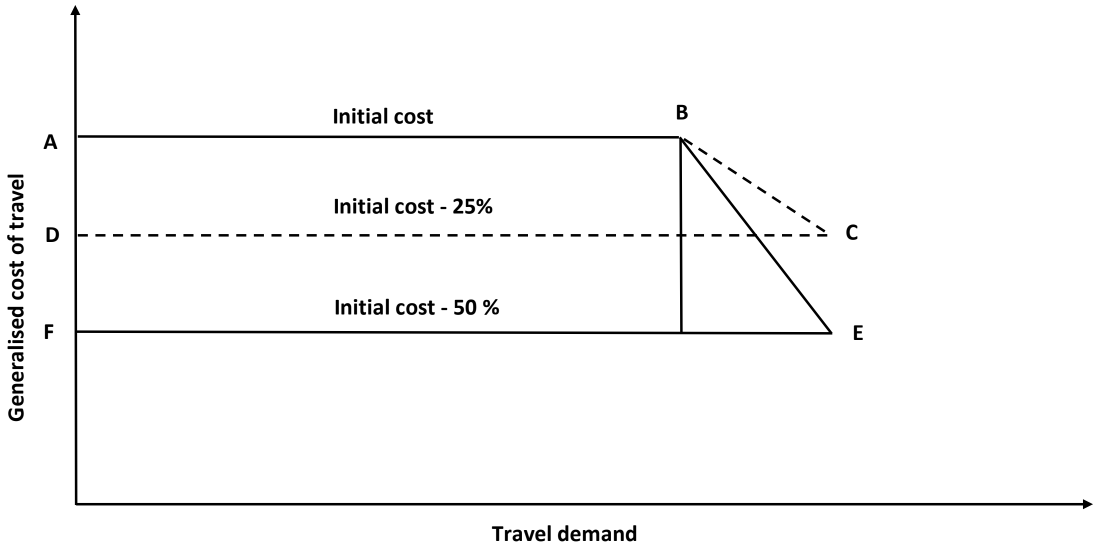

Figure 1: Change in consumer surplus associated with two values of elasticity of demand with respect to generalised cost of travel

The initial generalised cost of travel is A. If demand elasticity is -0.5, a reduction of the generalised cost by 50%, from point A to point F, will generate an increase of 25% in travel demand. The change in consumer surplus will be the area A-B-E-F. If, on the other hand, elasticity is -1.0, a reduction of the generalised cost of travel of 25% will induce 25% increase in travel demand. The change in consumer surplus will now be the area A-B-C-D, which is considerable smaller than the area A-B-E-F. The more elastic demand is, the smaller will be the increase in consumer surplus associated with a reduction of the generalised cost of travel.

Do studies of potential changes in the generalised cost of travel associated with the introduction of connected and automated vehicles indicate how large the changes will be? Some studies give indications, but the results are not entirely consistent. There is, however, agreement that fuel consumption is likely to be reduced and that the value of travel time savings will be reduced. The latter can be thought of as a reduction of the contribution of the monetary valuation of travel time to the generalised cost of travel. If estimates can be given of the contribution these items make to the generalised cost of travel, the overall change may be estimated. A definition of the generalised cost of travel is proposed in a subsequent section, based on a review of estimates found in the literature.

Meanwhile, the other impacts listed in Table 3 will be considered. In addition to an increase in traffic volume, there is a reduction of travel time, less air pollution and a reduction of the number of accidents. Are these impacts included in the generalised cost of travel, or can they be added to changes in the generalised costs of travel?

Savings in travel time will enter the generalised costs of travel in the form of a reduction of the costs of travel time; both because these costs are incurred for a shorter period and because the monetary valuation of each unit of time may be lower in an automated vehicle than in a manually driven vehicle. How much shorter travel time gets, is shown by the column for travel time; at 100% market penetration, a reduction of about 7% is predicted. This should be interpreted as a reduction of travel time for everybody. While each traveller will value and include in his or her generalised cost of travel the reduction of travel time he or she experiences, it is not likely that the benefit for other travellers will be included. Thus, the general reduction of travel time benefitting everybody can be interpreted as a reduction of the external costs of congestion. The reduction of the external costs of congestion can be added to the reduction of the generalised cost of travel without double counting.

In Table 3, changes in air pollution have been assumed to be proportional to changes in fuel consumption. This is correct for CO_2, but not necessarily for other pollutants. Microsimulation in work packages 5-7 of LEVITATE may produce estimates of the changes in emissions of specific pollutants associated with increased market penetration of connected and automated vehicles. A reduction of fuel consumption is included in the generalised cost of travel. However, the public health benefits of reduced pollution are not likely to be included in the generalised cost of travel. It is therefore appropriate, and does not involve double counting, to add a monetary valuation of the external benefits of reduced air pollution to the generalised cost of travel.

The final impact listed in Table 3 is changes in the number of accidents. Part of the societal costs of accidents are internalised and are part of the generalised cost of travel. This applies to all costs that are paid for by means of insurance. However, not all costs of accidents are internalised by means of insurance. More specifically, most of the human costs, i.e. the loss of welfare associated with loss of life or health losses, are not insurable and to a large extent external. It is therefore correct to add a reduction of the external costs of accidents to represent the societal value of a reduction of the number of accidents.

To sum up, the following monetary valuations of the potential impacts of connected and automated vehicles listed in Table 3 will be exhaustive, not involve double counting and refer to final outcomes of these impacts:

1. Changes in the amount of travel are valued in terms of the generalised cost of travel. The generalised cost of travel is the sum of the costs of vehicle operation (including depreciation), travel time and the internal part of the cost of accidents.
2. The benefits of an increased amount of travel is the monetary value of the increase in consumer surplus, estimated according to the generalised cost of travel.
3. A reduced amount of travel has disbenefits corresponding to the loss of consumer surplus estimated by relying on the generalised cost of travel.
4. Changes in travel time result from changes in road capacity and congestion. For each traveller, these changes are part of the generalised cost of travel. However,

each traveller will not include as a benefit the savings in travel time for other travellers. Thus, savings in travel time should be included as a reduction of the external costs of congestion.
5. Changes in fuel consumption are included in the generalised cost of travel. However, the resulting changes in air pollution are not included and should be added as a benefit, applying monetary valuations of the external costs of air pollution.
6. Changes in the number of accidents are partly reflected in changes in the generalised cost of travel. To capture all societal costs associated with changes in the number of accidents, the external cost of accidents should be added to the costs that are included in the generalised cost of travel.

The following sections reviews studies providing estimates of the relevant monetary valuations.

3.3 The generalised cost of using an automated vehicle

The generalised cost of using an automated vehicle will be defined as the sum of the following cost items:

1. The additional cost of buying the vehicle, i.e. how much more expensive an automated car will be compared to a manual car. These costs will be converted to a cost per kilometre of driving.
2. Variable costs of vehicle operation. This includes all costs that are, roughly, proportional to kilometres driven and are incurred at an approximately constant rate per kilometre driven. This includes fuel, tyres, and other variable costs.
3. Internal cost of accidents; paid by means of insurance. Most insurance schemes are still not based on pay-as-you-drive but involve paying a fixed premium per year.
4. Valuation of travel time. This is the valuation of the time each car occupant spends in the car or public transport vehicle. It does not include the time other road users spend in traffic.

3.3.1 Cost of ownership of automated cars

Studies of the cost of ownership of an automated car were reviewed in deliverable D3.2 (Elvik et al. 2020). The review is reproduced here for convenience.

Car ownership costs include the costs of buying and keeping a car and the costs of operating it. Studies have been made to determine whether vehicle automation will change these costs.

Fagnant and Kockelman (2015) estimate that an automated vehicle initially will cost 10,000 US dollars more than a conventional vehicle, but that the additional cost will fall to 5,000 US dollars at 50 % market penetration and to 3,000 US dollars when automated vehicles reach 90 % market penetration. They refer to other studies that estimate the cost of an automated vehicle to be between 25,000 and 50,000 US dollars. The study did not estimate the generalised cost of travel, but assumed in a cost-benefit analysis that at 90% market penetration, accidents would be reduced by 90%, freeway congestion reduced by 60%, arterial congestion (presumably urban) reduced by 15% and fuel consumption reduced by 25%.

Bansal and Kockelman (2017) estimate the cost of level 3 automation to 15,000 US dollars in 2015, dropping to 11,607 dollars in 2020 and 3,220 dollars in 2045. The cost of level 4 automation was estimated as 40,000 US dollars in 2015, reducing to 30,951 dollars in 2020 and 8,586 dollars in 2045.

Daziano et al. (2017) mention that the cost of an add-on package capable of full automation on certain highways is 10,000 US dollars.

Wadud (2017) reported a cost of ownership analysis for automated vehicles. He estimated current costs of owning and operating cars by income quintiles (shares of one fifth) in Great Britain. He estimated that buying an automated vehicle in 2020 would cost 16,600 US dollars more than a conventional vehicle, but that cost would fall by 5 % per year. Total costs of ownership were estimated to increase by 29.6% in the lowest income quintile, falling to 16.3%, 7.9% and 2.9% in the next income quintiles. Only the upper fifth income quintile (the top 20% income earners) would save costs. For this group, a reduction of car ownership costs of 6.4% was estimated. For commercial vehicles, cost savings ranging from 15 to 30% were estimated. It should be noted that no savings in insurance costs was assumed. Wadud argued that although automated vehicles will have a lower accident rate than conventional vehicles, they will be more expensive to repair or replace, resulting in an unchanged insurance premium. The cost estimates can be used to develop estimates of the generalised cost of travel.

Bösch et al. (2018) compared the costs of owning and operating conventional cars to automated cars. They assumed a purchasing price of Swiss francs 15,000 for a small car, 35,000 for a midsize car and 66,000 for a van. One Swiss franc corresponded to 0.98 US dollars in 2018. For private cars, the cost per kilometre of an automated car were found to be 4 % higher than the cost of a conventional car. The main contributor to the increased cost was depreciation, which was higher because the automated car was assumed to be more expensive than the conventional car. Insurance costs were assumed to decline by 50%. The per kilometre cost of a taxi was estimated to be 85% lower for an automated taxi than for a taxi with a driver.

Shabanpour et al. (2018), in a stated preference study, assumed a purchasing price for an automated vehicle of either 40,000, 50,000 or 60,000 US dollars.

Slowik and Sharpe (2018) estimated the additional cost of level 5 automation technology for a truck to be 23,400 US dollars. The technology included sensors, communication systems and processing software.

Tirachini and Antoniou (2020) give cost estimates for fully automated vehicles of 29,490 Euro for a car, 43,433 Euro for a van, 281,234 Euro for a minibus, 419,429 Euro for a standard bus, and 627,696 Euro for an articulated bus. Presumably, all these estimates refer to the extra costs of an automated vehicle compared to an otherwise identical non-automated vehicle.

There is no consensus about what the additional cost of an automated vehicle will be, but most estimates range from a low of 10,000 US dollars to a high of 40,000 US dollars. It is likely that automated cars will be offered at different prices, just as conventional cars are today. It is proposed to use the following costs for buying an automated car:

Best estimate:	25,000 US dollars
Lower estimate:	10,000 US dollars
Upper estimate:	40,000 US dollars

It is reasonable to expect the cost of an automated car to drop over time. In deliverable D3.2 three logistic functions were fitted to model the market penetration of automated vehicles over time. These functions predicted that market penetration would take between 11 years (fastest) and 27 years (slowest), with 17 years as best estimate. It is logical to relate these estimates to the three cost estimates above, meaning that at the lowest cost, market penetration would take 11 years, at the middle cost it would take 17 years and at the highest cost, it would take 27 years.

Bansal and Kockelman (2017) assumed that the real price of an automated car would drop by 5% each year. It is probably reasonable to assume falling costs, as technological innovation, learning-by-doing, and economies of scale in manufacturing will tend to reduce production costs as automation technology matures and automated cars are manufactured in large numbers. As an example, a colour TV had a price tag of about NOK 6,500 in Norway in 1975. Today, a flat screen TV can be bought from about NOK 10,000 (1 NOK = 0.09 US dollars in March 2020). During the same period consumer prices increased by a factor of almost 5.8. A colour TV is considerably cheaper today than it was in 1975 (the 1975-price multiplied by 5.8 ≈ 37,500). In real terms, the price has fallen by about 3% per year.

In the analyses of potential impacts of connected and automated vehicles presented in deliverable D3.2, effects are stated as a function of the rate of market penetration of connected and automated vehicles, It is, however, no problem to convert the three durations for full market penetration above to percentages year-by-year. If, following Bansal and Kockelman (2017), a 5% price reduction each year is assumed, this results in the following estimates of cost at various levels of market penetration (Table 4).

At the lowest cost estimate, prices are estimated to decline by less than 50% from the initial level. At the highest initial cost estimate, prices are estimated to decline by 75%. The reason for this difference is that at the lowest initial price, full market penetration is assumed to take only 11 years (more people can afford an automated car if it is cheap than if it is expensive), whereas at the highest initial price, full market penetration is assumed to take 27 years.

When converting the ownership costs to a per kilometre cost, it will be assumed that vehicles run 200,000 kilometres in their service life and are written down linearly to a value of zero at the end of service life. The cost of replacing the vehicle at the end of its service life is set equal to the predicted price at 100% market penetration. Mean service life is set equal to the mean time for a complete turnover of the market, i.e. either 11, 17 or 27 years. Replacement cost is included in terms of a capital cost, which is equal to the amount of money one has to deposit at the start of the period in order to pay the cost of replacement in due time. A deposit will earn interest during either 11, 17 or 27 years.

Current market interest rates on bank deposits in Europe are extremely low, close to zero. Rather than using these rates, the currently recommended discount rate for use in cost-benefit analysis has been applied. This rate is 3% per year. Thus, for the lowest cost estimate, the predicted replacement cost after 11 years is 5,688 US dollars (Table 4). A deposit growing at annual rate of 3% will have grown by 38% in a period of 11 years. Thus, the deposit needed to pay the replacement cost is 5,688/1.38 = 4,109. This amount is converted to a per kilometre cost for the service life of the vehicle by dividing it by 200,000. The replacement deposit is listed in the bottom row of table 4.

Table 4: Cost of buying an automated car in fixed prices.

Market penetration of automated vehicles (%)	Low estimate (US dollars)	Best estimate (US dollars)	High estimate (US dollars)
0	10 000	25 000	40 000
10	9 451	22 912	34 827
20	8 933	20 999	30 323
30	8 443	19 246	26 401
40	7 980	17 638	22 987
50	7 542	16 166	20 014
60	7 128	14 816	17 425
70	6 737	13 578	15 172
80	6 367	12 445	13 210
90	6 018	11 405	11 501
100	5 688	10 453	10 014
Replacement deposit	4 109	6 324	4 508

The prices are stated in US dollars. A rate for converting them to Euros, which may be more relevant in LEVITATE, will be given later.

3.3.2 Vehicle operating costs

There are very few studies of whether vehicle operating costs will be different for automated vehicles than for manual vehicles. Only two studies have been found (Wadud 2017, Bösch et al. 2018). Fortunately, both studies are rigorous and go in great detail. They have therefore been used to estimate changes in vehicle operating costs.

Both studies include more than vehicle operating costs. Wadud includes both ownership costs, dealt with above, and the costs of travel time, to be discussed in section 3.3.4. When these items are omitted, his study found that operating costs of automated vehicles will, on the average, be about 3% lower than for manual vehicles. Mean variable cost per kilometre would decline from 0.208 pounds per mile to 0.202 pounds per mile. Changes in insurance costs were then not included, as these reflect internalised accident costs, which will be treated as a separate cost item.

Bösch et al. (2018) also included ownership costs. The following cost items specified by Bösch et al. are treated as variable operating costs: fuel, cleaning, parking and tolls, tax and maintenance and wear. These costs were estimated at 0.199 Swiss francs per kilometre for manual cars and 0.193 Swiss francs for automated cars. This is a cost reduction of 3%, identical to what Wadud found.

Assuming that most of the work on these papers took place the year before they were published, the costs estimated by Wadud (2017) were converted to Euro applying the 2016 exhange rate between UK Pounds and Euro. Cost per kilometre, for manual and automated cars then became, respectively, 0.232 and 0.225 Euro per kilometre. For Bösch et al. (2018) the 2017 exchange rate between Swiss francs and Euro was applied. Costs per kilometre in Euros were 0.179 Euros per kilometre for a manual car and 0.175 Euros per kilometre for an automated car. The estimates are close to each other.

3.3.3 Internal cost of accidents

The societal cost of accidents consists of one part which is internalised by road users and is part of the generalised cost of travel and one part which is external, i.e. not paid for by road users. To correctly estimate the monetary value of the safety benefits of connected and automated cars, it is neccesary to identify both the internal and external cost of accidents.

Several studies have been made to determine internal and external costs of accident and traffic injury. In an early study, Elvik (1994) made a distinction between three types of external costs:

1. The system externality: These are costs that are paid by society in general, for example free hospital care.
2. The physical externality: These are costs one group of road users impose on another group of road users in accidents in which both groups are involved. As an example, it is almost exclusively cyclists who are injured in crashes with trucks. Thus, trucks have an external cost of injury involving cyclists.
3. The traffic volume externality: these are the marginal costs associated with the addition of one vehicle to traffic.

Elvik found that the system externality and the physical externality represented 42% of the total costs of traffic injury. Dividing these external costs by kilometres of driving gives the average external cost of traffic injury. He was not able to estimate the traffic volume externality.

A report on the external costs of transport by van Essen et al. (2019) took as a starting point that external costs of accidents are all costs that are not covered by risk oriented insurance premiums. Costs that are not covered by insurance are external. This definition implies that the monetary valuation of welfare, expressed in terms of willingness-to-pay for reduced risk of death or injury, is treated as an external cost. Treating the monetary valuation of welfare losses, often referred to as human costs, as external is contrary to almost all other theoretical or empirical studies of external accident costs (Elvik 1994, Jansson 1994, Lindberg 2001, 2005). A more common point of view is that human costs are internal, as they reflect the willingness-to-pay of those who sustain injuries or benefit from a reduction of risk. It is true that in stated preference studies designed to estimate human costs, no actual payments are made. But if there was an effective payment mechanism, the cost would definitely be internal.

Van Essen et al. (2019) appear to agree, as they write: "Traffic participants are assumed to be aware of the fact that their decision to enter the traffic may result in an accident (they internalise this risk). Therefore, their own human costs are considered internal to them, once they have made the decision to enter the traffic." But this means that one cannot use insurance payments as the only criterion for classifying costs as internal or external.

To define more precisely which costs are internal or external, Elvik (1994) made a distinction between four parties:

1. Road users
2. Household members
3. Private third parties ("the rest of society")
4. The public sector

These parties should be viewed as role categories only. Thus, an individual may both be road user who is involved in an accident, the member of the household of a road user who is involved in an accident, a "third party" who is delayed by an accident he or she is not involved in, or a tax payer who contributes to funding public sector activities.

Furthermore, Elvik made a distinction between material costs, which are payments made by one or more of the four parties, and immaterial costs, which are not payments, but monetary valuation of goods not traded in markets. Based on these distinctions, internal costs are all material and immaterial costs incurred by road users in their role as road users becoming involved in accidents. This includes not just insurance payments, but also the valuation of human costs, and loss of income, to the extent private insurance or public social security does not guarantee full replacement of income in case of an injury.

Van Essen et al. (2019) also state the share of various cost items that they regard as external. In table 5, the percentage of costs classified as external is compared between Elvik (1994) and van Essen et al. (2019). Note that if, for example, 50% of costs are classified as external, this means that 50% are internal. In general, the studies do not differ greatly with respect to the share of costs classified as external. Elvik classifies a higher share of medical costs as external. His study applied to Norway, in which the public sector provides medical care free of charge, except for minor expenses. There may still be private costs, in particular for those who are seriously injured. They may, as an example, need to adapt their home to the use of a wheelchair, and although the public will pay part of the expenses, there will be significant private costs.

The costs associated with loss of output are also to a large extent external in Norway. The basic rule is that you get fully paid when on sick leave. This, however, only lasts up to one year. If you have not recovered and returned to work after one year, income support is reduced and you will suffer a loss of income.

Table 5: Classification of accident costs as external or internal.

Cost item	Percent external cost (Elvik 1994)	Percent external cost (van Essen et al. 2019)
Victim's human cost	0	Not clear
Household members' human cost	100	Not mentioned
Medical costs	71	50
Lost output	61	55
Property damage costs	14	0
Administrative costs	33	30
Other costs	100	Disregarded
All cost items	29	

Van Essen et al. (2019) assumed that all costs of property damage are internal. However, even some of these costs may be external. Insurance pays for damage to vehicles and people. If you cause damage to objects not covered by insurance, the owner of the uninsured objects must pay for repair and replacement. With respect to administrative costs, the two studies agree that about 30% of these costs are external.

One item in Table 5 needs explanation. That is the item called household members' human costs. This item includes human costs not included in the willingness-to-pay for reduced risk. In some early studies of willingness to pay, the question was asked whether the amount respondents stated they were willing to pay included the benefits of reduced risk to household members, or just their personal benefit. Most respondents answered that only their personal benefit was included. However, the death or serious injury of one member of a family will have an impact on other family members. Based on a literature survey, Elvik (1994) conservatively estimated the human costs for household members to 12.5% of the self-regarding value of reduced risk as stated in willingness to pay surveys. Since respondents stated that this was not included, it is an external cost.

The estimates of the share of external costs per cost component given in Table 5 can be combined with the harmonised cost estimates developed in SafetyCube (Wijnen et al. 2017) in order to estimate what a representative value for the share of external costs in Europe would be. To provide a basis for such an estimate, Table 6 reproduces the harmonised injury cost estimates developed in SafetyCube.

It will be assumed that the human costs are fully internalised. Applying the percentages for external costs estimated by Elvik (Table 5), the external costs are found to be 247,179 Euro, which is 11% of the total cost. This is considerably less than the 29% estimated by Elvik (1994) for Norway for 1991. Applying the estimates of van Essen et al. (2019), the external costs are 366,403 Euro, or 16% of the total costs.

Table 6: Harmonised costs of traffic injury in Europe. Source: Wijnen et al. (2017), SafetyCube deliverable D3.2

Cost component	Fatal injury	Serious injury	Slight injury
Human costs	1 587 001	230 385	15 597
Medical costs	5 430	16 719	1 439
Lost output	655 371	43 627	2 669
Property damage	11 555	7 622	5 317
Administrative costs	6 346	4 364	1 876
Other costs	3 638	413	519
Total costs	2 269 346	303 130	27 418

The three estimates, 29% for Norway in 1991, 11% for the harmonised costs in 2015, applying the shares of external costs from Elvik (1994), and 16% for the harmonised costs in 2015 from van Essen et al. (2019) are quite far apart.

A recent Norwegian study (Rødseth et al. 2019) estimated the system externality as 12% of total cost of accidents. Thus, the mean of the three most recent estimates is that the system externality represents 13% of the total cost of accidents.

With respect to the physical externality, Elvik (1994) estimated that it represented 13% of the total costs. In the most recent Norwegian study, the physical externality was 33% of the total cost. Van Essen et al. (2019) state what they refer to as the "risk internalisation factor" for six types of vehicles. On the average, the value of the factor is 0.56, implying that the physical externality, i.e. injuries a vehicle cause to those who are not occupants of the vehicle, is 44%.

The traffic volume externality will not be considered here, but needs to be modelled when doing cost-benefit analyses of connected and automated vehicles. Based on the recent Norwegian study (Rødseth et al. 2019) the sum of the system externality and the physical externality is 46% of the total cost of traffic injury. The study by van Essen et al. (2019) suggests that 60% of the costs are external (16% for system externality plus 44% for physical externality).

It is not essential to obtain very precise estimates; indicating the order of magnitude is sufficient. Based on the studies quoted above, it is concluded that, as a simple rule, 50% of the costs of traffic injury will be classified as internal and 50% as external.

3.3.4 Internal costs of travel time

The final item of the generalised costs of travel to be discussed, is the internal cost of travel time. The comprehensive study by van Essen et al, (2019) specifies external costs of traffic congestion, but does not discuss internal costs of travel time. The best source of estimates of the internal costs of travel time, is the meta-analysis presented by Wardman et al. (2016).

Table 7 shows estimates of the internal costs of travel time for European countries. Based on the bottom row of the Table, a European average value can be estimated.

Table 7: Internal values of travel time for European countries. Based on Wardman et al. 2016

Table 9
Implied values of time (€ per hour 2010 incomes and prices).

	GDP_PPP per capita	Gross labour cost	Car commute		Car other			Car EB			Train EB	Bus Comm	Air EB
			Urban free flow	Urban cong	Urban free flow	Urban cong	Inter free	Urban free	Urban cong	Inter free	Inter	Urban	Inter
Austria	27925	28.0	8.04	11.43	7.08	10.06	9.79	15.89	22.59	21.97	32.06	6.09	58.83
Belgium	26290	35.3	7.54	10.72	6.64	9.44	9.18	14.84	21.10	20.52	29.99	5.72	55.02
Bulgaria	9733	3.1	2.64	3.75	2.33	3.31	3.22	4.80	6.83	6.64	9.95	2.06	18.26
Croatia	13499	8.6	3.73	5.30	3.28	4.67	4.54	6.96	9.90	9.63	14.31	2.88	26.25
Cyprus	22142	17.7	6.29	8.94	5.54	7.88	7.66	12.21	17.36	16.88	24.78	4.80	45.47
Czech Rep	17617	9.8	4.94	7.02	4.35	6.19	6.02	9.42	13.39	13.02	19.23	3.79	35.28
Denmark	28030	36.7	8.07	11.47	7.11	10.10	9.82	15.96	22.69	22.06	32.20	6.12	59.08
Estonia	14227	7.6	3.94	5.61	3.47	4.94	4.80	7.39	10.51	10.22	15.17	3.04	27.83
Finland	25461	28.8	7.29	10.36	6.42	9.13	8.88	14.31	20.34	19.78	28.94	5.54	53.10
France	23807	32.6	6.79	9.65	5.98	8.50	8.27	13.26	18.85	18.33	26.86	5.17	49.28
Germany	26107	28.8	7.48	10.64	6.59	9.37	9.11	14.72	20.93	20.35	29.75	5.68	54.60
Greece	19830	17.0	5.60	7.96	4.93	7.01	6.82	10.77	15.32	14.90	21.93	4.28	40.23
Hungary	14341	7.0	3.98	5.65	3.50	4.98	4.84	7.46	10.60	10.31	15.30	3.06	28.08
Ireland	28248	28.9	8.13	11.57	7.16	10.19	9.91	16.10	22.89	22.26	32.48	6.16	59.59
Italy	22263	26.8	6.33	8.99	5.57	7.92	7.70	12.29	17.47	16.99	24.93	4.82	45.75
Latvia	11366	5.5	3.11	4.42	2.74	3.90	3.79	5.73	8.15	7.92	11.82	2.41	21.69
Lithuania	12674	5.4	3.49	4.96	3.07	4.37	4.25	6.48	9.22	8.96	13.34	2.70	24.48
Luxembourg	60120	32.9	18.06	25.68	15.91	22.62	21.99	37.94	53.95	52.46	75.11	13.43	137.81
Macedonia	7852	3.3	2.10	2.99	1.85	2.64	2.56	3.76	5.35	5.20	7.84	1.65	14.39
Malta	18382	11.9	5.17	7.35	4.55	6.47	6.29	9.89	14.06	13.67	20.16	3.96	36.99
Netherlands	29432	31.1	8.49	12.08	7.48	10.64	10.34	16.87	23.98	23.32	33.99	6.43	62.37
Norway	39945	41.6	11.73	16.68	10.33	14.69	14.28	23.85	33.92	32.98	47.71	8.81	87.54
Poland	13890	7.2	3.84	5.47	3.39	4.81	4.68	7.19	10.23	9.94	14.77	2.97	27.10
Portugal	17751	12.6	4.98	7.08	4.39	6.24	6.06	9.50	13.51	13.14	19.39	3.82	35.58
Romania	10143	4.1	2.76	3.92	2.43	3.45	3.36	5.03	7.16	6.96	10.42	2.14	19.12
Serbia	7929	4.9	2.13	3.02	1.87	2.66	2.59	3.81	5.41	5.26	7.93	1.66	14.55
Slovakia	16230	7.7	4.53	6.44	3.99	5.67	5.52	8.58	12.20	11.87	17.55	3.48	32.21
Slovenia	18798	14.6	5.29	7.52	4.66	6.63	6.44	10.14	14.42	14.02	20.66	4.05	37.92
Spain	22259	20.7	6.32	8.99	5.57	7.92	7.70	12.28	17.47	16.98	24.93	4.82	45.74
Sweden	27449	33.6	7.89	11.22	6.95	9.88	9.61	15.58	22.16	21.55	31.46	5.99	57.72
Switzerland	32376	50.1	9.39	13.36	8.27	11.76	11.44	18.79	26.72	25.98	37.78	7.10	69.33
U.K.	24909	20.0	7.12	10.13	6.27	8.92	8.67	13.96	19.84	19.30	28.24	5.41	51.82
U.K. −39%	24909	20.0	4.34	6.18	3.82	5.44	5.29	8.52	12.10	11.77	17.23	3.30	31.61
% GLC			41%	58%	36%	51%	50%	78%	110%	107%	159%	31%	289%

The mean European gross labour cost (GLC in column 2 of Table 7) is 22.89 Euro (per hour). Thus mean European internal values of time in 2010 Euros are:

- Car commute, urban, free flow: 9.38
- Car commute, urban, congested: 13.28
- Car other trips, urban, free flow: 8.24
- Car other trips, urban, congested: 11.67
- Car other trips, interurban, free flow: 11.45
- Car business, urban, free flow: 17.85
- Car business, urban, congested: 25.18
- Car business, interurban, free flow: 24.49
- Bus commute, urban: 7.10

Values for walking and cycling can also be deduced from the study of Wardman et al. (2016) as they are given as multipliers of the values for in-vehicle time. The values in

Table 7 refer to individuals. Thus, to obtain values per vehicle hour, one must account for vehicle occupancy.
Studies reviewed in deliverable D3.2 suggest that the value of time will be lower in automated vehicles than in manually operated vehicles. The values above refer to manually operated vehicles. The section reviewing studies of the value of time in automated vehicles in deliverable D3.2 is inserted here for convenience.

Willumsen and Kohli made a Delphi survey of 45 transport experts and asked them about changes in the valuation of travel time associated with vehicle automation. They made a distinction between commuting trips, trips made as part of work and other trips (leisure trips). As can be seen from Table 8, the mean values of travel time given by the experts indicated a relative reduction of about 15% regardless of trip purpose.

Kolarova et al. (2018) studied the value of travel time savings in conventional and automated vehicles. They found that the value of time in a private automated vehicle was about 45-55% lower than in a conventional private car. In a driverless taxi, the value of time was about 15-35% lower than in a conventional private car.

Table 8: Relative valuation of travel time in automated vehicles. Current valuation = 100.

Study	**Vehicle use**	**Current valuation of travel time = 100**			
		Commute	In work	Leisure	Mean
Willumsen, Kohli 2016	Individual	84.1	87.1	85.2	85.5
		Low inc	Middle inc	High inc	Mean
Kolarova et al. 2018	Individual	45.4	44.3	57.8	49.2
	Shared	69.0	67.3	87.7	74.7
		Low inc	Middle inc	High inc	Mean
Steck et al. 2018	Individual	69.4	69.5	69.5	69.5
	Shared	90.0	90.0	90.0	90.0
		Driver	Passenger		Mean
Flügel et al. 2019	Individual	69.6	44.6		57.1
	Shared	79.0	88.1		83.8
All studies	**Individual**				**65.3**
	Shared				**82.8**

The study by Steck et al. (2018) is very similar to the study by Kolarova et al. (2018), but the results differ slightly. A reduction of the valuation of travel time in automated vehicles of about 30% was estimated for individual use of the automated vehicles. For shared use, the reduction in the valuation of travel time was 10%. Flügel et al. (2019) made a stated preference study. The mean reduction in the value of travel time savings was a little more than 40% for individual use of automated vehicles and around 15% for shared use of automated vehicles.

The results of studies comparing individual and shared use of automated vehicles are consistent. All studies show a larger reduction of the value of time for individual use, suggesting that individual use of automated vehicles will be felt as more comfortable than shared use.

The studies suggest that, as a first approximation, one may assume a 35% reduction of the value of travel time saving for individual use of automated vehicles, with a lower limit of 15% and an upper limit of 50%. For shared use of automated vehicles, a mean reduction of the value of travel time savings of 15% is suggested, with a lower limit of 10% and an upper limit of 25%.

3.4 External costs of transport

In 2019, the European Commission (van Essen et al. 2019) published the "Handbook on the external costs of transport". This book is a huge state-of-the-art review of estimates of the external costs of transport. It includes the following major impacts of transport:

1. Accidents
2. Air pollution
3. Climate change
4. Noise
5. Congestion
6. Well-to-tank emissions
7. Habitat damage
8. Other external costs

This list includes many of the potential impacts of connected and automated vehicles. Some of these impacts have been discussed already and are partly internal, partly external. This applies to accidents, for which it was concluded that 50% can be regarded as internal, 50% as external. Moreover, the harmonised cost estimates developed in SafetyCube will be applied; but updated to 2020 prices.

Air pollution, climate change and noise can be treated as external impacts, although a CO_2 tax on motor fuel has been introduced in some countries. As far as congestion is concerned, the internalised cost of it is included in the internal value of travel time, discussed above. The external cost of congestion must be added to the internal. Finally, well-to-tank emissions, habitat damage and other external costs are regarded as irrelevant for the analysis of costs and benefits of introducing connected and automated vehicles.

Table 9 lists the relevant monetary valuations of external impacts of transport as presented in 2016-values in the Handbook published by the European Commission.

Some of the external costs discussed in the Handbook are presented in great detail. In this deliverable, only main items will be presented.

Table 9: Monetary valuations of external impacts of transport. Source: Van Essen et al. 2019

Impact	Unit of measurement	Monetary valuation (Euro)
Air pollution	One kilogram of NH3	17.50
	One kilogram of NMVOC	1.20
	One kilogram of SO2	10.90
	One kilogram NOx in city	21.30
	One kilogram NOx in rural area	12.60
	One kilogram PM2.5 in metropolis	381
	One kilogram PM2.5 in city	123
	One kilogram PM2.5 in rural area	70
Climate change	One tonne of CO2 equivalent – short term	100
	One tonne of CO2 equivalent – long term	269
Noise	50-54 dB per person per year	17
	55-59 dB per person per year	31
	60-64 dB per person per year	34
	65-69 dB per person per year	63
	70-74 dB per person per year	67
	75 or more dB per person per year	72
Congestion	One vehicle km passenger car urban	0.2234
	One vehicle km passenger car rural	0.0193
	One vehicle km bus interurban	0.1599
	One vehicle km light freight vehicle	0.0944
	One vehicle km heavy freight vehicle	0.2053

4 Recommended monetary valuations

This chapter summarises the recommended monetary valuations of societal impacts of connected and automated vehicles based on the review presented in Chapter 3. The recommended values are stated in Euro in 2020 prices and are mean values for Europe (EU 27 plus Norway, Switzerland and United Kingdom). The monetary valuations include the following potential impacts of connected and automated vehicles: changes in traffic volume (travel demand), travel time, accidents and pollution, including climate change.

In order to develop recommended monetary valuations of the potential impacts of connected and automated vehicles, the valuations presented in Chapter 3 have been converted to Euros and updated to 2020 prices. The next section describes how this was done. The following sections discuss the application of the monetary valuations with respect to alternative impact scenarios.

4.1 Updating and harmonising valuations

Some of the monetary valuations listed in Chapter 3 were given in other currencies than Euro. All of them were stated in prices applying to 2010, 2015, 2016 or 2017.

4.1.1 Vehicle ownership costs

Starting with the estimates of the costs of purchasing an automated car, it will be assumed that these cost estimates apply to 2016 or 2017. The mean purchasing power parity conversion rate between Europe 27 (i.e. The European Union without the United Kingdom) and US dollars for 2016 and 2017 was 119. This means that the price stated in US dollars was, on average 19% higher than it would have been if stated in Euro. Thus, to convert to Euro, the dollar values given in Table 4 should be divided by 1.19.

To update the cost estimated to 2020 prices, they should be multiplied by 1.05. The net correction factor based on purchasing power parity and price adjustment is 0.88. The cost of buying and replacing an automated vehicle with these adjustments are presented in Table 10.

When applying the cost estimates, they are included in the generalised costs of travel, which are usually stated as a cost per kilometre. A lifetime distance of 200,000 kilometres is assumed (in Norway a car is driven about 13,000 kilometres per year and the mean age at scrapping is about 18 years; 13,000 · 18 = 234,000). The value of a vehicle depreciates linearly to a value of zero at the end of their service life. The per kilometre cost for the first automated cars to enter the market, based on the best estimate of purchasing price, will then be:

Depreciation = 22,000/200,000 = 0.110 Euros per kilometre

Capital costs (deposit to pay for replacing the car) = 5,565/200,000 = 0.028
Total ownership costs per kilometre = 0.110 + 0.028 = 0.138

This is an increase in cost compared to operating manual vehicles.

Table 10: Harmonised and updated estimates of cost of buying an automated car in fixed prices.

Market penetration of automated vehicles (%)	Low estimate (Euros 2020)	Best estimate (Euros 2020)	High estimate (Euros 2020)
0	8 800	22 000	35 200
10	8 317	20 163	30 648
20	7 861	18 479	26 684
30	7 430	16 936	23 233
40	7 022	15 522	20 228
50	6 637	14 226	17 612
60	6 273	13 038	15 334
70	5 929	11 949	13 351
80	5 603	10 951	11 624
90	5 296	10 037	10 121
100	5 005	9 199	8 812
Replacement deposit	3 616	5 565	3 967

The estimated costs per kilometre are in the same order of magnitude as found by Wadud (2017) and Bösch et al. (2018).

4.1.2 Vehicle operating costs

With respect to the variable cost per kilometre, Wadud estimated the costs to an average of 0.208 UK Pounds in 2016. This corresponds to a cost of 0.17 Euros per kilometre when converted to 2020 using the purchasing power parity for 2016 and price inflation from 2016 to 2020. Bösch et al. (2018) estimated variable vehicle operating cost to 0.199 Swiss francs. This corresponds to 0.128 Euros per kilometre in 2020 following conversion by purchasing power parity and price inflation.

It is proposed to use the value of 0.150 Euros per kilometre of driving as the best estimate of the variable costs of operating a manual vehicle. As noted in Chapter 3, an automated vehicle is expected to have 3% lower costs, resulting in a saving of roughly 0.005 Euros per kilometre of driving.

A lower value of variable vehicle operating cost of 0.10 Euros per kilometre is proposed. An upper value of 0.20 Euros per kilometre is proposed. In all cases, the cost saving associated with automated vehicles is 3%.

4.1.3 Accident costs

Turning to accident costs, the harmonised values given in Table 6 were in 2015 prices. These values have already been adjusted by means of purchasing power parities; hence only a price update is needed. Updated to 2020 prices, the monetary values become 2,382,820 Euros for a fatality, 318,290 Euros for a serious injury and 28,790 Euros for a slight injury. Assuming a 50-50 split between internal and external costs, for fatalities the internal costs become 1,191,410 Euros, for a serious injury 159,145 Euros, and for a slight injury 14,395 Euros. The external costs amount to the same.

To indicate uncertainty, the lower and upper values of the harmonised cost estimates developed in SafetyCube (Wijnen et al. 2017) will be applied. For a fatality, the lower estimate is 70% of the best estimate; the upper estimate is 145% of the best estimate. For a serious injury, the lower estimate is 70% of the best estimate; the upper estimate is 280% of the best estimate. For a slight injury, the lower estimate is 75% of the best estimate; the upper estimate is 300% of the best estimate.

When applying these cost estimates in a cost-benefit analysis, it is necessary to estimate the injury rates per kilometre of driving for a certain use case. There are large local variations in injury rates. Furthermore, official road accident statistics, which is the most commonly used source of data for estimating injury rates, is subject to incomplete reporting, in particular for slight injuries. If acceptable estimates of the level of reporting can be found, one should apply a correction for incomplete reporting when estimating injury rates. An example of how this can be done is given in the section discussing the application of the monetary values to specific use cases.

4.1.4 Cost of travel time

The internal costs of travel time estimated on the basis of the study by Wardman et al. (2016) have been harmonised by means of purchasing power parities and therefore only need to be updated from 2010-prices to 2020-prices. The Eurocost price index was used to update cost estimates. The 2010 values were adjusted upwards by 13%. Table 11 presents updated estimates for manual and automated cars. For trips in automated cars, the best estimate of the value of time is 35% lower than for manual cars.

There is uncertainty both in the current values of time, and in the reduction of the value of time associated with the transition to automated cars. With respect to the current values of time, it is proposed that the lower estimate is 80% lower than the best estimate, and the upper estimate is 60% higher than the best estimate. Thus, unlike the costs of traffic injury, the lower value is further from the mean than the upper value. As for the reduction of the value of time associated with automated cars, the lower limit for individual use is 50% reduction of the value of time; the upper limit is 15%. For shared use, represented by bus in Table 11, the best estimate of the reduction in the value of travel time is 15%, with a lower limit of 25% and and upper limit of 10%.

Table 11: Internal costs of travel time for manual and automated cars. Euros per person per hour. Derived from Wardman et al. 2016

Mode of travel and trip purpose	Cost for manual cars (Euros per person per hour)	Cost for automated cars (Euros per person per hour)
Car, commute, urban, free flow	10.60	6.89
Car, commute, urban, congested	15.01	9.75
Car, other, urban, free flow	9.31	6.05
Car, other, urban, congested	13.19	8.57
Car, other, interurban, free flow	12.94	8.41
Car, business, urban, free flow	20.17	13.11
Car, business, urban, congested	28.45	18.49
Car, business, interurban, free flow	27.63	17.96
Bus, urban, all trips, all conditions	8.02	6.82

If it is assumed that these uncertainties are independent, they will combine multiplicatively. Thus, the lower estimate for individual use of automated cars will be: $0.20 \cdot 0.50 = 0.10$, or 10% of the best estimate of the current value of time for manual cars. The upper estimate will be: $1.60 \cdot 0.85 = 1.36$. This means that it is not even certain that the value of time will be lower for automated cars. However, a combination of the extreme values is highly unlikely. It is therefore suggested that in applying the valuations, the best estimates are used as baseline and sensitivity analysis done by varying one factor at a time. The joint distribution of uncertainties is unknown and any specification of it would be speculative.

When applying the values of travel time as a component of the generalised costs of travel, it will be convenient to convert them to values per kilometre of travel. To do so, an estimate of mean speed of travel is needed. Such estimates will often be available for urban areas or can be developed by taking a few test trips.

4.1.5 Other external costs

Estimates of other external costs have been based on the report by van Essen et al. (2019). The values presented in Table 9 have been adjusted up by 5% to represent 2020 prices and are given in Table 12.

Table 12: Monetary valuations of external impacts of transport. Updated to 2020 prices Source: Van Essen et al. 2019

Impact	Unit of measurement	Monetary valuation (Euro)
Air pollution	One kilogram of NH3	18.40
	One kilogram of NMVOC	1.25
	One kilogram of SO2	11.45
	One kilogram NOx in city	22.40
	One kilogram NOx in rural area	13.25
	One kilogram PM2.5 in metropolis	400
	One kilogram PM2.5 in city	129
	One kilogram PM2.5 in rural area	74
Climate change	One tonne of CO2 equivalent – short term	105
	One tonne of CO2 equivalent – long term	282
Noise	50-54 dB per person per year	18
	55-59 dB per person per year	33
	60-64 dB per person per year	36
	65-69 dB per person per year	66
	70-74 dB per person per year	70
	75 or more dB per person per year	76
Congestion	One vehicle km passenger car urban	0.2345
	One vehicle km passenger car rural	0.0203
	One vehicle km bus interurban	0.1679
	One vehicle km light freight vehicle	0.0991
	One vehicle km heavy freight vehicle	0.2156

When applying these cost estimates, the values for air pollution, climate change and noise need to be converted to values per kilometre of travel. The values for congestion are stated per vehicle kilometre and can therefore be applied directly.

4.2 Conversion of values to rates per vehicle kilometre

To be able to add all values, they must be converted to a common denominator. The best denominator is vehicle kilometres of travel. This section explains, first, how to construct an estimate of the generalised costs of travel and changes in the generalised costs of travel associated with the introduction of connected and automated cars. Next, it is explained how estimates of external costs can be converted to rates per vehicle kilometre. Finally, an example is given of how to estimate changes in all costs associated with the introduction of connected and automated cars.

4.2.1 The generalised costs of travel

The generalised costs of travel are the sum of vehicle ownership costs, vehicle operating costs, internal costs of travel time, and internal costs of traffic injury. The first two items have already been stated per vehicle kilometre:

Vehicle ownership costs (increase compared to manual cars):	0.138 Euros/km
Vehicle operating cost (baseline value):	0.150 Euros/km

The next item to consider is internal costs of travel time. This is a complex item, since the valuation of travel time depends on trip purpose, location (urban/rural) and whether traffic is congested or not. Values per vehicle kilometre also depend on travel speed and on car occupancy. Choices must be made with respect to all these influencing factors.

One may, as a starting point, use a typical mix of trip purposes. Based on a Norwegian travel behaviour survey (Hjorthol et al. 2014), about 25% of daily short trips are commuting trips, 2% are business trips and the rest, 73%, have other purposes. Applying the internal values of time for free flow in Table 11, this gives a value for a manual car of 9.85 Euros per person per hour. For trips taken in congested traffic, the value is 13.95 Euros per person per hour. Assuming 75% of trips are in free flow conditions and 25% in congested conditions, the mean value of travel time per person per hour becomes 10.87 Euros.

To convert this to a value per vehicle kilometre, an assumption must be made about car occupancy. If an occupancy of 1.5 is assumed, the value of time per vehicle hour becomes $1.5 \cdot 10.87 = 16.31$ per vehicle hour.

The next step is to convert the value per vehicle hour to a value per vehicle kilometre. To do so, an assumption must be made about mean speed. For a typical urban route in the city of Oslo, a mean speed of slightly less than 20 km/h was found (Stridh 2019). This is probably a typical value for urban streets with frequent traffic signals. For a car travelling at a speed of 20 km/h with an occupancy of 1.5, the internal value of travel time per vehicle kilometre is $1/20 \cdot 16.31 = 0.815$. The vehicle spends 1/20 of an hour (3 minutes) to travel 1 kilometre.

This example shows the steps taken to obtain an estimate of internal costs of travel time per vehicle kilometre. It should be obvious that many choices must be made and that, depending on these choices, different values of time per vehicle kilometre will be obtained. It is therefore essential that all choices are documented, and that reference is given to the studies informing these choices.

The internal costs of traffic injury are also an element of the generalised costs of travel. To estimate these costs, one needs estimates of injury rates per vehicle kilometre of travel, preferably adjusted for incomplete reporting of injuries. Later in this deliverable, the city of Oslo will be used as a case. To develop an estimate of vehicle kilometres of travel in Oslo, data used to develop an accident prediction model for Norway (Høye 2016) were used. It was estimated that traffic in Oslo is roughly 2 300 million vehicle kilometres per year. Based on official accident statistics for 2018, there was 0.0022 fatalities per million vehicle kilometres, 0.0182 serious injuries per million vehicle kilometres and 0.2030 slight injuries per million vehicle kilometres.

The rate for fatalities is treated as correct. The rates for serious and slight injuries are affected by incomplete reporting. Based on recent Norwegian studies (Elvik and Sundfør 2017, Elvik 2017, Elvik and Bjørnskau 2019, Elvik 2019, Lund 2019) injury rates adjusting for incomplete injury reporting were estimated. The adjusted rates were 0.050 for serious injuries and 0.650 for slight injuries.

Multiplying the injury rates by the internal cost per injury, the internal cost of traffic injuries per million vehicle kilometres is estimated to be 0.020 Euros per vehicle kilometre.

All elements of the generalised costs of travel have now been estimated. Estimates of vehicle ownership costs refer to the increase in costs attributable to the fact that automated vehicles are expected to be more expensive than conventional vehicles. The other three cost items: vehicle operating costs, internal costs of travel time and internal costs of traffic injury all refer to conventional vehicles. These costs are:

Vehicle operating costs:	0.150 Euros/km
Travel time costs:	0.815 Euros/km
Internal accident costs:	0.020 Euros/km

The internal costs of travel time dominate. This is mainly attributable to the choice made of an urban street where speed was as low as 20 km/h. Had an urban arterial road with a speed of 60 km/h been chosen, the costs of travel time would have been a third of the above estimate.

The change in the generalised cost of travel associated with the introduction of automated cars can now be estimated. The comparison below is for ceteris paribus conditions, i.e. all else is equal.

Cost item	Manual car	Automated car
Depreciation		0.110
Replacement deposit		0.028
Vehicle operating cost	0.150	0.145
Travel time	0.815	0.530
Internal cost of traffic injury	0.020	0.020
Total costs	0.985	0.833

These cost estimates apply to the first automated cars to be introduced. As noted above automated cars are expected to become cheaper as their market penetration rate increases. Thus, changes in the generalised costs of travel will depend on market penetration rate. Above, it has been assumed that vehicle operating cost is reduced by 3% and that the value of travel time is 35% lower in an automated car than in a conventional car. No changes in travel time have been assumed; it is just the valuation per unit of time that changes. Overall, the generalised cost of travel in an automated vehicle is about 15% lower than in a conventional vehicle. It is worth emphasising that this reduction is fully attributable to the lower valuation of travel time in automated cars. Had the same valuation of travel time been applied for automated cars as for manual cars, the generalised costs of travel would have been higher for automated cars than for manual cars. Litman (2020), among others, estimate vehicle operation costs to be higher for automated cars than for manual cars. The above estimates are consistent with this, as the added depreciation and replacement (capital) costs make the operation of automated cars more expensive than the operation of manual cars.

Changes in the generalised cost of travel in an automated car as the market penetration of automated cars changes are discussed in a later section. To complete the conversion of monetary values to rates per vehicle kilometre, costs of air pollution, climate change and congestion are discussed next.

4.2.2 Air pollution and climate change

The Handbook of external costs of transport (van Essen et al. 2019) has been applied to estimate the costs per vehicle kilometre of air pollution and climate change. These two external impacts were merged, as their relationship to fuel consumption is very similar.

The Handbook of external costs of transport presents a large number of estimates of the external costs of air pollution and climate change, specified according to vehicle type, Euro emissions class, and type of traffic environment. In this deliverable, estimates for Euro class 6 emission standards have been chosen. The reason for this choice, is that connected and automated vehicles will not be on the market for many years to come. In the meantime, the fleet of conventional vehicles will be renewed and by the time connected and automated vehicles enter the market, most conventional vehicles can be expected to conform to class 6 emission standards. Furthermore, traffic environment was simplified into three categories: rural roads, urban roads and motorways. With these simplifications, Table 13 gives estimates in 2020 prices of the external costs of air pollution and climate change per vehicle kilometre. It is assumed that all costs of air pollution and climate change are external.

Table 13: External costs of air pollution and climate change per vehicle kilometre. Euros per vehicle kilometre 2020 prices

Vehicle type	Rural roads (Euro/km)	Urban roads (Euro/km)	Motorways (Euro/km)
Car	0.011	0.015	0.012
Motorcycle	0.008	0.009	0.013
Bus	0.004	0.008	0.004
Light commercial vehicle	0.015	0.021	0.017
Heavy goods vehicle	0.005	0.009	0.005

The costs are quite low, but in the same order of magnitude as the external costs of traffic injury, estimated above. When applying them, mean cost estimate for all types of vehicle will be used.

4.2.3 Traffic congestion

Estimates of the external costs of traffic congestion are given in Table 45 of the Handbook of external costs of transport. These estimates, updated to 2020 prices, are given in Table 14.

It is seen that the costs of congestion, per vehicle kilometre, are much higher than the costs of air pollution and climate change.

Table 14: External costs of traffic congestion. Euro per vehicle kilometre. Source: Van essen et al. (2019), Table 45

Vehicle type	Traffic situation	Urban arterial (Euro/km)	Other urban road (Euro/km)	Motorway (Euro/km)	Other rural road (Euro/km)
Car	Over capacity	0.209	0.433	0.191	0.300
	Congested	0.162	0.379	0.148	0.258
	Near capacity	0.113	0.308	0.104	0.204
	Free flow	0.000	0.000	0.000	0.000
Bus	Over capacity			0.171	0.223
	Congested			0.131	0.190
	Near capacity			0.092	0.150
	Free flow			0.000	0.000
Heavy goods vehicle	Over capacity			0.095	0.123
	Congested			0.072	0.105
	Near capacity			0.051	0.083
	Free flow			0.000	0.000

All costs of congestion in urban areas have been attributed to cars. The costs were estimated by means of the deadweight method, which gives lower estimates of the costs of congestion than the delay cost method.

4.3 Aggregating costs according to dose-response curves

The principal analytic tool used to predict the societal impacts of connected and automated vehicles is the dose-response curves developed in deliverable D3.2 (Elvik et al. 2020). These curves show how the size of each impact is related to the market penetration rate of connected and automated vehicles. There are two versions of each curve: ceteris paribus and net impact. The ceteris paribus curves assume that all else is equal; more specifically that traffic volume does not change. The net impact curves account for predicted changes in traffic volume.

Estimates made in section 4.2.1 suggest that the generalised costs of travel will be smaller for automated cars than for conventional cars, principally as a result of a lower valuation of time in automated vehicles than in manually driven vehicles. It is reasonable to expect that travel demand will increase when the generalised costs of travel go down. However, the estimate of induced travel demand shown in Table 3 was based on a review of studies of how traffic volume changes as a result of changes in road capacity, not on an estimate of the generalised costs of travel and the elasticity of travel demand with respect to the generalised costs of travel.

It is therefore necessary to determine: (1) how the generalised cost of travel will change as automated cars penetrate the market, and (2) whether the change in travel demand one may expect as a result of the estimated change in the generalised costs of travel at full market penetration of automated cars is consistent with the change in travel demand estimated as a response to increased road capacity.

4.3.1 Changes in generalised costs of travel as automated cars penetrate the market

The initial generalised cost of travel in an automated car, given the assumptions made, was estimated to be 0.833 Euros/km in section 4.2.1. This cost, obviously, will vary, as noted in section 4.2.1. Thus, for example, the costs of travel time will be lower, and contribute less to the overall cost, the higher the speed of travel. The numbers used should therefore be interpreted as illustrative only; their principal application is to serve as examples in explaining how the generalised costs of travel can be expected to change as automated cars penetrate the market.

It will be assumed that all automated cars have a service life of 200,000 km. As discussed above, one can expect the cost of buying an automated car to decline over time. The initial cost is 22000/200000 = 0.110 Euros/km. At 100% market penetration (Table 10) it is 9199/200000 = 0.046 Euros/km. The replacement deposit (capital cost) is assumed to be constant at the amount estimated in section 4.2.1, 0.028 Euros/km.

Fuel cost is assumed to make up 25% of vehicle operating cost and will decline by about 12% at full market penetration, see Table 3. This means that vehicle operating cost will decline from 0.150 Euros/km at 0% market penetration to 0.141 Euros/km at 100% market penetration.

The internal cost of travel time in the first automated cars to enter the market was estimated at 0.530 Euros/km (for an urban street with travel speed 20 km/h). Travel time is expected to decline by about 7% (Table 3) at 100% market penetration. The internal cost of travel time will then decline to 0.492 Euros/km.

The initial internal cost of traffic injury was estimated as 0.020 Euros/km. At 100% market penetration, the number of accidents was estimated to decline by about 27%, making the internal cost of traffic injury 0.015 Euros/km.

Summing up, the generalised costs of travel for automated cars is estimated to decline from 0.833 Euros/km for the first automated car to 0.721 Euros/km at 100% market penetration of automated cars. The generalised costs of travel for all cars will be a mixture of the generalised costs of travel for a manual car and an automated car, with the shares shifting as automated cars penetrate the market. Figure 2 shows changes in the generalised costs of travel as automated cars penetrate the market.

The generalised cost of travel, given the assumptions made, will decline from 0.985 Euros/km at 0% market penetration to 0.721 Euros/km at 100% market penetration. This is a decline of nearly 27%.

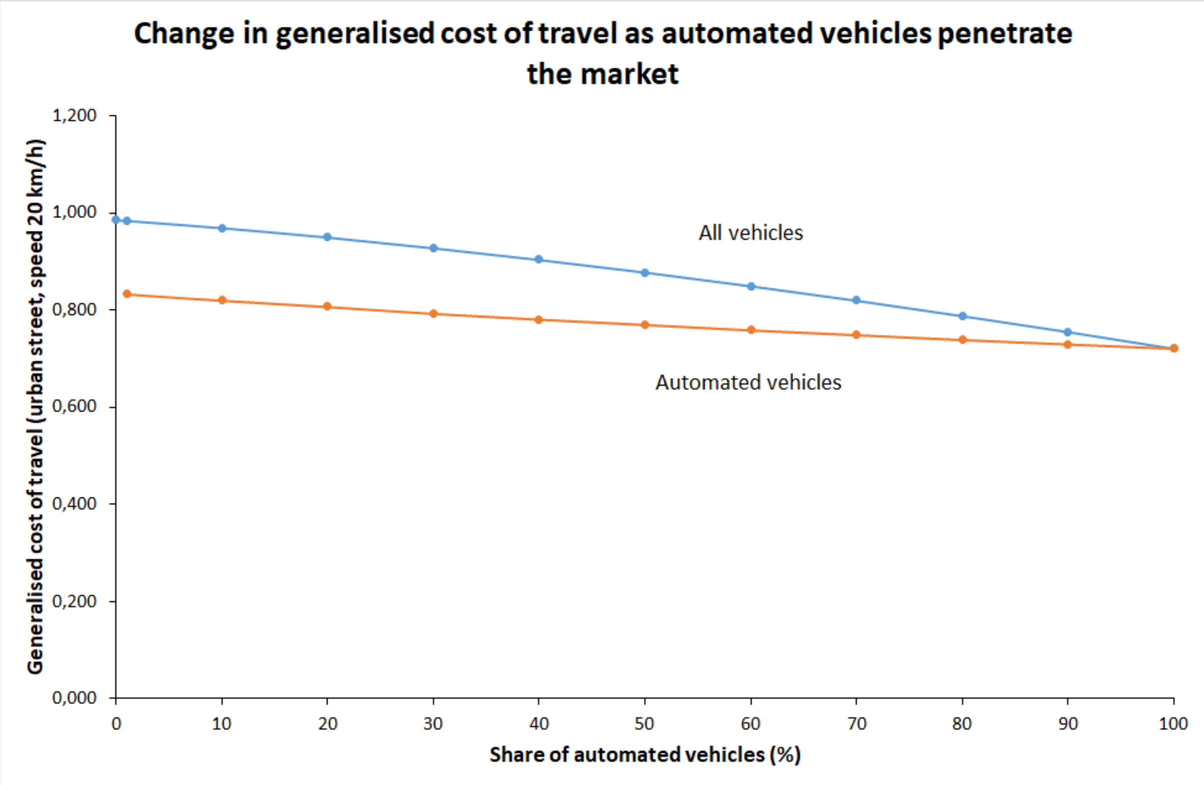

Figure 2: Changes in generalised costs of travel as automated cars penetrate the market

The estimated increase in vehicle kilometres of travel in Table 3 is 26%, very close to the estimated change in the generalised cost of travel. The question is whether these estimates are consistent with current knowledge about travel demand elasticities.

4.3.2 Travel demand elasticities

Litman (2019) gives a comprehensive overview of travel demand elasticities. Numerical estimates vary considerably and are often different for short-term elasticities and long-term elasticities. A general formula for estimating the change in travel demand associated with an elasticity η is:

$$Q_2 = Q_1 \cdot \left(\frac{p_2}{p_1}\right)^{\eta}$$

Q_2 is travel demand after the price changed from p_1 to p_2. Q_1 is travel demand before the price changed and η is the arc elasticity (an arc elasticity accounts for the fact that percentage changes are non-linear, i.e. form a geometric series).

Elasticities can be estimated for each of the components of the generalised costs of travel or for the sum of components (Wardman and Joner 2020). Component specific elasticities combine multiplicatively.

According to Litman (2019) the elasticity of travel demand with respect to the generalised costs of travel is around -0.5 to -1.0 in the short term and -1.0 to -2.0 in the long term. Applying a value of -1 to the ratio of generalised costs at 0% (p_1) and 100% (p_2) market penetration rate gives:

$0.732^{-1} = 1.366$

Corresponding to an increase of travel demand of about 37%. The increase estimated in Table 3 is 26% but has a lower bound of 13% and an upper bound of 43%.

A more conservative approach is to apply component specific estimates to the changes in the generalised costs of travel. Thus, the introduction of automated vehicles is estimated to be associated with a reduction of travel time of about 7%. Applying an elasticity (Litman 2019) of -0.74 gives:

$0.928^{-0.74} = 1.057$

The other components of generalised costs are estimated to decline by 24.5% as automated vehicles reach 100% market penetration. Applying an elasticity of -0.26 (Litman 2019) gives:

$0.755^{-0.26} = 1.076$

Combining these estimates gives:

$1.057 \cdot 1.076 = 1.137$

Which is an increase in travel demand of about 14%, close to the lower limit estimated according to the review of travel demand induced by increased road capacity.

It is concluded that the estimated increase in travel demand of about 26% is consistent both with studies of behavioural responses to increases in road capacity and with an application of estimates of travel demand elasticities to the estimated change of 27% in the generalised costs of travel.

4.3.3 Aggregation of costs to systemic level

The changes in the generalised costs of travel are a direct impact of connected and automated vehicles according to the taxonomy presented in deliverable D3.1 (Elvik et al. 2019). In that deliverable, a distinction was made between direct impacts, systemic impacts and wider impacts. It is an objective of Levitate to include as many of these impacts as possible into the policy support tool being developed.

The external impacts discussed above, i.e. external changes in travel time (mostly as a result of less congestion), changes in air pollution and climate and external changes in the number of accidents are all wider impacts. These impacts are stated as costs per vehicle kilometre. In order to estimate the monetary value of both the direct and wider impacts for a specific use case, it is necessary to estimate the total number of vehicle kilometres for that use case. This section explains how the monetary estimates of the various impacts can be aggregated to a systemic level in order to show total societal costs and benefits.

To show how to apply the monetary values to a certain traffic system, the city of Oslo will be used as an example. Once again, the main point is not whether the monetary valuations or the estimates of aggregate impacts are "correct" in the sense that they are close to what will actually happen once automated vehicles reach the market. All estimates are hypothetical and illustrative only and are only intended to help explain the logic and steps of analysis.

The first step is to estimate the aggregate direct impacts, i.e. the impacts for the users of automated cars based on changes in the generalised costs of travel. These costs are assumed to decline from 0.985 Euros/km at 0% market penetration to 0.721 Euros/km at 100% market penetration. The resulting change in consumer surplus is shown in Figure 3.

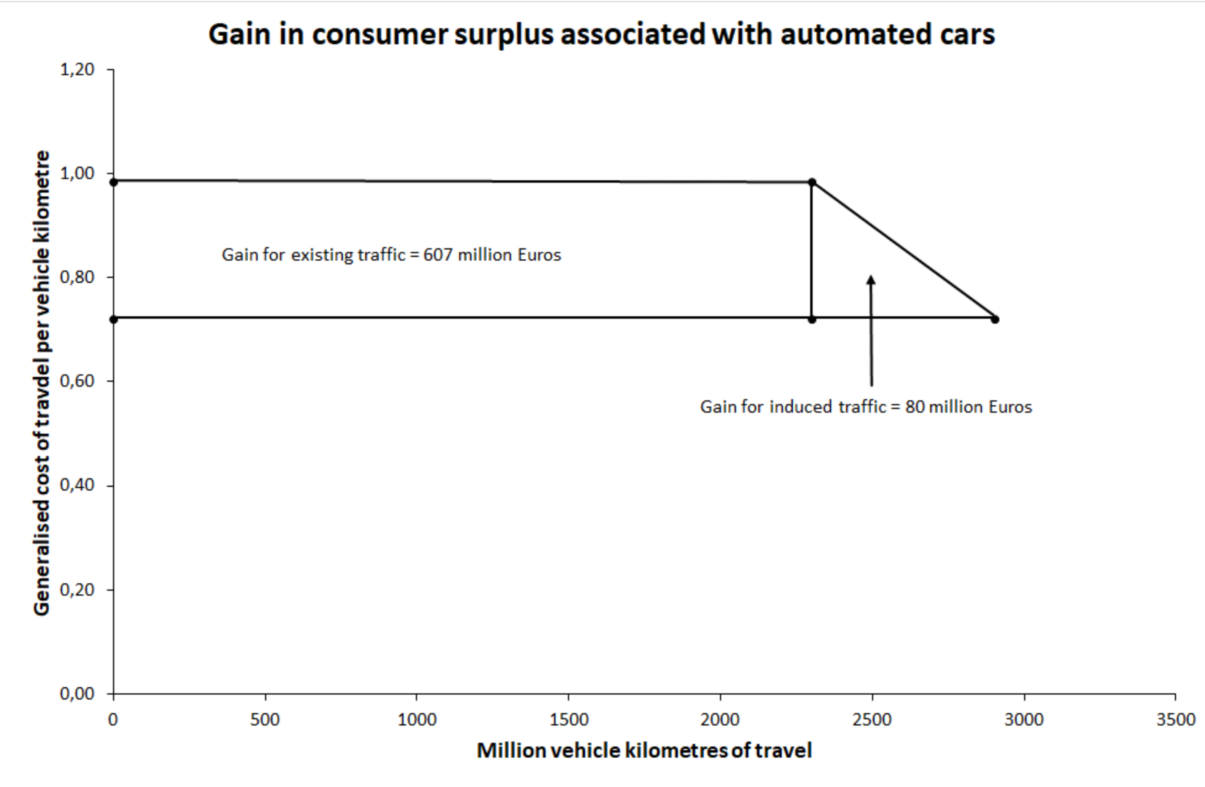

Figure 3: Change in consumer surplus associated with automated cars

The estimated gain in consumer surplus is 687 million Euros, of which 607 million is for existing traffic and 80 million for induced traffic.

The next step is to estimate the monetary value of changes in the external impacts. There are three external impacts: changes in travel time, changes in air pollution and climate, and changes in the external costs of accidents.

The change in travel time at 100% market penetration was estimated as a reduction of 7%. As speed limits are assumed to remain the same, the saving in travel time is assumed to arise from less congestion, due to the more efficient utilisation of road capacity made by automated cars. The reduction of travel time applies to all traffic, but only part of the gain is internalised; the rest is captured by the external costs of traffic congestion. The costs of congestion can be very high; the costs per vehicle kilometre given in Table 14 are higher than both the costs of air pollution and climate change and the external costs of traffic injury.

The costs for "Other urban road" applying to passenger cars have been used. Traffic has been divided into four conditions:

1. Above capacity = highly congested = 6 km/h (8.4% of traffic)
2. Congested = at capacity = 12 km/h (8.3% of traffic)
3. Dense traffic = near capacity = 20 km/h (8.3% of traffic)
4. Free flow = no congestion = 30 km/h (75.0% of traffic)

25% of traffic is in congested conditions, 75% in free flow. Applying the costs estimates in Table 14, this gives a mean cost per kilometre at 0% market penetration for automated vehicles of 0.093 Euros/km. Applying this cost to the net changes in travel time (i.e. changes after controlling for induced traffic), and using the estimates of vehicle kilometres for Oslo, gives a saving in annual congestion costs of 85.1 million Euros.

In a cost-benefit analysis, analytic choices would have to made about the duration of this impact and the discounting of it. For the moment, these issues will not be discussed. Deliverable D3.4 will deal with cost-benefit analysis of connected and automated vehicles.

Changes in air pollution were estimated to a saving of 20.7 million Euros per year at 100% market penetration of automated vehicles. For accidents, there was initially a small increase at low levels of market penetration, then a decline. The net impact was estimated as the area between a counterfactual level of accidents and the estimated level of accidents at different levels of market penetration. This is illustrated in Figure 4.

At 100% market penetration of automated cars, the number of accidents is estimated to be reduced by about 27%. The horizontal line is the counterfactual level of accidents, i.e. the number of accidents at 0% market penetration assuming that both traffic volume, the risk of accidents and the distribution of injuries by severity remain constant. The estimated impact is a net impact, meaning that the effect of induced traffic has been controlled for. In monetary terms, the annual savings of external costs of traffic injury amount to 52.1 million Euros.

Thus, in total, the internal benefit in terms of increased consumer surplus amounts to 687 million Euros per year. The external benefits in terms of less congestion, less air pollution and climate change and less accidents amounts to 158 million Euros per year. The largest benefits accrue to the users of automated vehicles, which is not surprising.

Of course, the amounts estimated here are an example only and only intended to illustrate the logic and steps of analysis. In a full cost-benefit analysis, the estimates would have to be discussed and justified more extensively than in this example.

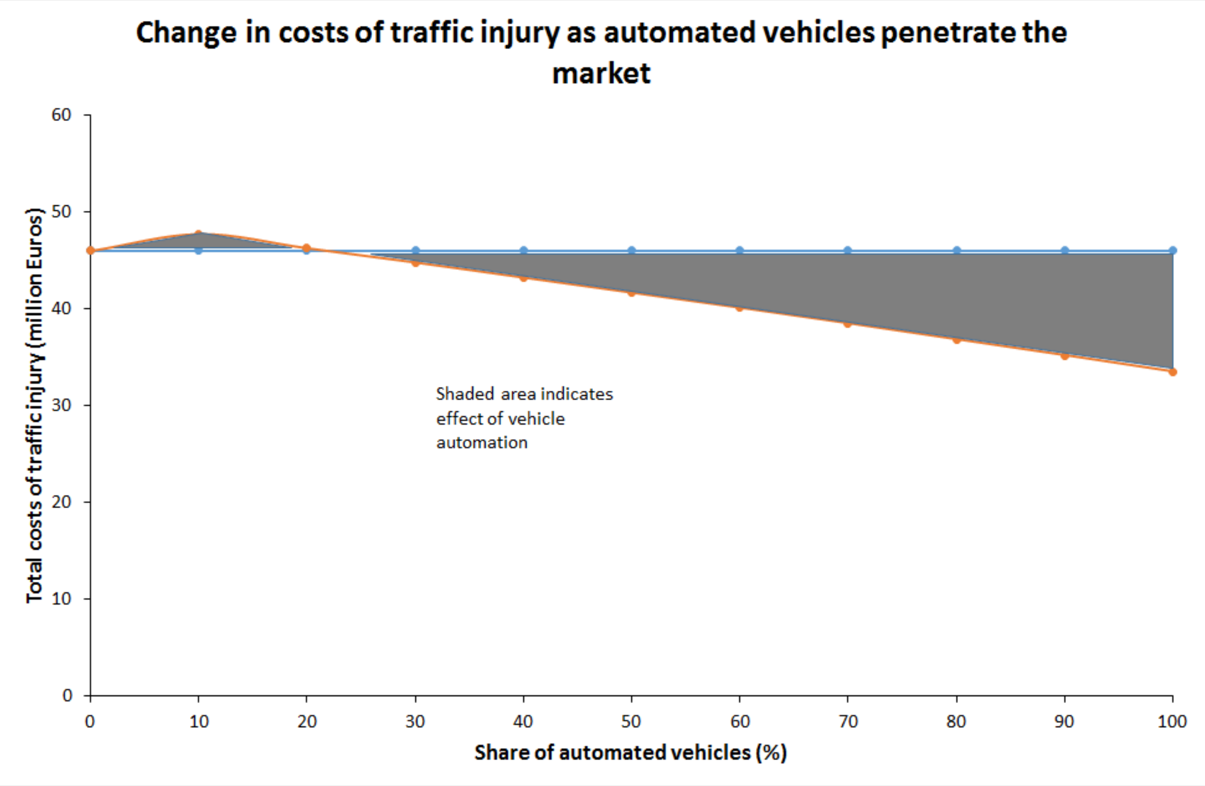

Figure 4: Change in external costs of traffic injury as automated cars penetrate the market

4.3.4 The traffic volume externality component in the costs of traffic injury

In section 3.3.3 it was pointed out that there are three components of the external costs of traffic injury: (1) The system externality, which refers to all costs inflicted on the rest of society, i.e. costs arising outside the transport system, e.g. hospital costs not paid for by injury victims; (2) The physical externality, which involves costs one group of road users impose upon another in accidents in which both groups are involved, and; (3) The traffic volume externality, which is the effect on the number of accidents of adding one vehicle to traffic.

It was concluded that the first two items are roughly evenly divided between internal and external costs. Discussion of the traffic volume externality was postponed until a later section.

A "pure" estimate of the traffic volume externality applies if everything else remains constant. In reality, this is of course never the case. When more vehicles enter traffic, there will be more congestion. The lower speed associated with congestion reduces accident severity. Thus, what we can estimate is only the net impact of a bundle of factors associated with traffic volume. This applies to Levitate as well. Automated cars will increase traffic volume, but at the same time reduce accident risk. The net impact will be a reduction of the number of accidents, i.e. the percentage decline in risk is greater than the percentage increase in traffic volume. However, the net decline in the number of accidents will be smaller than it would have been if traffic volume had not increased. Therefore, the traffic volume externality of automated cars can be defined as the difference between the number of accidents that would have occurred without the increase in traffic volume, and the number predicted to occur at the predicted rate of traffic growth. As shown earlier, at 100% market penetration, traffic growth of 26.2% is assumed.

The difference between the predicted number of accidents with the predicted increase in traffic and the predicted number of accidents without the predicted increase in traffic shows the marginal effect on the number of accidents of the increase in traffic volume, i.e. the traffic volume externality. This is shown in Figure 5.

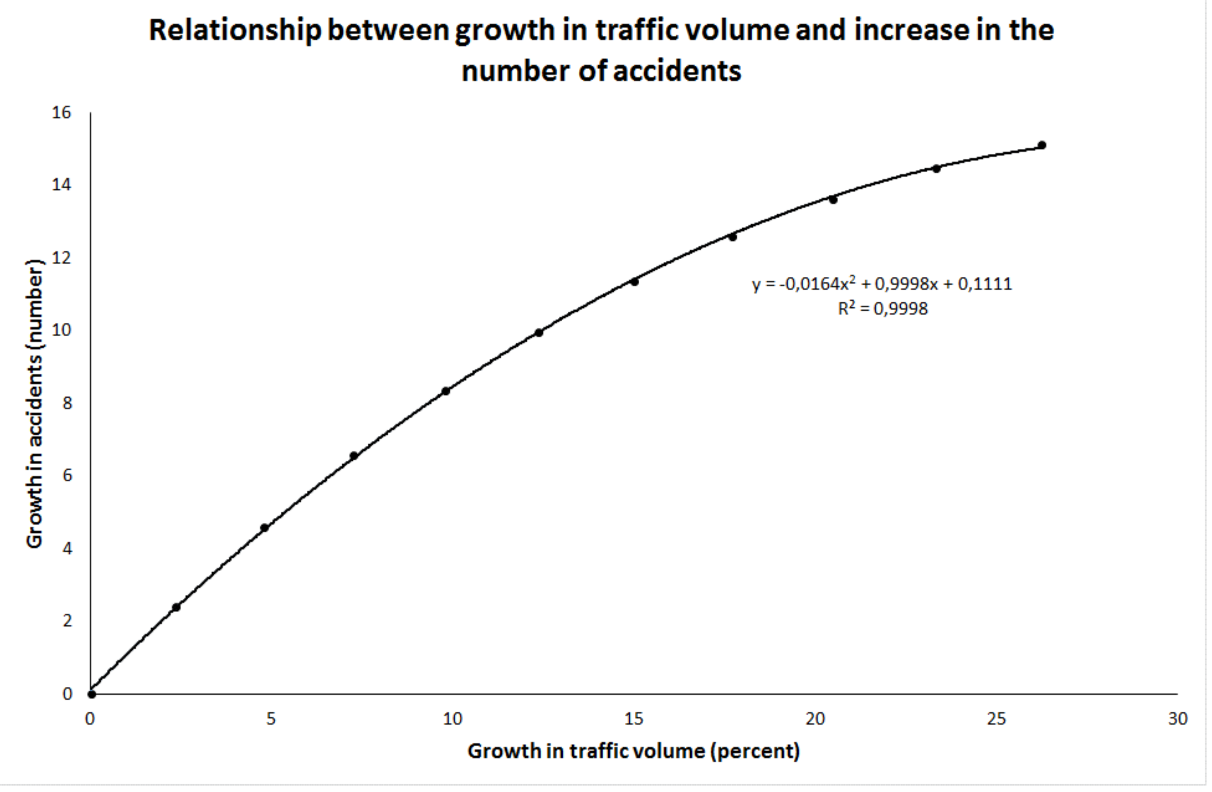

Figure 5: The traffic volume externality attributable to the traffic growth associated with the introduction of automated cars

A second-degree polynomial describes the relationship almost perfectly. If the first derivative of the polynomial is taken as an estimator of the marginal traffic volume externality, it ranges from 1.000 at the origin to 0.139 at the uppermost part of the function, with a simple mean value of 0.585. Thus, each new vehicle added to the traffic system contributes to a less than proportional increase in the number of accidents.

5 Willingness to pay for connected and automated vehicles

This chapter summarises studies of the willingness to pay for connected and automated vehicles. A previous version of the review was published in deliverable D3.2. The main point of including studies of willingness to pay is to assess whether there is likely to be sufficient demand for connected and automated vehicles for them to penetrate the market. If not, this knowledge is relevant for several policy options regulating the introduction of connected and automated vehicles. One option, if the benefits of connected and automated vehicles are large, would be to subsidise them in order to speed up market penetration. Another option would be to influence demand in the direction of shared vehicle ownership and use, in order to avoid the increase in traffic volume that might be the result of individual ownership and use of connected and automated vehicles.

5.1 Studies of willingness to pay for connected and automated vehicles

Several studies have been made on the willingness to pay for connected and automated vehicles. This section gives a short presentation of each of these studies. It is to a large extent based on the review of Elvik et al. (2020).

5.1.1 Payre, Cestac, Delhomme 2014

The first study (Payre, Cestac and Delhomme 2014) was published in 2014. The sample surveyed consisted of 421 French drivers. They were asked, among other things, about their willingness-to-pay (WTP) for automated cars. Mean willingness to pay was 1624 Euros. This referred to those who envisaged that they would buy a fully automated vehicle. The paper reports that mean willingness-to-pay was 1468 Euros among women and 1877 Euros among men. It states that minimum willingness-to-pay was 0 and maximum willingness-to-pay was 10,000 Euros.

5.1.2 Schoettle and Sivak 2014

Schoettle and Sivak (2014) report the results of a study of public opinion about automated cars in six countries. One of the questions in the survey concerned willingness to pay for automated vehicles. Unfortunately, the report by Schoettle and Sivak (2014) presents few details about the results of the WTP-question. The only information that can be extracted is the percentage stating zero WTP and the median WTP for the full sample.

In four of the six countries included in the study, median willingness-to-pay was zero US dollars, i.e. more than half of respondents indicated that they were not willing to pay anything. Median willingness-to-pay was 1600 US dollars in China and 600 US dollars in India.

5.1.3 Kyriakidis, Happee, De Winter 2015

Kyriakidis, Happee and de Winter (2015) present the results of survey made in 109 countries. There were 4886 respondents in total. Among the questions asked, was how much respondents were willing to pay for a partially or fully automated car. The answers referring to a fully automated car have been studied further.

Kyriakidis et al. (2015) do not report mean or median WTP for fully automated cars. They state that 4.9% of respondents indicated that they were willing to pay 30,000 US dollars or more for an automated car. 22% answered that they were not willing to pay anything. More detailed information is given in Figure 4 of their paper. In that figure the number of respondents is shown for the following categories of WTP:> 50,000; 30,001-50,000; 15,001-30,000; 10,001-15,000; 7,001-10,000; 5,001-7,000; 3,001-5,000; 1,001-3,000; 501-1,000; 1-500; and 0. The following mean values were assigned to these categories: 60,000; 40,000; 22,500; 12,500; 8,500; 6,000; 4,000; 2,000; 750, 250, 0. The percentage of respondents in each category was estimated, based on Figure 4 in the paper by Kyriakidis et al.

Based on this information, mean WTP was estimated as 6,820 US dollars and median WTP as 519 US dollars. Note the large difference between the mean and median WTP.

5.1.4 Bansal, Kockelman, Singh 2016

Bansal, Kockelman and Singh (2016) conducted an internet-based survey in Austin, Texas, about public interest in new vehicle technology. The survey included questions about the willingness to pay for SAE level 3 and 4 vehicle automation technology. Sample size was 347. The results for SAE level 4 vehicles will be presented.

Mean willingness-to-pay (WTP) for an SAE level 4 car was 7,253 US dollars. This included respondents with a positive WTP. The paper is not perfectly clear about whether everybody stated a positive WTP or if a share of the sample had zero WTP. It states, however, that (page 6): "19% of respondents were not at all interested in owning Level 4 AVs". In view of the fact that all other WTP-studies have found that many people are not willing to pay anything at all for automated vehicles, it will, confer the quote above, be assumed that 19% of the sample had zero WTP.

WTP was given in the following categories: < 2,000; 2,000-5000; 5,000-10,000 and above 10,000. It will be assumed that mean WTP in the three first categories were, respectively: 1,000, 3,500 and 7,500. Mean WTP in the open-ended upper category (> 10,000) was estimated so that overall mean WTP became 7,253. Mean WTP in the upper category based on this assumption was 17,350 US dollars. To be consistent with the midpoint of range adopted for the other categories, 17,350 US dollars was assumed to be the midpoint of the upper range. Thus, maximum WTP was estimated to be 24,700 US dollars.

Median WTP can be estimated as 2,570 US dollars. Furthermore, if the assumption that 19% of the sample had zero WTP is correct, the adjusted mean WTP becomes: (0.81 · 7253) = 5,875 US dollars.

5.1.5 Bansal and Kockelman 2017

Bansal and Kockelman (2017) presented a survey among 2167 Americans regarding, among other things, their willingness to pay for vehicle automation. The study investigated willingness to pay for several technologies, as well as SAE level 3 and 4 automated vehicles. Again, the focus here is on SAE level 4 vehicles.

For the full sample, mean WTP for an SAE level 4 car was US dollars 5,857. 59% of respondents answered that their WTP was zero. Median WTP was therefore zero. Mean WTP for those with a positive WTP was 14,196 US dollars. Willingness to pay was in the ranges: 0; less than 6,000; 6,000-13,999; 14,000-25,999; > 26,000. It is assumed that mean WTP in these ranges, respectively, were: 0; 3000; 10,000; 20,000 and 34,726. Mean WTP in the uppermost open-ended interval was determined so that mean WTP for all intervals equalled 5,857. It was assumed that mean WTP in the uppermost interval was located at midpoint of the interval. Maximum WTP was then estimated as US dollars 43,452.

5.1.6 Daziano et al. 2017

Daziano, Sarrias and Leard (2017) conducted a stated preference survey in a sample of Americans designed to elicit willingness to pay for partly and fully automated cars. Sample size was 1260. No information was given about the share of the sample that had zero WTP. Mean WTP was US dollars 3,538 for partial automation and US dollars 4,917 for full automation. Variation in WTP with respect to several variables was analysed in the paper. As expected, WTP increased with increasing income.

5.1.7 Bansal and Kockelman 2018

Bansal and Kockelman (2018) report the results of a study of willingness to pay for automation technology in a sample of people living in the state of Texas, USA. Sample size was 1088. Mean WTP for SAE level 4 automation was estimates as US dollars 7,589. This was the mean WTP among those who had a positive WTP.

The study did not state the proportion with zero WTP for SAE level 4 automation. It does state, however, that 29% were not willing to pay anything for connectivity, a much cheaper technology than SAE level 4 automation. Furthermore, it states that the question about willingness to pay for automation technology was only presented to those who indicated that they were planning to buy a new vehicle within the next five years. This group represented 69% of the sample. Considering the high proportion of zero WTP found, for example, by Bansal and Kockelman (2017), it is not altogether unreasonable to assume that those not planning to buy a new vehicle within the next five years (31% of the sample) had zero WTP for SAE level 4 automation technology.

The following assumptions have been made regarding mean WTP in the intervals provided: Less than 1,500 = 750; 1,500-5,999 = 3,750; 6,000-11,999 = 9,000; 12,000 or more = 16,870. Maximum WTP = 31,500.
The adjusted estimate of mean WTP is: $(0.69 \cdot 7589) = 5{,}267$. Median WTP can be estimated as US dollars 3,470. The difference between mean and median WTP is smaller than in the other studies discussed so far.

5.1.8 Liu, Yang and Xu 2019

Liu, Yang and Xu (2019) conducted a survey in China about public acceptance of automated vehicles. Sample size was 441. One of the questions was about willingness to pay for automated cars. Answers were given in twelve categories, ranging from zero to more than 20,000 Chinese yuan. 31% of the sample stated zero WTP, the rest had a positive WTP for fully automated cars.

Applying the usual midpoint of interval assumption for mean WTP within each category, and assuming a mean WTP of 250,000 Yuan for the open-ended upper interval, mean WTP for the full sample can be estimated as 24668 CNY. Based on the conversion rate given in Liu et al. (2019), this corresponds to US dollars 3,577. Median WTP was USD 763.

5.1.9 Liu et al. 2019

Liu et al. (2019) repeated the study of Liu, Yang and Xu (2019), adding a sample from a second Chinese town, thus enlarging sample size from 441 to 1135. Willingness to pay for automated cars was elicited using the contingent valuation method, providing twelve categories (intervals) for WTP and asking respondents to choose one of these. The categories were the same as in Liu, Yang and Xu (2019). Mean WTP was US dollars 4,454. Median WTP was US dollars 1,114.

5.1.10 Shin, Tada and Managi 2019

Shin, Tada and Managi (2019) report a study made in Japan regarding advantages and disadvantages of automated cars and willingness to pay for automated cars. Mean WTP for the full sample was US dollars 1650. For those who indicated an intention to buy an automated car, mean WTP was US dollars 2520. Both these amounts are lower than what most other studies have found.

5.2 Synthesising the results of studies of willingness to pay for connected and automated vehicles

Is it possible to synthesise the findings of the studies presented above? There are two main questions a formal synthesis should answer:

1. What is the best estimate of mean and median willingness to pay for a fully automated car?
2. How does willingness to pay for an automated car vary in the population, i.e. how many are willing to pay more or less than the mean WTP and how much more or less?

To combine estimates of mean WTP, these must be made as comparable as possible. This means that they should be converted to a common currency, refer to the same level of automation and apply to the full sample, not just those with positive WTP. To accomplish this, the following changes were made in the estimates of mean WTP in the studies presented above:

1. The estimate of Payre et al. (2014) was converted to US dollars using 2013-exchange rate (EURO 1624 = US dollars 1222). Further it was adjusted to full sample (0.78 · 1222) = 953.
2. For Bansal et al. (2016) and Bansal and Kockelman (2018) full sample mean WTP as stated above (US dollars 5,875 and 5,267) was used.
3. Only studies referring to fully automated cars of SAE level 4 or higher were included.

Following these adjustments, nine estimates of mean WTP were available. Figure 6 shows a forest plot of these estimates. The simple mean WTP was US dollars 4,374. Median WTP was US dollars 4,917. The two low estimates of 953 and 1,650 US dollars pulled down the mean to a lower value than the median. Estimates were not weighted by sample size, as the study by Shin et al. (2019) would then dominate completely, due to its extremely large sample (188,089).

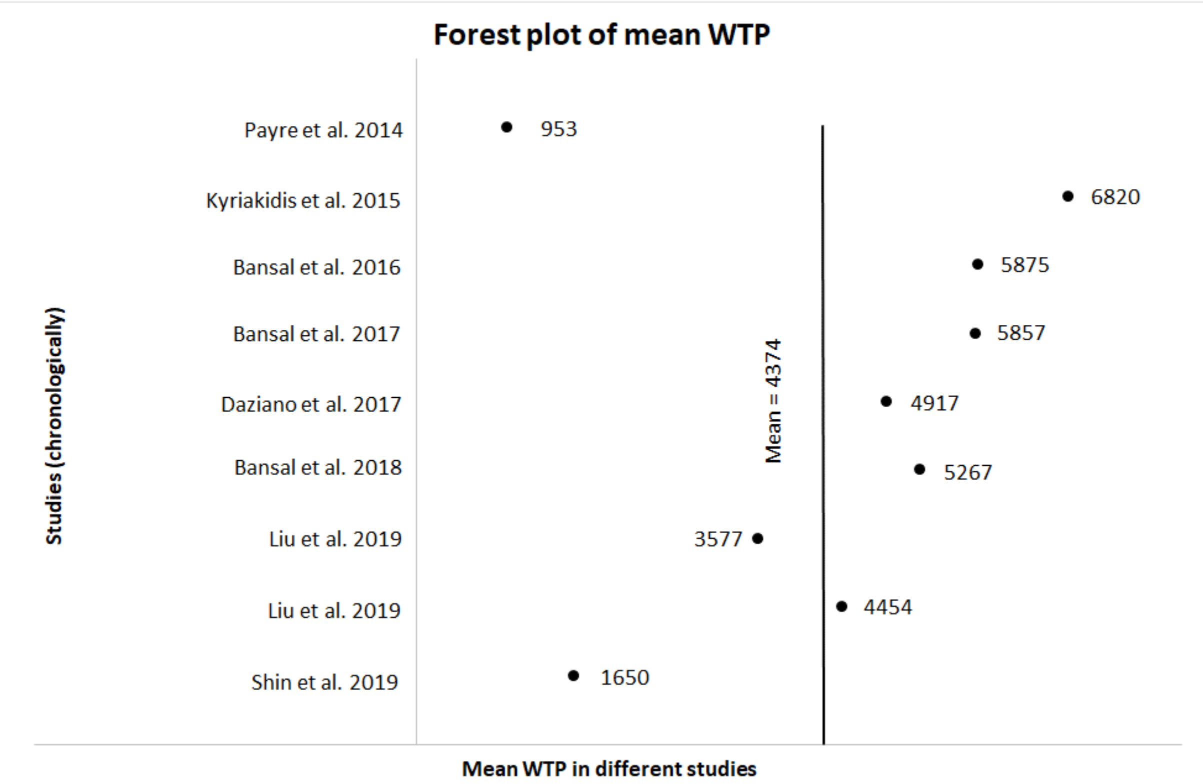

Figure 6: Forest plot of estimates of mean willingness to pay for an automated car

Except for the studies by Payre et al. (2014) and Shin et al. (2019), the estimates of mean WTP are between 3,500 and 7,000 US dollars. This range is quite small. The study by Schoettle and Sivak (2014) found that 68% of Japanese respondents stated zero WTP for SAE level 4 automation, the highest of the six countries included in their study. Apparently, willingness to pay for vehicle automation is lower in Japan than in the other countries where studies have been made. It is not clear why mean WTP in France was so much lower than in the other studies.

The following general tendencies can be found in the studies of willingness to pay for automated cars:

1. The share of respondents stating zero WTP ranges from 19 to 68%, with a mean value of 38.5% and a median value of 30.5%.
2. The share of respondents with a positive WTP of US dollars 10,000 or more varies between 9% and 27%. The mean percentage willing to pay 10,000 US dollars or more is 19.5% when all studies are included; 23.5% when the studies in China by Liu et al. are excluded.
3. In studies stating both mean and median WTP, mean WTP was US dollars 5,308 and median WTP was US dollars 1,114. The median value of mean WTP in these studies was US dollars 5,562, and the median value of the median values was US dollars 939.

As a rough approximation, it is suggested that maximum willingness to pay is 40,000 US dollars. 5% are willing to pay at least 25,000 US dollars; 20% have a WTP of 10,000 US dollars or more. Median WTP is around 2,000 US dollars. About 30% have zero WTP for fully automated vehicles. This means that about 30% have a WTP between 10,000 and 2,000 US dollars and 20% have a WTP between 2,000 and 0 US dollars.

Based on these assumptions, it is possible to derive a hypothetical demand curve for connected and automated vehicles. This curve is shown in Figure 7.

The curve is clearly hypothetical and uncertain. Yet, the results of the WTP studies are more consistent than the results of nearly all other studies of willingness to pay for a non-market good (which automated cars still are). The range of estimates of mean WTP is roughly from 1,000 to 7,000 US dollars. This range is quite narrow compared to the ranges of estimates found in most studies of willingness to pay in hypothetical markets. Thus, Wardman et al. (2016) report a much larger range in estimates of the value of travel time savings, although changes and variations in travel time is something most people are familiar with. The monetary valuation of travel time savings does therefore not involve an abstract and non-familiar good to any larger degree than the valuation of a car having automation technology.

The valuation of changes in the risk of injury, on the other hand, has produced an extremely large range of estimates. Lindhjem et al. (2012) collected 937 estimates of willingness to pay to reduce mortality risks from transport and environmental factors. The range of values of preventing a fatality was more than 44,000, i.e. the highest estimate was more than 44,000 times higher than the lowest. Compared to this enormous range, the quite small range found in WTP-studies of vehicle automation is reassuring.

On the other hand, three of the studies (Bansal et al. 2016, 2017, 2018) were made by the same team of researchers, using the same approach in all studies, although the samples were different. Still, one would expect the method in these studies to share important features, perhaps leading to what is known as common method variance, i.e. variance becomes artificially small because the studies employ the same method (Podsakoff et al, 2003). Against this, it can be argued that replications using the same method are valuable, because theory offers limited guidance about whether a positive WTP will exist at all, and, if so, how large it will be. In valuation studies in general, the use of different methods in different studies is a far larger problem than the consistent use of the same method to ensure comparable replications of studies.

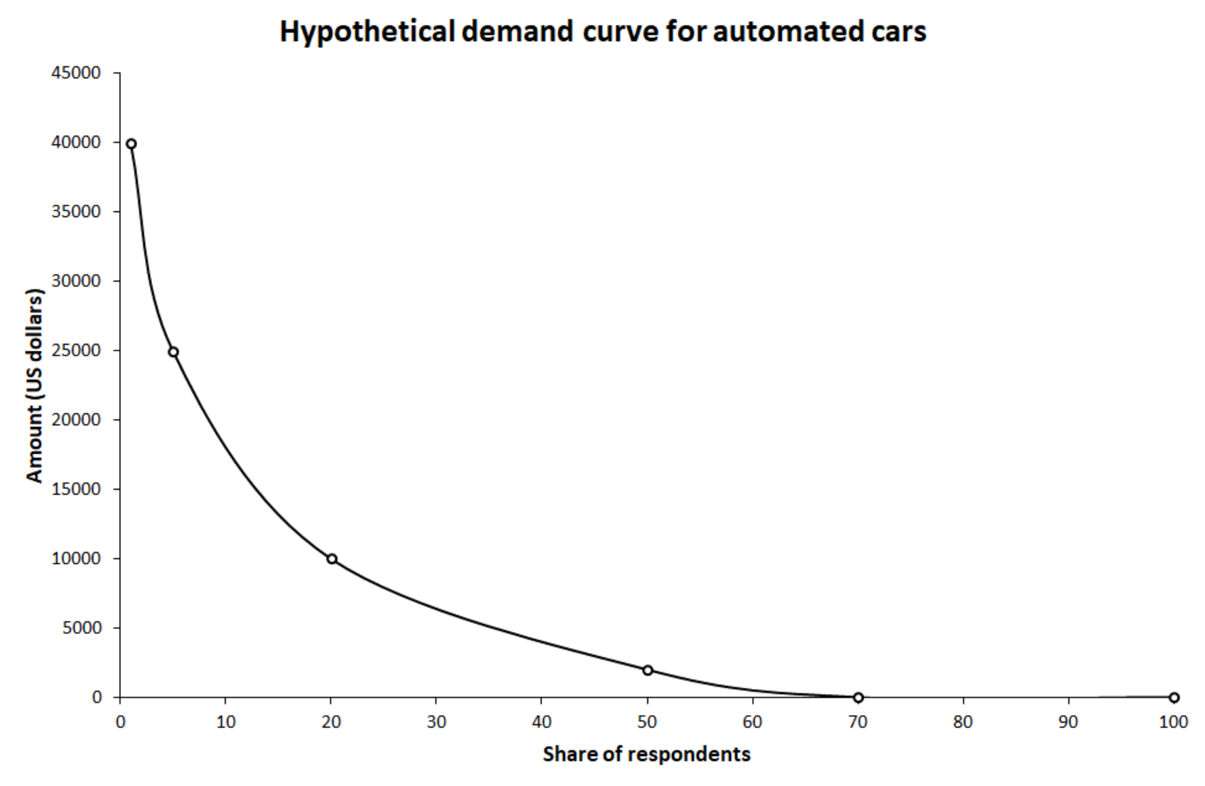

Figure 7: Hypothetic demand curve for automated cars

5.3 Comparing cost estimates to willingness to pay

Given the fact that mean WTP ranges roughly from 1,000 to 7,000 US dollars, and cost estimates range roughly from 10,000 to 40,000 US dollars, one might conclude that there will be no demand for automated cars. Mean WTP is, however, not very informative. There is always, in almost any market, large variation in WTP and the highest values for WTP are well within the range of the cost estimates.

Thus, although initially a majority of consumers may find automated cars too expensive, this is unlikely to last very long. It is likely that prices, in real terms, will go down as technology matures and manufacturing becomes more efficient.

It is likely that automated cars, like cars today, will be offered at different prices. If the cheapest model costs 10,000 US dollars, the synthesis of WTP-studies suggest that about 20% of consumers would be willing to pay at least that much for an automated car. An automated car priced at 10,000 US dollars above a manual car might therefore sell in sufficient numbers to be commercially sustainable.
An automated car priced at 40,000 US dollars would have a much smaller market. Yet, even at this price, the WTP-studies suggest that a few consumers, say 1-5%, might be willing to buy the car. There is a market for luxury cars today and it is likely that there would be a market for luxurious automated cars. Therefore, car manufacturers would probably offer an automated car priced at 40,000 US dollars above the price of a manual car to the market.

Based on current estimates of costs and willingness-to-pay, it is likely that the majority of consumers would initially regard an automated car as too expensive. This, obviously, would not necessarily prevent mass ownership from becoming a reality. In 1960, most Norwegian households could not afford a car. Today, nearly all households own a car, and many households own more than one car.

6 Impacts without monetary valuation

It is not possible to assign monetary valuations to all potential impacts of connected and automated vehicles. This chapter lists impacts without monetary valuations and discusses how these impacts can be dealt with in wider impact assessments, in which cost-benefit analysis is only one element. The objective of the chapter is to discuss whether impacts that cannot be expressed in monetary terms lend themselves to quantitative analysis, or, if not at least an indication of whether they go in the desired direction or not. It is concluded that a quantitative analysis of some non-monetary impacts is to some extent possible.

6.1 Monetised and non-monetised impacts

In chapter 2 an overview was given of the potential impacts of connected and automated vehicles. Chapter 3 surveyed available monetary valuations of these impacts and chapter 4 proposed recommended valuations. To what extent is it possible to obtain monetary valuations of the impacts of connected and automated vehicles and thereby include these impacts in cost-benefit analyses? Table 15 gives an overview of monetised and non-monetised impacts.

Starting with direct impacts, four are monetised, three are not. The non-monetised impacts include travel comfort, access to travel and individual route choice. There are valuation studies for travel comfort, but these studies refer to manually operated vehicles and the transferability of the results to automated vehicles is not clear. Moreover, the value of travel time is a wide concept, and may be interpreted as including at least some components of travel comfort. Thus, in their comprehensive meta-analysis, Wardman et al. (2016) list multiplicators to the baseline value of in-vehicle time for congested time, wait time and several other components of travel time. Studies quoted above indicate that the value of travel time will be lower in an automated vehicle than in a conventional vehicle, particularly for an individually used automated vehicle. Presumably, automated vehicles will be offered with at least the same level of comfort as current cars in terms of characteristics like heating and ventilation, possibilities for adjusting seats and space for luggage. It is therefore not judged as a serious omission in a cost-benefit analysis that a separate valuation of travel comfort is not yet available.

Improved access to travel for those who currently cannot drive is a potentially important benefit of automated vehicles. While no studies valuing this benefit have been found, it is not altogether unreasonable to say that it must at least be equal to the amount spent to obtain a driving licence. The driving licence must at least be worth what you spend to obtain it; otherwise the expenditure would make little sense. In the absence of other evidence, it is suggested that mean expenditure to obtain a driving licence can be used to indicate the lower bound of the value of independent mobility for those who currently are not allowed to drive a motor vehicle.

Table 15: Overview of monetised and non-monetised impacts of connected and automated vehicles

Impacts	Monetised	Non-monetised
Direct impacts		
Travel time	X	
Travel comfort		X
Valuation of time	X	
Vehicle operating costs	X	
Vehicle ownership costs	X	
Access to travel		X
Route choice (individual)		X
Systemic impacts		
Amount of travel	X	
Road capacity		X
Congestion	X	
Infrastructure wear	X	
Infrastructure design	X	
Modal split of travel		X
Optimisation of route choice	X	
Vehicle ownership rate		X
Shared mobility	X	
Vehicle utilisation rate	X	
Parking space	X	
Traffic data generation		X

Individual route choice can presumably be influenced if automated cars collect data that permit them to offer alternative route choices. This should not be confused with a traffic management system in which a traffic management centre has the capability of directing traffic to specific routes in order to minimise congestion. It should rather be interpreted as an information system offering users of automated vehicles alternative routes in non-congested conditions, in which the choice made will have little or no impact on other road users. No study of the monetary value of this functionality has been found. However, as it will presumably only be used in non-congested traffic, the societal impacts will be minor and not likely to distort the results of cost-benefit analyses adopting a societal perspective.

Table 15: Overview of monetised and non-monetised impacts of connected and automated vehicles

Impacts	Monetised	Non-monetised
	Wider impacts	
Trust in technology		X
Road safety	X	
Propulsion energy	X	
Energy efficiency	X	
Vehicle emissions	X	
Air pollution	X	
Noise pollution	X	
Public health	X	
Employment		X
Geographic accessibility	X	
Inequality in transport		X
Commuting distances	X	
Land use		X
Public finances	X	

There are monetary valuations of quite a few of the systemic impacts. Not all of them have been discussed previously. Optimisation of route choice, for example, is conceived of as the direction of traffic to those routes that minimise congestion. The value of this benefit is the value of reduced congested (discussed above) and possibly a benefit in terms of reduced vehicle operating costs. Monetary valuations are available for these benefits.

Likewise, the value of shared mobility, is the reduction of the generalised costs of travel associated with it. To estimate this benefit, shared mobility by means of automated vehicles must be compared to an alternative. If the alternative is current public transport, shared automated mobility (ride sharing) is likely to be cheaper, because transport operators save the costs of a driver. Preliminary estimates of the savings are given by, e.g. Tirachini and Antoniou (2019). If the alternative is a manual car, shared automated mobility will save vehicle ownership and operation costs, but replace these costs with a fare for ride sharing (although there is no driver, the service will have costs that users must pay). The cost elements involved in comparing shared automated mobility with other modes of transport are, in general, well-known.

Vehicle utilisation rate refers to how effectively the mobility opportunities a vehicle offers are utilised. Current utilisation rate for individually owned cars is dismally low. A car is typically parked about 23 out of 24 hours, and, on average, less than two people sit in the car when it is used. In principle, vehicle automation and connectivity enables a higher vehicle utilisation rate (more hours of operation each day, more of the seats occupied). The benefits of this is the increase in consumer surplus. To estimate this in a cost-benefit analysis, one must specify a reference situation, i.e. a situation where vehicle utilisation rate does not change. A market mechanism generating increase vehicle utilisation rate could, for example, be a car sharing scheme. The alternative, or reference situation, would then be owning your own car, but not driving very much with it. In that case, selling the car and joining a car sharing scheme would save costs. Increasing vehicle utilisation rate would, on the other hand, probably increase vehicle operating costs and shorten the service life of the car. The relevant cost elements are all fairly well known and a cost-benefit analysis of increased vehicle utilisation rate is judged as feasible based on the monetary valuations presented in this deliverable.

No monetary valuation of parking space has been presented in this deliverable. The cost is likely to vary considerably. If parking is provided in a large parking house close to a city centre, it is likely to be expensive. If it is provided outdoors in a non-congested area, it may be quite cheap. Commercial parking facilities presumably charge prices that make the business earn money. Parking fees should be possible to obtain on a case-by-case basis for inclusion in a cost-benefit analysis.

No monetary value has been assigned to road capacity. The benefits of any changes in road capacity resulting from vehicle connectivity and platooning will be shorter and more predictable travel time. This benefit is included in the value of travel time savings. There is thus no need for any separate monetary valuation of road capacity.

The modal split of travel can be interpreted as a kind of market equilibrium. The basic assumption made to justify such an interpretation is that each road user chooses the mode of transport he or she thinks is best (i.e. choice of mode of transport is subjectively rational). Clearly, it is easy to think of cases where this assumption is wrong. Passionate car drivers, for example, may be ignorant of public transport and may waste time in traffic jams they could avoid by using public transport. However that may be, the principle of consumer sovereignty applies fully to the choice of mode of transport. Of course, this does not make it illegimate for government to try to influence the modal split of travel. Many cities want to curb car use, and encourage walking, cycling and public transport. As usual, the societal benefits of any change in the modal split of travel are estimated in terms of the change in consumer surplus associated with them. There may, in addition, be societal benefits in terms of reduced external costs of congestion, air pollution or accidents. The relevant elements of costs and benefits are known, and cost-benefit analysis of changes in modal split associated with vehicle automation is judged as feasible.

No monetary valuation has been assigned to vehicle ownership rate, and none is needed. Vehicle ownership rate changes as a result of consumer choices. Mainstream economic theory assumes that consumer choices are subjectively rational, i.e. consumers choose the basket of products and services that gives them the greatest satisfaction. Again, this assumption is widely criticised and not necessarily correct. However, for analytic purposes it remains difficult to rely on a different assumption. Thus, any changes in vehicle ownership rate should be valued in terms of the corresponding changes in consumer surplus. If, as several studies suggest, see deliverable D3.2, individual vehicle ownership becomes less common as automated vehicles offer new mobility options, this can only occur because the new mobility options provide greater benefits than continuing to own a car. The task of the analyst is to model the choices made by consumers and estimate the change in consumer surplus associated with these choices.

Finally, traffic data generation is listed as a systemic impact. This refers to the fact that automated cars may provide traffic management centres with live data on their location and traffic volume on different roads. The value of this information depends on the use made of it. If used to manage traffic so that congestion is minimised, this benefit is included in the schedule of monetary valuations presented in this deliverable.

With respect to wider impacts, most of them are included in the monetary valuations listed in this deliverable. Impacts on propulsion energy, energy efficiency, vehicle emissions and air pollution form a causal chain for which the monetary valuation applies to the final outcome of the chain. In this case, this is the public health impacts of air pollution. These impacts are included in the valuations of specific pollutants listed in chapter 3 of the deliverable.

Changes in geographic accessibility manifest themselves in terms of changes in travel time and are therefore covered by the values of travel time savings. Impacts on public finances are measured directly in monetary terms. The wider impacts not included in the schedule of monetary valuations are: trust in technology, employment, inequality in transport and land use.

All these impacts are potentially very important. If, for example, automation technology is not trusted and therefore not used, its benefits will be lost. If a lack of trust in technology slows down or completely stops its market penetration, society loses the net benefits full market penetration would provide. If estimates of the consumer surplus and other impacts, as illustrated in chapter 4, can be developed the loss of benefits can be estimated in monetary terms. However, such an estimate may not adequately reflect all aspects of trust and its importance for quality of life. If you really need to make a trip, but abstain from it because you do not trust the technology, you may have to adjust your daily life in more ways than just changing travel behaviour. In general, loss aversion implies that the value of losing something exceeds the value of gaining it. The consumer surplus is an estimate of the gain, or benefit, associated with a trip. The loss experienced by not feeling able to make the trip may be larger than merely the loss of consumer surplus. Yet, if some quantified estimate of loss aversion can be developed (e.g. the slope of a utility function), it may be applied as a multiplier to the loss of consumer surplus in an economic analysis.

Vehicle automation may produce extensive changes in employment. Drivers will lose their jobs, but effects could extend to jobs in insurance (less collisions, less work for insurers) and the police (no need for enforcement because automated cars comply with all rules). These impacts are difficult to predict and their relevance debatable. Not more than just about a hundred years ago, the majority of people were farmers or farm workers. Today, less than 5%, usually closer to 2-3% of the work force in the developed countries work in farming. Is the loss of employment in farming to be lamented and entered in national accounts as a loss? Almost nobody would say "yes". Quite the opposite, the enormous gain in the productivity of farming has been to everybody's advantage. Vehicle automation holds the promise of making travel and transport more efficient, i.e. less wasteful and more productive in many ways. The attendant loss of employment is transitory. The prediction that technological innovation will create mass unemployment has so far been wrong. While it is understandable that those who may lose their jobs as a result of technological innovation worry about it, this is irrelevant in a cost-benefit analysis.

Inequality in transport reflects societal inequalities in a wider sense. It is nevertheless relevant to ask whether vehicle automation will increase or reduce inequalities in transport and whether changes in inequality can be included in cost-benefit analyses of the societal impacts of connected and automated vehicles.

Inequalities in transport are principally evidenced in terms of a gradient with respect to social status regarding the amounts and types of travel. In short, the rich travel more than the poor, and use more expensive modes of transport (luxury cars, first class air tickets). In addition, and no less important, the unwanted impacts of transport in terms of accidents or exposure to noise and pollution are inversely distributed. The poor have higher rates of accidents than the rich and live in more polluted areas. Will the introduction of connected and automated vehicles change this?

On the one hand, automated vehicles may give access to independent mobility for groups now excluded from it, like children (at least above a certain age) and those who have an impairment preventing them from driving a car. On the other hand, automated cars are expected to be more expensive than current cars, and may therefore first enter the luxury car market segment. The rich may be the first to enjoy the benefits of automated transport. Inequality in transport may then increase.

There is no obvious way of including changes in inequality in a cost-benefit analysis. One might try to account for inequality by identifying the groups that benefit from vehicle automation and apply utility weights to the groups reflecting the marginal utility of money. The utility weights would reflect the fact that 1,000 Euros are worth more to a poor individual than to a rich individual. Until now, utility weights have usually not been applied in cost-benefit analysis. Estimates of the marginal utility of money can be found in the literature (Layard, Mayraz and Nickell 2008). However, to apply these estimates in a cost-benefit analysis, one would need to know the income distribution among those affected by vehicle automation. To make the analysis tractable, income groups would have to be defined, and the results could be influenced by how these groups were defined. It is therefore concluded that potential changes in inequality in transport cannot be included in cost-benefit analyses of connected and automated vehicles. The next section discusses whether the impacts can be quantified and whether some basis can be found for assessing whether the impacts are wanted or unwanted.

Changes in land use is the final wider impact to be discussed. Like changes in employment, changes in land use are difficult to predict. If individual ownership of automated vehicles becomes common, urban sprawl may increase. If, on the other hand, shared mobility becomes common, cities may grow denser, as shared mobility favours a large market in a small geographic area. Many cities have a political objective of stopping urban sprawl and ideally reversing it. It is not clear how to assign monetary values to changes in land use. The price of a piece of land will be known; indeed one of the factors producing urban sprawl is that land is cheaper the further from a city centre it is located. But the price of land mainly reflects how attractive or demanded a property is for a certain use, like residential. It does not reflect the societal impacts of the increase in travel demand associated with urban sprawl. Indeed, houses located far from traffic, in quiet and low-polluted environments have higher prices than otherwise identical houses located close to traffic.

It is concluded that changes in land use cannot be assigned a specific monetary value for use in cost-benefit analysis. One may, however, use studies comparing cities of varying densities (population per square kilometre) in terms of travel demand, energy consumption or other measurable characteristics, some of which can be converted to monetary terms.

6.2 Analysis of non-monetised impacts

This section discusses the possibility of quantifying the non-monetised impacts of connected and automated vehicles for inclusion in a wider impact assessment consisting of a cost-benefit analysis and an assessment of impacts not included in the cost-benefit analysis.

6.2.1 Trust in technology

Use of connected and automated vehicles will be based on trust in the technology. If trust is lost, due either to malfunctions of the technology or cyber attacks, use of connected and automated vehicles may be greatly reduced. Should this happen when connected and automated vehicles have reached a high market penetration rate, societal impacts could be extensive, as the transport system would cease to function.

One way of quantifying a loss of trust in technology, is to apply the utility model of prospect theory (Kahneman and Tversky 1979). According to prospect theory, the utility of a prospect (a wide concept, that may include ordinary consumption) is evaluated from a reference point. The normal reference point is the status quo, or that things remain as they are right now.

Let us assume that automated vehicles are in widespread use. This state of affairs is the reference point and the utility of automated vehicles is assessed in the domain of gains, i.e. the utility of automated vehicles is viewed as positive and may be estimated in terms of the consumer surplus associated with their use. This is indicated by the utility function in the upper right quadrant of Figure 8.

The expenditures on automated cars is shown along the horizontal axis. The area under the utility function can be thought of as the consumer surplus associated with these expenditures. The reference point is where the axes for money and utility cross.

If, due to loss of trust, the use of automated vehicles ceases completely, the expenditures are saved, but the consumer surplus is lost. From a reference point where automated cars are used, this will be experienced as a loss. According to prospect theory, the disutility of a loss is larger than the utility of an equally large gain, due to loss aversion. This is shown by the loss of utility function in the lower left quadrant of Figure 8.

It is seen that the loss of utility associated with not being able to use automated vehicles is larger than the gain in utility from using them. If an estimate of the monetary value of the utility of using automated vehicles is available, one can use this as an anchor point for estimating the loss of utility from not being able to use automated cars.

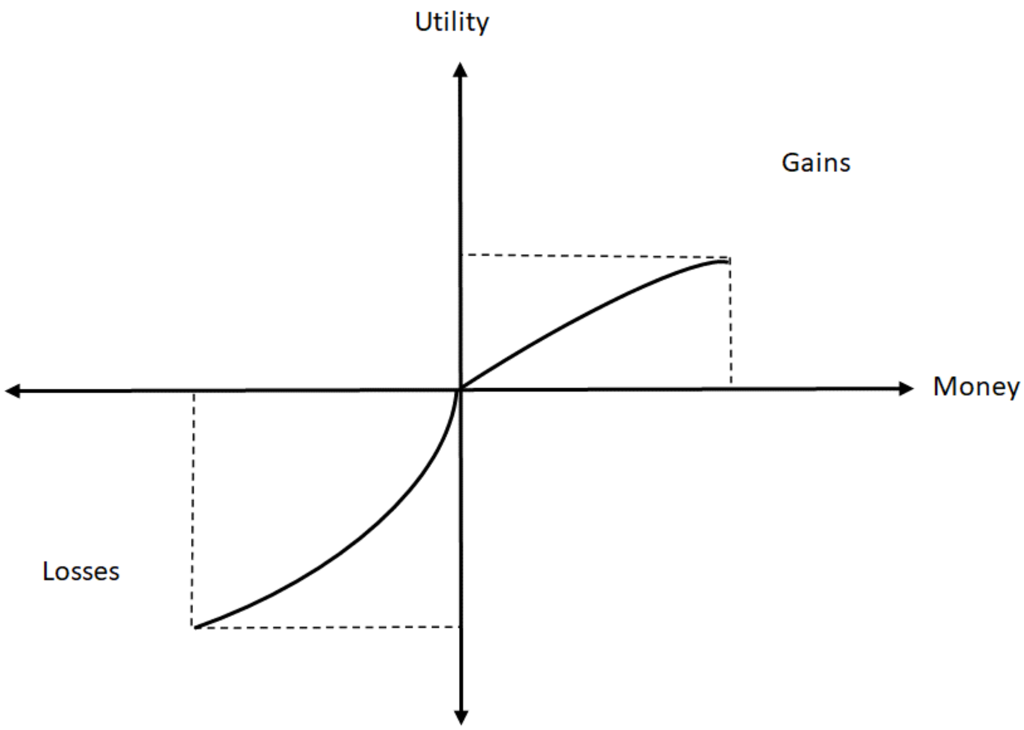

Figure 8: Model of loss of trust in automation technology by means of prospect theory

As illustrated in Figure 8, the loss of utility from not using automated cars is about twice as large as the gain in utility from using them.

6.2.2 Inequality in transport

There are many dimensions to inequality in transport. The most prominent, and possibly easiest to measure, is differences in travel behaviour according to social status. Such differences, and changes in them over time, are analysed extensively by Banister (2018).

Banister, as well as Palma (2011) are concerned about how best to measure inequality. A widely used estimator is the Gini-index. It varies between 0 (perfect equality) and 1 (complete inequality). It is widely applied to the income distribution in a society. The smaller the share of total income earned by the poorest, say, 10% of the population, and the larger the share earned by the top 10%, the larger is the value of the Gini-index.

The Gini-index can be applied to any distribution within a population, not just income distribution. Thus, Elvik (2009) computed the Gini-index for the distribution of risk between groups of road users in Norway. To estimate the Gini-index, groups of road users were rank ordered from the one with the lowest fatality risk to the one with the highest fatality risk. For each group, its percentage contribution to exposure (person kilometres of travel) and fatalities was estimated. This resulted in the plot shown in Figure 9.

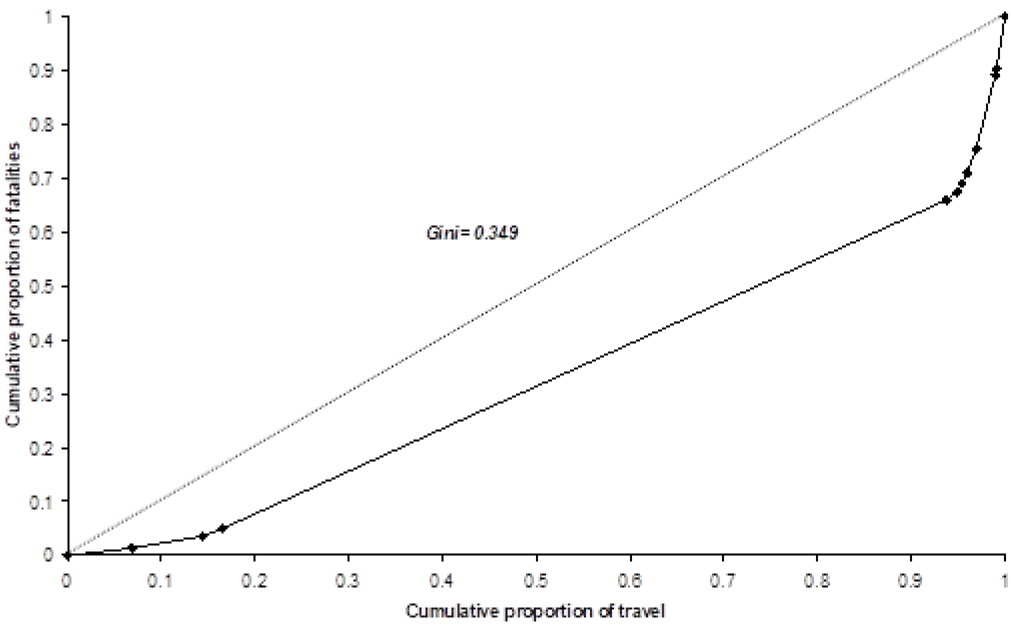

Figure 9: Gini-index for distribution of risk between different groups of road users (modes of travel) in Norway. Based on Elvik (2009).

The groups of road users were formed according to mode of travel, i.e. pedestrians, car occupants, bus passengers, truck drivers, etc. The Gini-index was estimated to the value of 0.349. By comparison, the Gini-index for income distribution in Norway is about 0.25. If a low degree of inequality is regarded as fair, the distribution of traffic fatality risk in Norway around 2000 was less fair than the distribution of income.

A limitation of the Gini-index is that it is not very sensitive to the lower and upper ends of the distribution. Thus, even if the poorest 10% get poorer, and the richest 10% get richer, the value of the Gini-index may not change much, if the middle 80% hold their ground. In a case like this, however, the distance between top and bottom would increase.

A close look at Figure 9 shows that the weakness of the Gini-index probably applies to the distribution of fatality risk in traffic. The long middle segment of the curve shows the risk to car occupants, who contribute almost 80% of person kilometres of travel. This segment runs almost parallel to the dashed 45 degree line indicating perfect equality. Even if the safest (in the lower left corner) modes of transport got safer and most risky (upper right corner) became even more risky, the shape of the curve would not change much and the value of the Gini-index would not capture the increased disparity in risk between the safest and most hazardous modes of transport.

Palma (2011) has proposed various other estimators of inequality that better reflect changes at the bottom and top of a distribution. One of these, now widely referred to as the Palma-index, is the share of a good owned or consumed by the richest decile (decile = shares of 10%) divided by the share of a good owned or consumed by the poorest four deciles. This index includes data for 50% of the distribution and leaves out the middle 50%.

If it is tentatively applied to Figure 9, the relevant good is the amount of travel, and the privilege is the fatality rate one is exposed to when travelling. By eyeball inspection, the safest 10% (upper decile) perform 20% of travelling. The most risky 40% perform about 10% of travel. The Palma-index becomes 2 (20/10) (D1/(D6-D10)).

Thus, inequality can be quantified in terms of at least two estimators. The next question is whether a basis can be found for judging the desirability of changes in inequality. This requires a concept of fairness in a distribution. Elvik (2009) tried to apply the two principles of justice proposed by John Rawls (1971, 2001) to the distribution of fatality risk in traffic. The most important of these principles is the difference principle, which in its briefest formulation states that inequality can be accepted if it is to the benefit of the least advantaged members of society.

In other words: complete equality is best, unless everybody gains from inequality. The application of this principle to inequality in transport is not straightforward. To apply it, one needs to compare different distributions, involving different degrees of inequality, with respect to which of these distributions that most benefit the least advantaged.

A starting point is to define the least advantaged. In transport, the least advantaged would include:

1. Those who have the least resources for making use of travel opportunities (lowest income, no driving licence, impairments limiting mobility)
2. Those who are most exposed to risk of injury when travelling
3. Those who are most exposed to negative external impacts of transport, like noise or pollution

As already noted, these groups may overlap considerably. Low income may prevent you from obtaining a driving licence and a car; it may force you to travel by foot or bike, which involves high risk of injury; and it may force you to live close to roads that carry heavy traffic volume. Data from travel behaviour surveys can often be applied to define the least and most advantaged groups with respect to the benefits offered by the transport system.

The next step would be to examine whether the introduction of connected and automated vehicles benefits the least advantaged or not. By benefitting them is meant that connected and automated vehicles improve their opportunities to travel, reduce their risk and reduce their exposure to externalities. It may well be that the rich get larger benefits from connected and automated vehicles than the poor, but if these vehicles also bring benefits to the poor, their introduction would be consistent with the difference principle, and would therefore be regarded as an improvement in terms of inequality.

It is still not possible to give a confident answer to the question of whether the introduction of connected and automated vehicles will be consistent with the difference principle. However, an operational definition of the principle at least provides a yardstick by which it is in principle possible to indicate the desirability of introducing connected and automated vehicles in terms of their impacts on inequality in transport.

6.2.3 Land use

A reasonable interpretation of the transport policy objectives of many cities today, is that these policies aim for a sustainable development of cities. Sustainability has at least three dimensions: environmental, economic and social. Environmental sustainability means, for example, less carbon emissions, lower energy use, less use of non-renewable natural resources, and less waste. Economic sustainability means that production and consumption does not exceed levels that future generations can continue without jeopardizing environmental sustainability. In other words, our current standard of living is not sustainable if future generations will have to consume less in order to maintain or restore environmental sustainability. Finally, social sustainability refers to various indicators of how well a society performs in terms of, for example, human health and longevity, social capital and governance.

A host of indicators of sustainability can be found in the literature. To relate these to land use and changes in land use that may be associated with the introduction of connected and automated vehicles, it may be useful to apply knowledge of the relationship between indicators of land use and sustainability indicators. The work of Newman and Kenworthy (1989) shows how this can be done. Figure 10 shows, as an example, the relationship between urban population density and the amount of travel in cities.

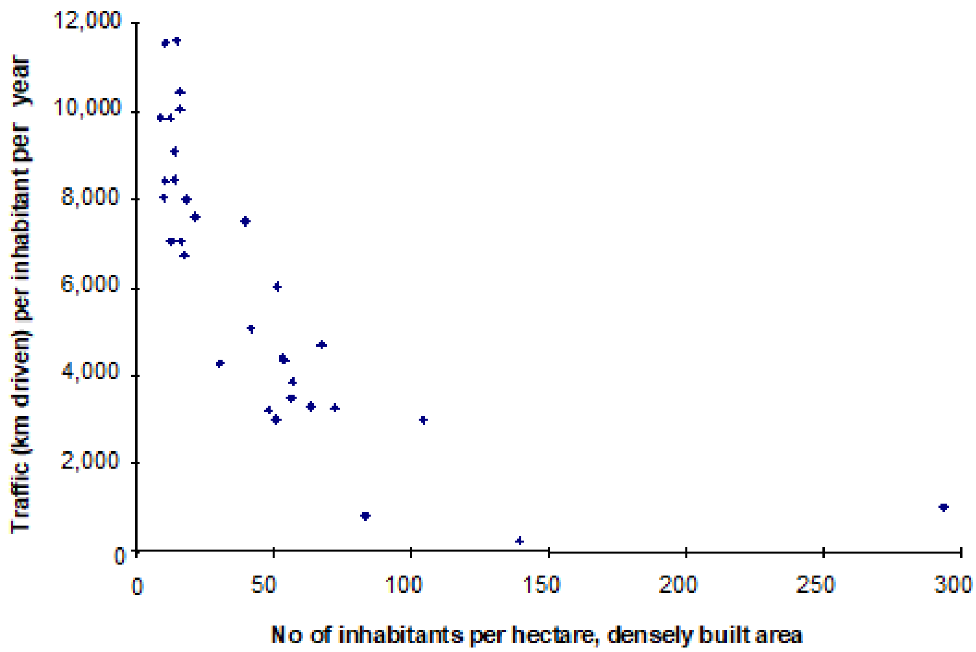

Figure 10: Relationship between urban population density and amount of travel. Source: Newman and Kenworthy (1989).

It is seen that the higher the population density, the less the amount of travel. An obvious objection is that this is a cross-sectional relationship which does not necessarily show what will happen if a city pursues of policy of dense development close to public transport facilities. However, statistics for the city of Oslo shows that after a top in 2007, car traffic has declined while public transport has increased. In the same period, the city has pursued a policy of building new residential areas close to public transport. Population density per square kilometre has undoubtedly increased in many parts of the city, corresponding to a movement downward from the left part to the right part of Figure 10, consistent with the data points shown in the figure.

By relating changes in land use associated with the introduction of connected and automated vehicles to sustainability indicators, one may obtain a set of quantitative estimates of whether the changes in land use, on the whole, favour sustainability or not.

7 Discussion and conclusions

The objective of this chapter is to discuss the application of the proposed monetary valuations of impacts of connected and automated vehicles in cost-benefit analyses of policy measures intended to ensure that the societal benefits of connected and automated vehicles are maximised. Issues that need more work are identified. How to embed cost-benefit analyses in wider impact assessments is discussed. Finally the main results of the study are summarised.

7.1 Discussion

An ideal cost-benefit analysis includes all relevant impacts of a measure or programme. Are we in a position to perform an ideal cost-benefit analysis of connected and automated vehicles based on the monetary valuations of impacts presented in this deliverable?

The answer is no. While there are monetary valuations of quite a few potential impacts, these valuations do not include all potential impacts of connected and automated vehicles. The three most important impacts without any monetary valuation are:

1. Loss of trust in automation technology
2. Changes in inequality in transport
3. Changes in land use

All these impacts can be quantified. It is also possible to indicate whether the impacts are desirable or not. They can therefore be included in a wider impact assessment in which a cost-benefit analysis is one major component, and an evaluation of the non-monetised impacts the other major component. The final assessment would be to determine the weights to be given to the cost-benefit analysis and the non-monetised impacts.

To perform cost-benefit analyses, many issues not discussed in this deliverable must be clarified. This includes, for example:

1. The level of government the analyses refers to.
2. Definition of the policies to be analysed.
3. Definition of the perspective adopted in the analyses.
4. Determining fixed parameters for the analyses.

There are at least three levels of government who take an interest in societal impacts of connected and automated vehicles: international bodies, national governments and local governments. At the international level, there is interest in harmonising technical standards for vehicles and testing their performance. International standards, ideally speaking global standards, promote economies of scale and may reduce the costs of producing connected and automated vehicles. All else equal, this would improve their benefit-cost ratio, as a given benefit would be obtained at a lower cost.

National governments also have a stake in the introduction of connected and automated vehicles. A national government has more policy instruments at its disposal than a local government. Thus, if local governments worry about urban sprawl as a result of individual ownership and use of automated cars, a national government may counteract this by imposing taxes on automated cars intended for individual use, while exempting automated cars intended for shared use from taxes. A local government would be confined to potentially less effective policy interventions, such as road pricing and parking regulations.

The phrase "cost-benefit analysis of connected and automated vehicles" is sometimes used, as if the market introduction and penetration of connected and automated vehicles somehow depends on a cost-benefit analysis. In a sense, it does. But that analysis is a market analysis car manufacturers would perform in order to assess how well automated cars will sell. If car manufacturers decide that there will be a market for automated cars, they will be offered and their spread throughout the vehicle fleet will be a matter of supply and demand only.

The numerical example developed in chapter 4 broadly conforms to such a laissez faire policy, i.e. there is no government intervention. Once ready, automated cars are offered to the market and the rest is up to consumers. It is tempting, based on the illustrative analysis in chapter 4, to ask whether the private benefits to a consumer would be large enough to offset the extra cost of buying an automated car. The extra cost was estimated as 0.138 Euros per kilometre of driving, whereas the saving in the costs of travel time was estimated as 0.285 Euros per kilometre of driving – clearly exceeding the added cost. However, the savings in the costs of travel time, given per kilometre, depend on speed. In the example in chapter 4, a low speed of 20 km/h was assumed. At higher speeds, the savings would be smaller. On the other hand, values of time vary between individuals and are positively related to income.

Policies regulating the introduction of connected and automated vehicles are likely to include taxation, subsidies, parking regulations, road pricing, geofencing areas where vehicles are permitted to be used and infrastructure measures. In cost-benefit analyses of these policies, a societal perspective should be adopted. A societal perspective differs from a market analysis or a consumer perspective by including external impacts producers or consumers typically do not include.

Monetary valuations are one of the fixed parameters of cost-benefit analysis. The other important fixed parameters are the time horizon of the analysis and the discount rate. These have not been discussed in this deliverable, but will be discussed in deliverable D3.4 on methods for cost-benefit analysis.

7.2 Conclusions

The objective of this deliverable was to provide monetary valuations of the potential impacts of connected and automated vehicles, ideally including all potential impacts. The main conclusions can be summarised as follows:

1. Many of the potential impacts of connected and automated vehicles can be converted to monetary terms for inclusion in cost-benefit analysis.
2. The proposed valuations are all European average values stated in Euros at 2020-price level.

3. For use in cost-benefit analysis, it is convenient to state monetary values as rates per kilometre of driving.
4. Potentially important impacts without monetary values include loss of trust in automation technology, changes in inequality in transport and changes in land use. All these impacts can be quantified and changes that are desirable or undesirable can be identified.
5. The analysis of policies influencing the introduction and use of connected and automated vehicles should take the form of a wide impact assessment in which cost-benefit analysis is one major component and evaluation of non-monetised impacts the other major component.

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