levitate

A taxonomy of potential impacts of connected and automated vehicles at different levels of implementation

Deliverable D3.1 – WP3 – PU

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Coordinator:	Pete Thomas, Prof – Prof. of Road & Vehicle Safety Loughborough University Ashby Road, LE11 3TU Loughborough, United Kingdom
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Lead contractor for this deliverable:
Rune Elvik – Institute of Transport Economics

Report Author(s):	Elvik, R. (TOI), Quddus, M., Papadoulis, A. (LOUGH), Cleij, D., Weijermars, W. (SWOV), Millonig, A., Vorwagner, A., Hu, B., Nitsche, P. (AIT)

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Executive summary

This deliverable presents a taxonomy of potential impacts of connected and automated transport systems (CATS) at different levels of implementation. The taxonomy is based on a systematic review of recent studies that have proposed taxonomies of impacts of CATS. There is considerable overlap among the lists of impacts presented by the studies, suggesting a high level of scientific consensus about the potential impacts of CATS.

A distinction is made between direct, systemic and wider impacts. Direct impacts are changes that are noticed by each road user on each trip. Systemic impacts are system-wide impacts within the transport system. Wider impacts are changes occurring outside the transport system, such as changes in land use and employment. Furthermore, a distinction is made between primary impacts and secondary impacts. A primary impact is an intended impact and goes in one direction only; it emanates from the automation technology and has a well-defined outcome. A secondary impact (rebound impact; behavioural adaptation) is generated by a primary impact and feeds back to the source of the primary impact. An example is that reduction of travel time as a result of less congestion tends to induce more traffic, which in turn increases congestion (although not necessarily back to the original level).

Some impacts are nested within each other. For example, lower operating costs, improved travel comfort and reduced travel time all contribute to reducing the generalised costs of travel. In travel demand modelling, the amount of travel is usually modelled as a function of the generalised costs of travel. In this deliverable, potential impacts have been identified at their lowest and most detailed level, although subsequent analyses may aggregate clusters of impacts into more general variables.

As a result of the detailed description of impacts, a large number of potential impacts have been identified. There are 7 direct impacts, 12 systemic impacts and 14 wider impacts; in total 33 impacts. Table S.1 lists these impacts. All impacts are assumed to be generated by automation technology. It is reasonable to expect that the higher the level of implementation of automation technology, the more extensive impacts will become. Implementation is a multidimensional concept. It is therefore envisaged that a broad range of methods must be used in order to adequately describe and quantify as many of the potential impacts as possible. Deliverable D3.2 will review methods for predicting impacts of connected and automated vehicles. One possibility is to think of impacts as dose-response functions, in which the dose is, for example, the market penetration of an automation technology and the response is the size of an effect, e.g. the percentage change in the number of accidents.

Several of the impacts are related to each other, i.e. one impact influences another impact. It is difficult to identify all interrelationships between impacts. However, for primary impacts that have rebound effects (secondary impacts), it is necessary to model the full causal pathway through the intermediate variables that generate rebound effects. Only by doing so will the final net effect be correctly estimated.

Table S.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
Value of travel 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 parking areas as share of all areas designated for traffic
Traffic data availablity	The availability of detailed trip data for transport planning

Table S.1: Potential impacts of connected and automated transport systems

Impact	Description of impact
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, functional limitations or place of residence
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

1 Introduction

This deliverable gives a taxonomy of potential impacts of connected and automated transport systems (CATS) at different levels of implementation. A taxonomy is an inventory and classification of impacts. The proposed taxonomy makes a distinction between direct, systemic and wider impacts of connected and automated transport systems. Direct impacts refer to the operation of connected and automated transport systems by each user. Systemic impacts are system-wide impacts on transport. Wider impacts are societal impacts resulting from changes in the transport system in terms of, for example, accessibility and cost of transport, and impacts like accidents and pollution and changes in land use and employment.

1.1 Levitate

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 transport, passenger cars and freight services.

2. 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.

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 toolbox allowing the impact of measures to be assessed individually. A Decision Support System will enable users to apply backcasting methods to identify the sequences of 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 objective. Developing methods for assessing and predicting the impacts of CATS consists of the following main stages:

1. Identification and classification of impacts of CATS
2. Description and measurement of impacts of CATS

3. Development of methods of backcasting and forecasting of impacts of CATS
4. Evaluation of comparability and amenability to monetary valuation of impacts of CATS
5. Developing methods for analysing costs and benefits of CATS

The objective of this deliverable is to cover the first two points on this list. The deliverable thus answers the following questions:

1. What are the potential impacts of CATS?
2. How are the potential impacts related to the level of implementation of CATS?
3. How can connected and automated transport systems influence road safety, mobility, environmental impacts of transport and societal changes outside the transport system?
4. What indicators can be used to describe and measure the potential impacts of CATS?

The next deliverable, 3.2, will discuss methods for forecasting the impacts of CATS. It is envisaged that forecasting will concentrate on those impacts that are regarded as most important and relevant from the stakeholder perspective of policy makers. In this deliverable, a wide net is cast, and the aim is to identify all potential impacts of CATS that have been discussed in the literature and the causal pathways connecting these impacts to each other.

2 A review of taxonomies

This chapter reviews studies that give an overview of potential impacts of connected and automated transport systems. The studies are reviewed in chronological order and for each study a list is made of the impacts it discusses and the relationships between these impacts. No single study includes all potential impacts of CATS. A consolidated list has been developed by including all impacts that are mentioned in at least one of the studies reviewed.

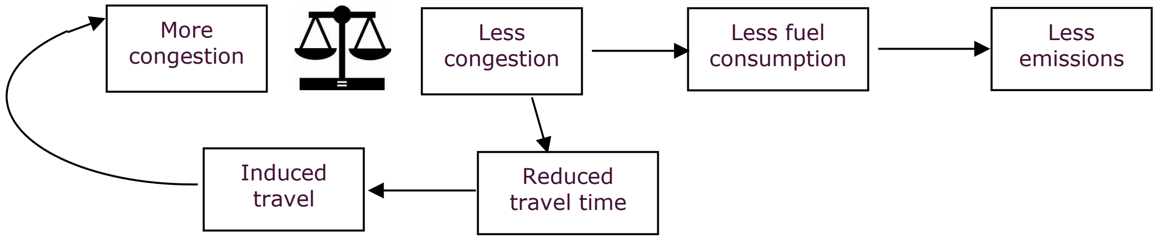
While connected and automated transport systems are developing fast, they have still not been implemented to such an extent that one can evaluate their impacts by means of, for example, before-and-after studies. Therefore, all the studies discussed in this chapter discuss potential impacts only. Which of the potential impacts that will turn into real impacts, depends on the level of implementation of CATS and on policy made to ensure that the implementation of CATS takes place in a way that will ensure maximum benefits of the technology. The studies reviewed in this chapter include only those that list potential impats of CATS or discuss these in general terms, not studies describing methods that can be used to evaluate specific impacts. Studies of evaluation methods will be reviewed in deliverable D3.2.

2.1 Fagnant and Kockelman 2015

Fagnant and Kockelman (2015) discuss potential impacts of automated vehicles under the following headings:

1. Safety
2. Congestion (travel time)
3. Fuel consumption
4. Vehicle emissions
5. Mobility among those without a driving license
6. Smart parking solutions
7. Savings in freight transport
8. No need for truck drivers
9. Change in distance travelled per vehicle
10. Change in vehicle ownership
11. Induced travel demand
12. Change in car ownership cost

Some of these impacts are related to each other. Thus, an expected reduction in congestion will lead to reduce fuel consumption which in turn reduces vehicle emissions. Reduction in congestion means reduction in travel time, which may induce new travel demand (a rebound effect). The causal chain can be modelled as follows:



The rebound effect is shown by a curved arrow. It counteracts the primary effect, i.e. all else equal induced travel increases congestion, thus reducing the initial effect of automated vehicles in terms of reducing congestion.

There is, in a similar manner, a relationship between savings in freight transport and no need for truck drivers, as the elimination of drivers is one of the main contributing factors to the savings. In addition, platooning of vehicles reduces fuel consumption and may reduce travel time.

According to Fagnant and Kockelman, a 90 % implementation rate for automated vehicles can increase road capacity by 80 %. They further note that the long-term demand elasticity of urban vehicle kilometres of travel with respect to lane-kilometres supplied is 0.74. Thus, as a rough estimate, the rebound effect will eliminate 74 % of the 80 % increase in road capacity, leaving a net gain of 21 %. (a rebound effect of 74 % means that 26 % of the primary effect remains; thus when road capacity increases by 1 %, the increase in traffic means that it only increase by 0.26%. Repeating these estimates percent-by-percent up to 80 % shows that the net increase in road capacity will be just 21 %). Fagnant and Kockelman perform a cost-benefit analysis including safety effects, reduced congestion and parking savings on the benefit side and the added purchase price of a vehicle on the cost side. The assumptions made in this analysis are quite simple and rest on an interpretation of available studies, not a detailed modelling or simulation of effects.

2.2 Hörl, Ciari and Axhausen 2016

Hörl, Ciari and Axhausen (2016) review potential impacts of automated vehicles. They list potential impacts under the following headlines:

1. Mobility
    a. Increase in road capacity as a result of:
        i. Connected vehicles
        ii. Fewer delays as a result of fewer accidents
        iii. Improved infrastructure
    b. Induced travel demand
2. City planning
    a. Changes in infrastructure
        i. Reduced need for parking spaces
        ii. Increased need for spaces for dropping off and picking up people
        iii. Charging stations for electric vehicles
    b. Changes in accessibility
        i. Increased urban sprawl

   c. Changes in emissions
      i. Less CO_2 emissions
      ii. Less noise (automated vehicles are assumed to be electric)
3. Car industry
   a. Production and business model
   b. Law, liability and insurance
4. Work organization
5. User profiles
6. Delivery of goods
7. Price

The first item is identical to items covered by Fagnant and Kockelman (2015). In both studies, road capacity is expected to increase, and induced demand is expected to arise. Hörl, Ciari and Axhausen identify three mechanisms producing an increase in road capacity: the fact that automated vehicles will be connected and thus travel at shorter headways with a uniform speed; the reduced probability of delays caused by accidents, as there is expected to be fewer accidents; finally, improved infrastructure enabling vehicle-to-infrastructure communication to optimise route choice, lane use or driving speed.

When modelling the changes in road capacity associated with different levels of implementation of CATS, it is the net result that counts. It is not necessary to model the three mechanisms explicitly, but the direct effect and rebound effect (induced travel demand) should be modelled explicitly and quantified.

Hörl, Ciari and Axhausen expect increased urban sprawl, but environmental benefits in terms of reduced CO_2 emissions and less noise. The latter two impacts arise principally because they assume that automated vehicles will be electric. This, of course, will increase electricity consumption and the net impact on the environment depends on how electricity and electric vehicles are produced. At this point, it is regarded as outside the scope of LEVITATE to assess environmental impacts of the production of electricity or electric vehicles. Users of the policy support tool will be informed that only emissions from driving are included, not the full life-cycle emissions.

The car industry may change its business model when automated vehicles become widespread. Rather than just producing the cars, vehicle manufacturers may see additional business opportunities in car-sharing schemes or taxi services such as Uber and Lyft. The additional costs of offering these services will be minimal once full automation is reached, as there will be no need for a driver.

The absence of a driver may change legislation regarding legal responsibility for accidents. Today, road users are held responsible for accidents; yet not without some important exceptions. In the United States vehicle recalls are not uncommon. A recall means that car manufacturers ask car owners to bring the car back to the factory to correct a malfunction or design failure made by the manufacturer. This kind of product liability will probably have to be extended considerably once vehicles become automated.

Work organisation has to do with increased flexibility in working hours. The Internet already facilitates working from home in many occupations; automated vehicles will make working while commuting easier. This may in turn lead to increased tolerance of longer commutes and thus urban sprawling.

Hörl, Ciari and Axhausen expect automated vehicles to be used as shared vehicles. This is somewhat inconsistent with the expectation of increased urban sprawl, at least if that takes the form of single family houses with a garden, US suburban style. This type of land use is very low density and does not easily lend itself to service by means of public transport or even shared private vehicles, although vehicle sharing may work for specific trip purposes (e.g. children all going to the same school). On the other hand, if urban sprawl takes the form of higher density developments, it may be easier to share the use of automated vehicles.

Delivery of goods is expected to become cheaper and need less manpower. Finally, Hörl, Ciari and Axhausen expect automated vehicles to be at least initially more expensive than conventional vehicles.

2.3 Chan 2017

Chan (2017) discusses potential impacts of automated driving systems and lists the following impacts:

1. Vehicle user impacts
    a. Fewer accidents
    b. More comfortable and less stressful trips
    c. Enhanced mobility for children, the disabled, etc.
    d. More productive trips (i.e. possibility of working)
    e. A more attractive mode of transport
    f. Less demanding or unnecessary vehicle ownership
    g. Automated event handling in case of vehicle failure
2. Transport system impacts
    a. Reduced congestion
    b. More effective real-time navigation, dynamic routing
    c. More accessible, reliable and flexible shared rides
    d. Fewer vehicles on the road as a result of ride sharing
    e. More efficient infrastructure
    f. More affordable mobility services for public agencies
    g. Improved economic returns for private investors
    h. Savings in parking areas or other road constructions
3. Societal impacts
    a. Less need for customized mobility services for those with special needs
    b. Greater incentive to shift from owning to sharing cars
    c. No driver shortage
    d. Reduced insurance and related ownership costs
    e. Reduced accident rates
    f. More environmentally friendly vehicles and infrastructure
    g. Increasing quality of transport services with respect to safety, reliability, security and productivity

Many of the items on this list of impacts were also listed by Fagnant and Kockelman (2015) and by Hörl, Ciari and Axhausen (2016). The list has a few redundancies. Thus, impact 1a may be seen as identical to 3e, unless 1a applies to individual drivers and 3e to the aggregate level. Impacts 1c and 3a are also, if not identical, then at least overlapping to a great degree. Impacts 1f and 3b seem to be almost the same. Impacts 3d and 3e are really two aspects of the same impact.

Some of the impacts are not discussed in further detail and it is not entirely clear how they arise or manifest themselves. Impact 2g, improved economic returns for private investors belongs to this category.

It is nevertheless clear that some of the impacts listed are included on all lists of potential impacts of CATS, as will be seen in subsequent sections. This applies to fewer accidents, reduced congestion, and reduced environmental effects of transport. Quite a few lists of impacts also include less need for parking areas.

Chan does not discuss the relationships between the impacts or attempt to form a causal diagram for them.

2.4 Milakis, van Arem and van Wee 2017

Milakis, van Arem and van Wee (2017) give a very comprehensive review of potential impacts of automated driving and discuss each of the impacts in some detail. They propose a distinction between first-order, second-order and third-order impacts, based on the model shown in Figure 1 (copied from their paper).

At the centre of the model is the vehicle automation technology. Its use in the transport system generates at first impacts that are directly noticed by road users, shown in the light blue circle. Outside of that are second-order impacts, relating to, for example, vehicle ownership rates and employment. Finally, the outermost circle identifies third-order impacts. Milakis et al. list the following first-, second- and third-order impacts:

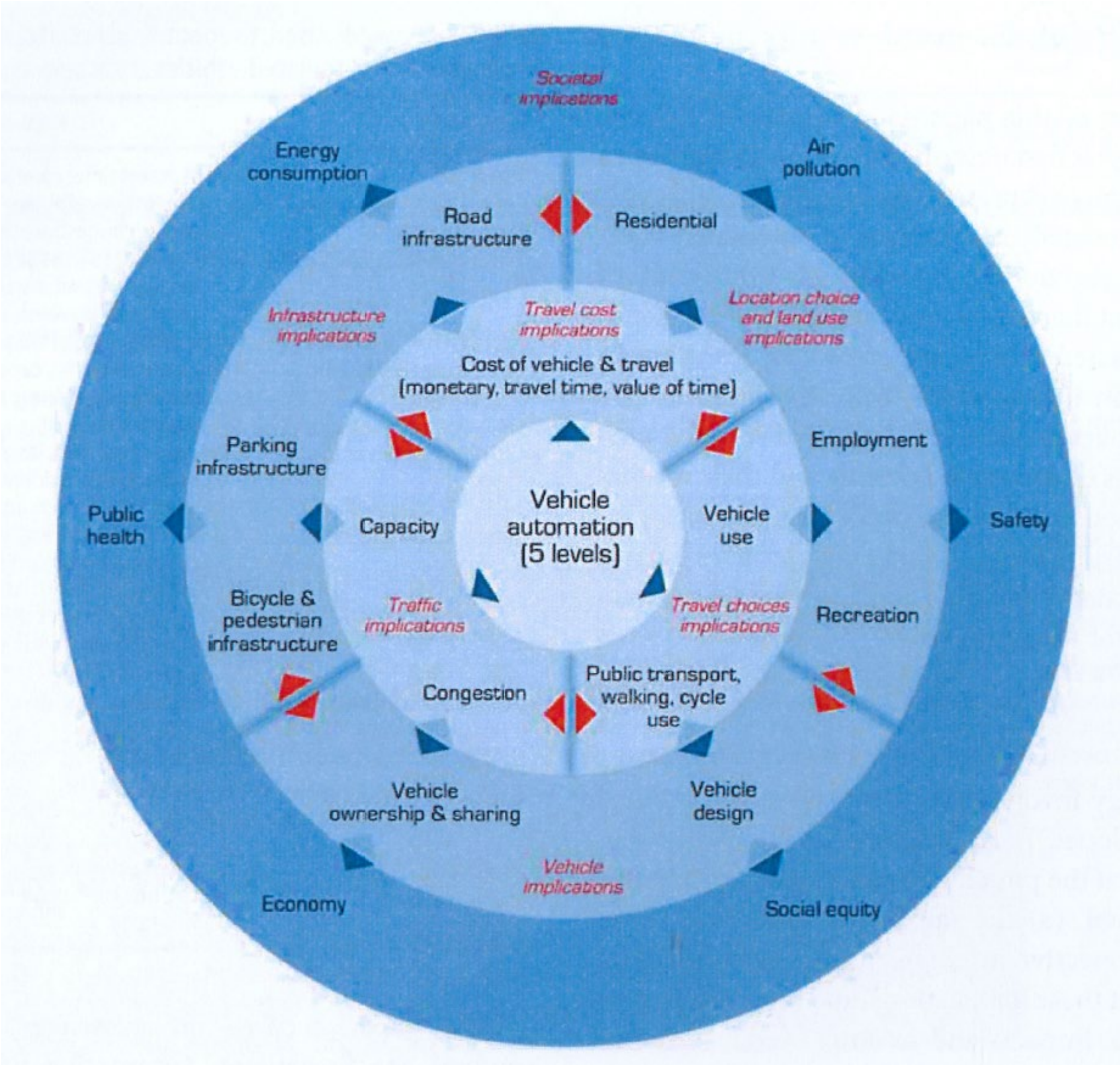


Figure 5 The ripple model of the effects of automated vehicles. Source: Milakis, van Arem and van Wee (2017)

1. First-order impacts
    a. Travel cost
        i. Fixed cost of automated vehicles
        ii. Travel comfort
        iii. Travel time
        iv. Value of travel time
    b. Road capacity
        i. Highway capacity
        ii. Intersection capacity
    c. Travel choices
        i. Vehicle kilometres travelled
2. Second-order impacts
    a. Vehicle ownership
    b. Location choices and land use
    c. Transport infrastructure
3. Third-order impacts
    a. Energy consumption and air pollution
        i. Fuel efficiency
        ii. Energy consumption (long term)
        iii. Emissions
        iv. Air pollution
    b. Safety
    c. Social equity
    d. Economy
    e. Public health

It is not made clear how impacts were sorted into the three main groups. Milakis, van Arem and van Wee review a large number of studies that have tried to assess these impacts. Some impacts are related to each other or nested within each other. Thus, as indicated, changes in travel cost (i.e. the generalised cost of travel) are the sum of the costs of owning and operating vehicles and the value of travel time. One should possibly also add part of the cost of accidents, but in the taxonomy proposed by Milakis et al. accidents belong to the third-order effects.

Milakis et al. survey the literature and indicate the likely sign of each impact. The fixed costs of automated vehicles are expected to be higher than for manually operated vehicles. Travel time is expected to be reduced. The signs of the impacts on travel comfort and the value of travel time are listed as indeterminate by Milakis et al., meaning that they do not indicate whether impacts will be favourable or unfavourable. Most studies that have tried to simulate the effects of CATS assume that the value of travel time will be reduced. Road capacity and vehicle kilometres of travel are both expected to increase, meaning that the rebound effect on congestion from increased vehicle kilometres is not expected to eliminate the benefits of increased road capacity.

Vehicle ownership is expected to decline, and shared vehicles (or shared use of them) will replace many individually owned vehicles. Effects on location choice and land use are indeterminate. The need for parking space is expected to decline. Note that Milakis et al. discuss this effect under the heading of transport infrastructure, whereas Hörl, Ciari and Axhausen discussed it under the heading of city planning.

Fuel efficiency is expected to increase, and emissions expected to reduce. A transition to electric vehicles will further increase energy efficiency and reduce air pollution. Safety is expected to increase, but it is noted that the gains in safety can be limited by behavioural adaptation, cyberattacks and software limitations. Regarding social equity, economy and public health, little is known, but better access to transport for those who cannot drive can be seen as a gain in equity.

2.5 Herrmann, Brenner and Stadler 2018

Herrmann, Brenner and Stadler (2018) is a book of 445 pages dealing with autonomous driving. It has a popular science style but covers many aspects of the introduction of CATS and its potential impacts. The following list of impacts are discussed in the book:

1. Road capacity (expected to increase)
2. Fuel economy (expected to improve)
3. Vehicle operating costs (expected to decrease)
4. Road safety (expected to improve)
5. Use of in-vehicle time (time liberated for use to work, entertainment, etc)
6. Land use (less need for parking space)
7. Dynamic routing (through interaction with intelligent infrastructure)
8. Transition to electric cars (may be faster)
9. Access to mobility (increased for people without a driving licence)

One aspect of the transition to automated driving discussed in this book is the ongoing competition between technology companies and car manufacturers concerning the development of fully autonomous cars. Technology companies, like Google, have taken the step straight to SAE level 5 automated vehicles, skipping the intermediate stages of 2, 3 and 4. The book argues that it is still not entirely clear who will win the competition, but that skipping the intermediate stages of automation is attractive, because there is a worry that some intermediate levels, in particular SAE level 3, will not function well. At SAE level 3, the car is autonomous, but only in defined operational domains. An operational domain could be defined in terms of, for example, the type of road (motorways only), or a certain range of environmental conditions in which the autonomous system functions. Sensors, for example, may have degraded function in rain, snow, or fog. In these conditions the driver may be requested to take over control of the vehicle.

If the car has been in autonomous mode for some time, the driver may be ill-prepared to take over control when asked to do so. This has been shown in many simulator studies as well as on-road studies (Eriksson and Stanton 2018). Some car manufacturers have established formal cooperation with technology companies in developing automated cars, but the possibility still exists that there will be two parallel paths in the transition to automated driving – one that may be called "evolutionary" and will proceed step-by-step through a number of levels, and one that may be called "disruptive" and will go straight for the highest level of automation. In principle, government can influence the course technological innovation takes, e.g. by indicating that SAE level 3 cars will not be approved for use on public roads.

When developing models for predicting the impacts of CATS, it is definitely most convenient to assume that the vehicles are at the highest level of automation, and that the only aspect of the transition to full automation considered is changes in the market penetration rate of fully automated vehicles. It is recognised, however, that this perspective is too narrow to adequately model all impacts of CATS. As an example, stand-alone technologies like cooperative intelligent cruise control, enabling vehicles to form platoons, may become available and used before full automation of all driving functions has been accomplished. It is then relevant to assess the impacts of platooning separately. Other specific technologies may also require separate impact assessments.

2.6 Hibberd et al. 2018

The report by Hibberd et al. (2018; 21 authors listed) is a deliverable from the ongoing L3Pilot project, a Horizon 2020 project with Volkswagen as coordinator. This project will test SAE level 3 automation systems in real traffic. It is part of the ongoing technological development in addition to being a research project.

Like other recent or ongoing projects, L3Pilot has developed a list of potential impacts of automated driving. An interesting aspect of the list is that it goes further than other lists in specifying indicators to measure the various impacts. Some of these indicators are listed below for the most important impacts discussed by the L3Pilot project:

1. System technical performance
   a. Vehicle data on system status
2. Driver behavior
   a. Vehicle data on lateral and longitudinal acceleration, lane position, etc
3. Interaction with other road users
   a. Vehicle data on time headway and time to collision
4. Impact on safety
   a. Simulated frequency of accidents
5. Environmental impacts
   a. Average fuel consumption per vehicle
6. Travel behavior (exposure)
   a. Number of trips per time unit; number of times parking; distribution of trip duration
7. Socio-economic impacts
   a. Several indicators based both on vehicle data and questionnaires

It is interesting to note that surrogate safety measures, like time headway and time to collision are assumed to be recorded by the vehicle. If it can be assumed that automated vehicles will have this capability, then objective data on safety indicators can be collected and used to monitor the safety performance of automated vehicles. A dilemma arises because current vehicles are normally not equipped to collect these data, although that is possible without automation. Thus, currently available data on, for example, the frequency of short headways or short times to collision, are incomplete; at best sample data based on video recordings are available. It is likely that once such data are collected on a routine basis, the frequency of short headways or short times to collision will be found to be higher than hitherto believed, suggesting – if changes in these indicators are used to evaluate changes in road safety – that automated vehicles are associated with a deterioration of safety, when in fact it is only the reporting of safety indicators that has become more systematic and complete.

It is also interesting to note that the simulated frequency of accidents is proposed as indicator or safety effect. While simulating accidents may be possible, it is easier to simulate surrogate events, involving the loss of safety margins. Surrogate events are vastly more frequent than accidents. Once automated cars start being used in traffic, naturalistic driving data could be a source of the frequency both of accidents and surrogate events.

Hibberd et al. present a figure modelling the effects of SAE level 3 automated vehicles. The figure is reproduced below as Figure 2.

The figure is impressive in its detail and the number of links indicated between the variables. The final impacts are listed to the right. Intermediate impacts are indicated between the leftmost and rightmost columns. For consistency, the variables to the left should be those that generate impacts, i.e. independent variables, in this case the performance capabilities of SAE level 3 automated vehicles. This principle is not fully adhered to in the Figure. Nevertheless, the figure is the most complete identification of potential impacts of CATS found in the studies that have been reviewed. It may thus serve as a model for developing a similar causal diagram in LEVITATE.

2.7 Hoadley et al. 2018

Hoadley (2018), on behalf of the Polis traffic efficiency and mobility working group, has written a paper discussing potential impacts for cities and regions of automated vehicles. The following potential impacts are identified:

1. Travel demand (increase expected)
2. Modal split of travel (less cycling, walking and public transport expected)
3. Space used for parking (reduction expected)
4. Urban sprawl (increase expected)
5. Commuting distance (increase expected)
6. Accessibility to transport (increase for those with low accessibility)
7. Inequality in transport (may increase)
8. Employment (may change)
9. Value of time (may become lower as it can be spent on productive things)
10. Public finances (may be weakened)
11. Road safety (may improve)
12. Utilisation of road space (may increase outside cities)
13. Data for traffic management (detailed data may become available)

The report notes that several of the potential impacts of automated vehicles are not obviously favourable. In particular, an increase in vehicle kilometres and a reduction of walking and cycling goes against current political objectives in many cities. It is, however, possible to counteract such a development by means of, for example, road pricing. With respect to safety benefits, the report notes that:

"Achieving road safety benefits presumes that systems are always on, always fully operational and will "fail safe". This is a big ask: In 2017, connected cars can be hacked; transport booking systems overbooked; fleet management systems can fail; power and communications systems have outages; components fail; and navigation guidance is not infallible."

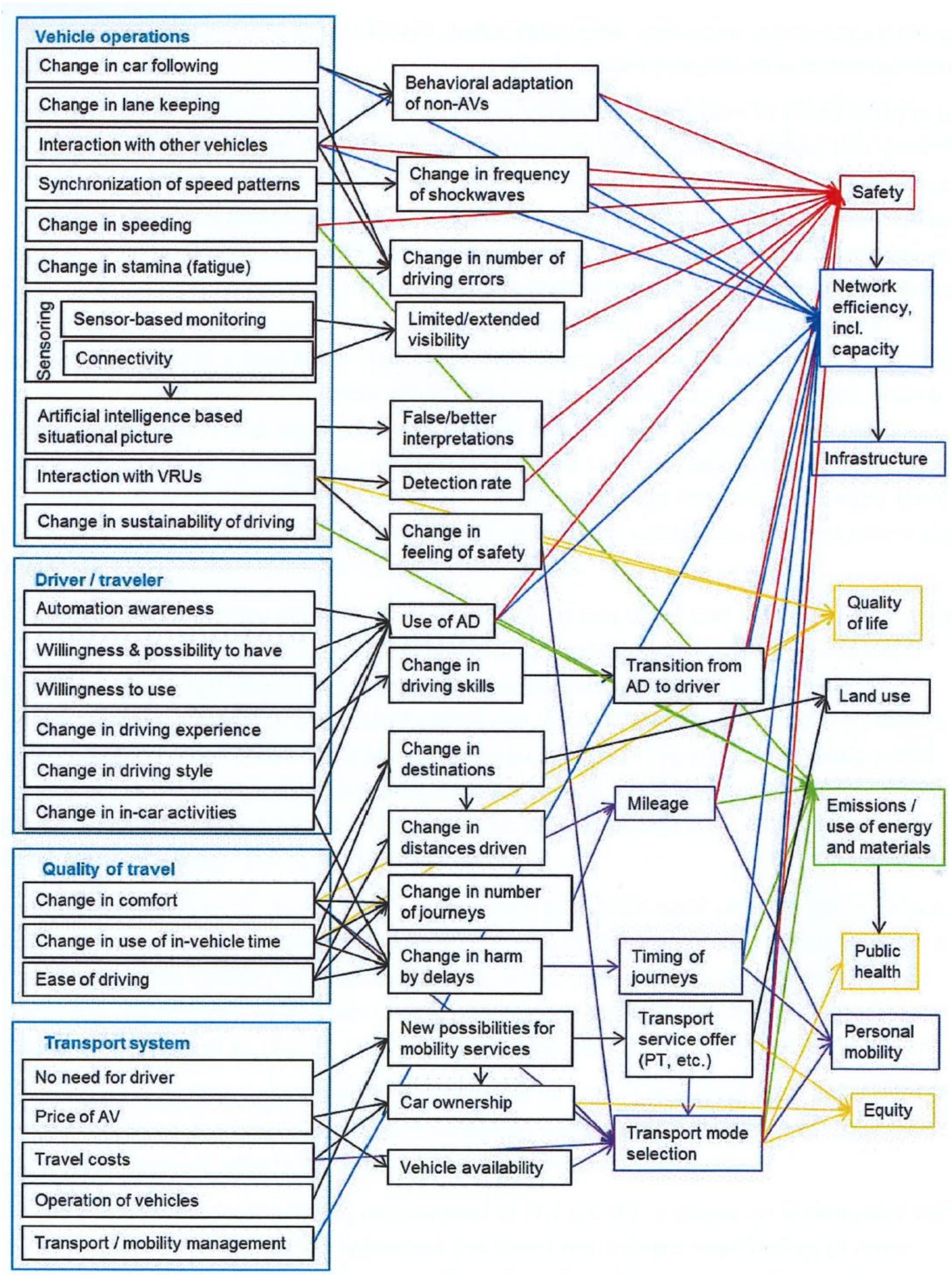


Figure 2 Impacts of automated driving. Source: Hibberd et al 2018, figure 2.5

These observations are correct. Automated systems need to have a very high reliability in order to perform better than human drivers. However, it should not be forgotten that human operators sometimes voluntarily choose to degrade their performance and erode their safety margins by drinking and driving, speeding, tailgating, or otherwise adopting a behaviour that involves an avoidable risk. Speeding, drinking and driving, and non-use of seat belts contribute to about 30-40 % of all traffic fatalities, and automated vehicles may eliminate this contribution.

2.8 Innamaa et al. 2018

Innamaa et al. (2018; 7 authors) present an impact assessment framework for automated road transport, based on a trilateral cooperative project involving the EU, the USA and Japan. The potential impacts of CATS are presented in a figure, which is reproduced below as Figure 3.

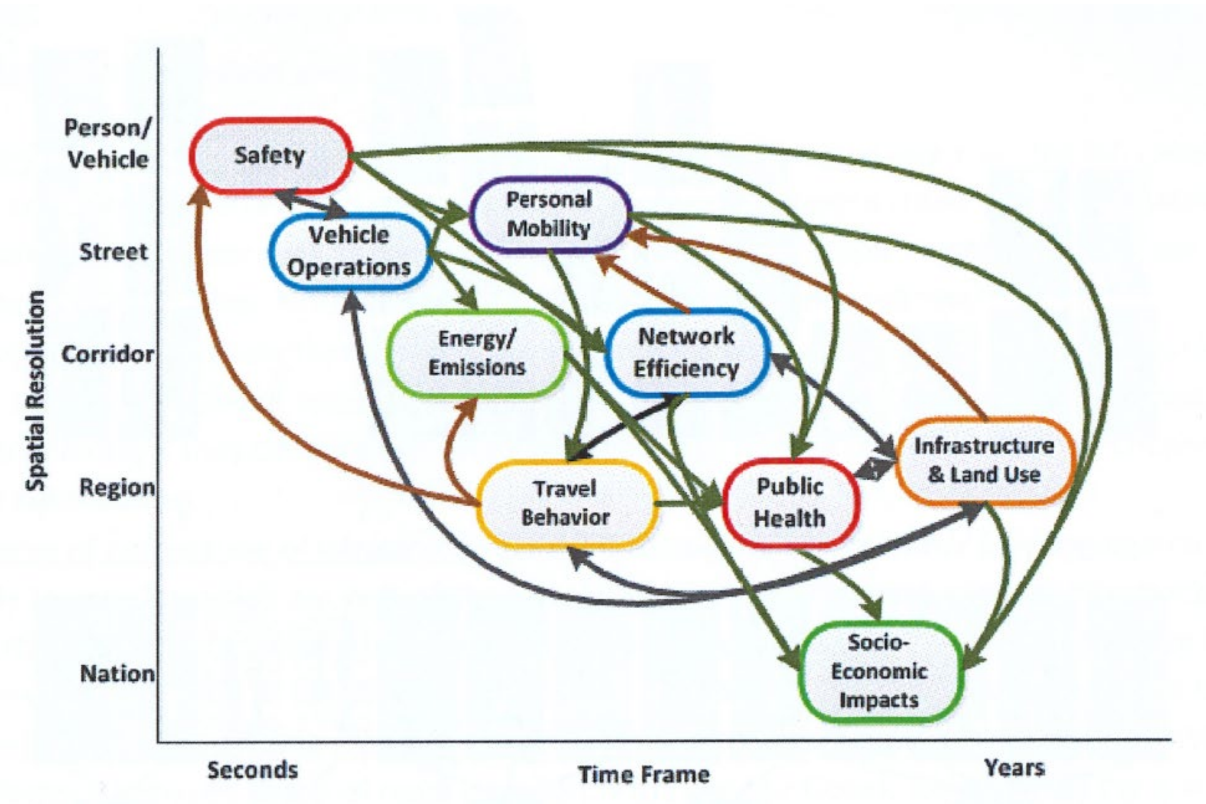


Figure 3 Potential impacts of connected and automated transport systems. Source: Innamaa et al. 2018, Figure 1

The list of impacts includes those that have been identified in other recent overviews. A distinction is made between two dimensions: (1) The time dimension (X-axis) and (2) the geographic scale of impacts. Safety impacts have been classified as an impact at the person/vehicle level occurring within a time-frame of seconds. This should probably not be interpreted as suggesting that safety impacts cannot be observed at, for example, the regional or national levels, or that safety impacts disappear after a few seconds. Safety impacts are likely to be observable at the national level and for a period of many years. The idea of sorting impacts in groups is attractive, but there is no consensus in the reviewed papers about how to do it. Milakis et al. (2017) discuss first-, second- and third order impacts. Hibberd et al. (2018) identify impacts at four stages of a causal chain, where the stages are partly in a logical order, partly in a chronological order. Finally, Innamaa et al. (2018) use geographic and temporal extension as sorting dimensions. Rather than finding the "correct" way to classify impacts, it is important to ensure that a taxonomy of potential impacts is:

1. Complete, i.e. includes all impacts that have been identified in at least one study
2. Operational, i.e. suggests at least one indicator of an impact intended to measure it.

According to these criteria, the review of Innamaa et al. (2018) is useful by listing impacts and indicators of them in an Appendix. The Appendix runs to five pages. For illustration, the main headings and a few selected indicators are listed for each of the impacts included:

1. Use of automated driving
    a. Number of times the driver takes over control per 1000 km
    b. Minimum time used to take over control
2. Vehicle operations
    a. Mean speed and speed variation
    b. Mean and minimum time headway to vehicle in front
3. Safety
    a. Number of accidents per 100 million km
    b. Number of conflicts with time to collision below a set value per 100 million km
    c. Proportion of time with time to collision less than a set value
4. Energy consumption and environment
    a. Energy consumption in kWh per year
    b. Emissions of local air pollution
5. Personal mobility
    a. Number of trips made per day
    b. Waiting time for vehicle (in shared mobility schemes)
    c. Number of new trips made per year
6. Travel behaviour
    a. Total kilometres travelled in a region
    b. Share of transport modes
    c. Network level journey time per week
7. Network efficiency
    a. Road capacity at design speed
    b. Peak period travel time along a route
8. Asset management
    a. V2I infrastructure for automation
    b. Pavement condition (ruts and evenness)
9. Costs
    a. Cost of buying automated vehicle
    b. Operating costs of automated vehicle
10. Public health

a. Population exposed to air pollution
b. Modal share of active transport (walking or cycling)

11. Land use
    a. Density of housing
    b. Parking area
    c. Space needed for roads
12. Economic impact
    a. Work time gained due to working while travelling
    b. Number of jobs lost to automation
    c. Share of household budget spent on transport

These are just a few of the indicators listed. The final choice of indicators will be influenced by their analytic tractability, i.e. how well they lend themselves to simulation or other forecasting techniques that will be used in LEVITATE.

2.9 Kockelman and Boyles 2018

Kockelman and Boyles (2018) have edited a book of about 450 pages presenting current knowledge about impacts of connected and automated transport systems. The list of (most) chapters in the book gives an overview of the type of impacts it covers:

1. Identification of CAV (connected and automated vehicles) technologies
2. Operational domains of CAVs
3. Estimating the safety benefits of CAV technologies
4. CAV applications pertaining to traffic management operations
5. Inertial measurement data with traffic flow models for traffic monitoring
6. Legal environment of self-driving vehicles with CAVs
7. Traffic models for automated vehicles
8. MOVES emission modelling
9. Application of traffic models
10. Design and implementation of shared autonomous vehicle system
11. Making the most of curb spaces in a world of shared autonomous vehicles
12. Benefit-cost analysis

Subsections in the chapters show that the impacts considered are: safety, mobility, connectivity, sustainability, land use, and economic impacts. Extensive simulations have been performed in order to predict these impacts. The results of these simulations may serve as input for developing functional relationships relating the effects of CATS to their level of implementation.

The report briefly discusses other impacts of CATS and notes, for example, that the need for traffic police is likely to be reduced. Thus, one may foresee impacts on employment in at least three occupations: (1) professional drivers, who will no longer be needed when all vehicles are fully automated and autonomous; (2) garage and service station personnel, as fewer accidents will reduce the need for repairs and a transition to electric vehicles eliminates (or strongly reduces) the need for fuel stations (it seems reasonable to assume that recharging of electric vehicles can be done by owners without the need for professional personnel); (3) traffic police, as automated vehicles will presumably not commit traffic violations. Overall, therefore, CATS is likely to reduce employment in the transport sector.

2.10 Pribyl et al. 2018

Pribyl et al. (2018; 13 authors in total) is a deliverable from the MAVEN project (MAVEN = Managing Automated Vehicles Enhances Network) which discusses potential impacts of CATS. The report mentions the following potential impacts of CATS:

1. Efficiency of transport
2. Road safety
3. Traffic flow
4. Vehicle emissions
5. Accessibility
6. Law, liability and insurance
7. Work organisation

These potential impacts are not discussed in great detail, but the report is clear about the need for developing a policy to regulate and manage the introduction of CATS to ensure that desirable impacts are obtained, and unwanted feedback impacts avoided.

2.11 Position papers on safety by FERSI and ITF

In addition to the studies quoted above, it is worth mentioning two position papers on road safety impacts of automated vehicles published in 2018 by FERSI and ITF.

The FERSI paper proposes ten principles for ensuring that automation will bring about enhanced road safety. The paper notes that pilot versions of automated vehicles may not be error-free (page 5): "A more realistic view is that we may be replacing, at least partially, crashes associated with human error by crashes caused by imperfect automated systems in the intermediate stages." The paper goes on to point out that benefits of automated transport in terms of less congestion depends on an increased use of shared transport. It is pointed out that (page 7): "To improve on human drivers, an AD system must typically have a fatal crash rate better than one fatality per billion of kilometres, making testing and verification of performance a difficult or even impossible task."

It is important to remember that not all modes of travel are going to be automated. Thus, FERSI points out (page 9): "Cyclists, pedestrians, motorcycle, and moped riders are not likely to gain immediate benefits from AD or ITS technology." Even if automation technology may ultimately be able to prevent cars from striking pedestrians, the non-automated modes of travel will have crashes between themselves, e.g. motorcycles crashing with pedestrians or cyclists, etc.

FERSI warns against introducing SAE level 3 automated driving (page 11): "As mentioned previously, human limits in staying alert and acting as a fallback when system automation fails may in fact preclude the introduction of level 3 AD systems completely, which would coincide with FERSI's general view."

In short, FERSI sounds a note of caution, and proposes ten principles it believes must be adhered to in order to make sure that vehicle automation will improve road safety. It is outside the scope of this deliverable to discuss these principles in detail; readers are referred to FERSI (2018).

The International Transport Forum (ITF 2018) has published a report entitled: "Safer roads with automated vehicles?" Like the FERSI paper, it sounds a note of caution, but with a different focus than FERSI. Some of the main conclusions listed at the start of the report are worth quoting (page 5): "It seems likely that the number of road crashes will decrease with automation, but crashes will not disappear. … Vehicle automation strategies that keep humans involved in the driving task seem risky …, the risk of unintended consequences that would make driving less safe, not more, could increase."

The report notes that programming code for automated driving has been found to contain 20-50 errors per 1000 lines of code, and that only 15 % of the errors are detected by quality checking routines. While not all of these errors may be very serious, they show that automated driving relies on computer software developed and written by fallible humans.

The ITF report devotes 10 pages to discussing the threat of cyber attacks. Although the risk of such attacks is not quantified and may be impossible to quantify in a meaningful way, it is clear that the risk is real and may limit the effectiveness of CATS as well as undermine trust in these systems. Deliverable 3.2 will discuss cyber threats more extensively.

3 Levels of implementation and indicators of impact

This chapter discusses the concept of levels of implementation of connected and automated transport systems (CATS). It is argued that there are many paths of implementation and that prediction of them remains difficult. For the purposes of developing methods for predicting the general impacts of CATS, it is necessary to model implementation in a way that permits quantified estimates of impact. At the very least, a definition and measurement of level of implementation is needed. Impacts will be defined as functions of level of implementation. This approach applies at a general level. In specific use cases, it will be supplemented with prediction of the impacts of specific technologies, such as technology allowing vehicle platoons to be formed. For most impacts, several indicators of impact can be imagined and have been used in the literature. This is not nessarily a problem if the indicators produce comparable results. Indicators of safety impact are discussed as an illustration of which indicators are available and how they can be interpreted.

There are two different types of prediction about CATS. One type is predictions about when different levels of automation will reach the market and how fast they will spread. These predictions are notoriously uncertain. As an example, see the predictions made in the report by Kristensen et al. (2018) about the introduction of CATS in Denmark. Thus, it is predicted that cars with SAE level 3 automation may reach 50 % market penetration between 2026 and 2042. For level 5 automation, 50 % market penetration is predicted between 2035 and 2060. ERTRAC (2019) predict that level 5 automated vehicles will become available from around 2030. Grush and Tiler (2018), on the other hand, do not expect level 5 vehicle to reach the market before 2050-2070. There is, in other words, large uncertainty. LEVITATE does not aim to make this kind of prediction.

The other type of prediction about CATS is prediction of the impacts it will have at different levels of implementation. These predictions refer to the types of impacts that were discussed in Chapter 2. To develop such predictions, it is necessary to model the level of implementation of CATS. However, level of implementation is a multidimensional concept. It is analytically convenient to rely on a single dimension in order to develop quantified predictions of impacts.

3.1 Dimensions of implementation

The implementation of connected and automated transport systems can be viewed as a process developing along four dimensions:

1. Levels of automation
2. Domains of operation
3. Involvement of traffic management
4. Market penetration

The first dimension refers to the categorization of levels of automation developed by SAE and others. SAE level 1 is a fully manual vehicle with no automation. Level 2 is advanced driver support systems; these systems do not take over control from the driver, but support the driver by assisting in braking, steering or other functions. Level 3 is a vehicle that can drive without driver control, i.e. the driver does not have to touch the steering wheel or the pedals, once automated functions have been engaged. It is generally envisaged that automated driving at this stage will be an option – it can be turned on or off – and restricted to clearly defined operational domains, e.g. motorways. When the vehicle is about to leave an operational domain, the driver will be asked to take over control. Level 3 is widely regarded as a hazardous solution (Eriksson and Stanton 2018), and FERSI, for example, calls for avoiding it altogether. Level 4 vehicles are fully automated, but still restricted to defined operational domains. Level 5 vehicles are fully automated; no driver is needed, and the vehicles can operate all over the road system.

It is not possible to predict with great confidence when vehicles at the different levels of automation will become available and how fast they will penetrate the market. It is not even clear whether technology will develop gradually through the SAE levels of automation, or whether a successful jump straight to level 5 can be made.

The second dimension of implementation refers to where automated vehicles are permitted to operate and whether they are allowed to mix with manually driven vehicles. At least three levels of implementation can be identified:

1. Automated vehicles can only operate on designated areas where other traffic is not permitted.
2. Automated vehicles are allowed to operate on some public roads where non-automated traffic is also found.
3. Automated vehicles are allowed to operate on all parts of the road system.

It seems realistic that implementation will proceed chronologically from implementation level 1 to level 3 (these levels should not be mixed up with SAE levels 1-3 of automation). Automated buses are already operating in many places, but generally in separate dedicated lanes where other traffic, except for bus passengers, is not allowed to enter. The next stage will be to allow automated vehicles in well-controlled traffic environments, motorways are likely to be the first place where automated vehicles are permitted to mix with other traffic.

City traffic is complex and may not support the use of some of the functions of CATS, like forming platoons of vehicles. The short distances between junctions and pedestrian crossings in cities make platooning difficult or counterproductive. One may, however, envisage a third dimension of implementation that will apply to urban areas or motorways. That dimension refers to whether traffic is being monitored and regulated by a traffic management centre or not. Many large cities have a traffic management centre which, for example, can program traffic signals, monitor queue lengths, open or close lanes to traffic, set variable speed limits, and so on. The control room will typically have a large number of screens showing true-time videos of traffic. Similar centres monitor motorways many places.

One can imagine that automated vehicles will be allowed to drive in cities and on motorways, but that the traffic management centre will be able to communicate with the vehicles and intervene if needed. Vehicles operating under such a regime are automated but not autonomous; i.e. they cannot always do what they “want”, but may have to obey commands issued by the traffic management centre. It does not seem altogether unlikely that the operation of automated vehicles in large cities will, at least initially, be controlled by a traffic management centre. Again, however, predicting the duration of such a phase of implementation seems difficult.

The fourth dimension of implementation concerns how fast vehicles at different levels of automation will penetrate the market. If the development of automation technology follows the "evolutionary" model of proceeding from SAE level 2 to 3, further on to SAE levels 4 and 5, there will be a long period of time when traffic will consist of a mixture of vehicles at all these levels of automation. The duration of such a phase depends, first, on how fast technology develops, and second, on the turnover rate of the vehicle fleet. Today, cars typically have a life span of 10-15 years. If we are now about halfway through level 2 automation, and there is a gap of 5 years between the introduction of each of the higher stages (i.e. 5 years before we get level 3 vehicles, 10 years before we get level 4 vehicles and 15 years before we get level 5 vehicles), the transition period until there is 100 % market penetration of level 5 vehicles could well take 30-35 years.

The full impacts of CATS may not be realised until the highest level of automation has reached full market penetration. It is the prediction of impacts at this stage of implementation that show the maximum potential CATS has for improving road safety, improving the utilisation of road capacity, and so on. Any prediction referring to an intermediate stage will only have validity for that particular stage of implementation. Obviously, this does not mean that such a prediction is useless. It is important to monitor the process of implementation as it goes on; predictions made for intermediate stages of implementation may provide support for monitoring.

In LEVITATE, the choice has been made to model impacts of CATS as a function of the market penetration rate of level 5 automated vehicles, whenever possible. This is a pragmatic choice made to avoid all the complexities and uncertainties involved in predicting the process of implementation and its intermediate stages. Besides, studies that aim to predict impacts of CATS typically assume that level 5 vehicles have been developed and predict impacts of different levels of market penetration of such vehicles. The literature adopting this approach is far more abundant than the literature trying to model all the stages of implementation before reaching full automation. Some studies do not refer explicitly to level 5 automation, or assume that traffic will consist of a mixture of vehicles at different levels of automation. These studies have been used if they support the development of quantified estimates of impact. Thus, not all quantified estimates of impact refer to level 5 automation exclusively.

In a policy making perspective, relevant information concerns how policy goals can best be attained. Policy goals express the results policy makers want to achieve; in that sense policy goals are desired impacts. If it is a goal to reduce congestion, it is of interest to know how far automated vehicles can contribute to this goal. If it is a goal to reduce space devoted to parking, it is relevant to know how far shared mobility based on vehicle automation can contribute to that goal. Moreover, policy makers would be interested in whether impacts are small or large. Therefore, modelling impacts as functions of the market penetration of automated vehicles will produce information which is relevant for policy makers, although policy makers will not ask the question: what are the impacts of CATS on, e.g. congestion, when all cars have been automated? Policy makers will rather ask: How far can CATS contribute to my goal of reducing congestion? Quantified estimates of impacts on congestion will help answer that question.

3.2 Indicators of safety impact

The impacts of CATS cannot be (fully) evaluated by studying final outcomes. The term "final outcome" refers to the last stage of a causal chain unfolding through many steps. For road safety, for example, accidents – or more specifically the injuries caused by accidents – are the final outcome. However, before an accident occurs, there may have been hard braking, a sharp turn of the steering wheel, loss of control, a conflict with another road user, or all of these. These are surrogate safety measures which indicate the loss of safety margins.

Until automated vehicles become common and make up a sizable share of traffic, it is not possible to evaluate their impacts in terms of final outcomes. It is, to be sure, possible to estimate a hypothetical impact on the number of accidents. One may, for example, rely on the assumption that the risk attributable to human factors is eliminated. Various estimates of this risk can be found in the literature, but the scope of factors included varies and estimates of risk vary between studies. An estimate of the potential gain in safety by eliminating human risk factors will therefore not be very precise, but only indicate a potential order of magnitude of an impact.

Table 1 lists surrogate safety measures that can be estimated in traffic simulation studies. A total of seventeen measures are listed. One of the most commonly used is time-to-collision (TTC) which measures a traffic conflict. There is still discussion about the understanding of what a traffic conflict is. On the one hand, traffic conflicts can be defined by evasive actions. For example, Parker and Zegeer (1989) stated that "a traffic conflict is an event involving two or more road users, in which the action of one user causes the other user to make an evasive manoeuvre to avoid a collision". On the other hand, a crash does not always involve an (unsuccessful) evasion action, e.g. due to inattention, which somehow weakens the relationship between conflicts and crashes according to the definition above. This led to the development of temporal and spatial proximity indicators, which should detect the closeness of two road users in time and space, even if there was no evasion action. This implies that there are quantitative indicators to assess temporal and spatial proximity, such as those given in Table 1. Usually, thresholds for those indicators are set to distinguish between conflict and undisturbed situation, e.g. if TTC<1.5 seconds, that indicates a conflict.

The traffic conflict approach with its surrogate safety measures is a well-recognised supplement to traditional crash analysis and has been applied in various studies related to safety assessments. However, there is still no clear evidence on the statistical relationship between collisions and conflicts. If, for example, a poor correlation is found, this can either be explained by the inaccurate and incomplete reporting of crashes or by the discrepancy between observation periods for conflicts and crashes. Conflict data are usually collected over a much shorter period of time than crashes and hence may not cover sufficient variability in traffic. Also, there is little research on the analysis of single-road-user conflicts (e.g. run-off-road) or multi-road-user and secondary conflicts. Researchers who found a strong correlation between crashes and conflicts recommend disaggregating both data sources into specific characteristics such as road type, manoeuvres or severity level (Zheng et al 2014).

Simulations can help to automate conflict analysis and to increase the number of "virtual observation" of conflicts. Gettman and Head (2003) investigated the potential for deriving surrogate measures of safety from existing microscopic traffic simulation models for intersections and developed the Surrogate Safety Assessment Methodology (SSAM). The authors conclude that this relationship provides a good estimate for future studies, because it is consistent with the range of correlations reported in several studies between AADT and crashes for urban, signalized intersections. They further found a conflict-to-crash ratio of 20,000 to 1, although this ratio varied by conflict type. In summary, traffic conflicts are more numerous than accidents, but are statistically related to the number of accidents (Gettman et al. 2008). It is therefore proposed to use traffic conflicts as an indicator of the safety impacts of CATS, although the generalisation of conflict results to overall crash rates requires careful consideration.

Table 1: Surrogate safety measures that are calculable in traffic simulation

Surrogate safety measure	Description of measure
Gap Time (GT)	Time lapse between completion of encroachment by turning vehicle and the arrival time of crossing vehicle if they continue with same speed and path.
Encroachment Time (ET)	Time duration during which the turning vehicle infringes upon the right-of-way of through vehicle.
Deceleration Rate (DR)	Rate at which crossing vehicle must decelerate to avoid collision.
Proportion of Stopping Distance (PSD)	Ratio of distance available to manoeuvre to the distance remaining to the projected location of collision.
Post-Encroachment Time (PET)	Time lapse between end of encroachment of turning vehicle and the time that the through vehicle actually arrives at the potential point of collision.
Initially Attempted Post-Encroachment Time (IAPT)	Time lapse between commencement of encroachment by turning vehicle plus the expected time for the through vehicle to reach the point of collision and the completion time of encroachment by turning vehicle.
Time to Collision (TTC)	Expected time for two vehicles to collide if they remain at their present speed and on the same path.
DR distributions	Deceleration rate distributions
Required braking power distributions	Required braking power distribution needed in order to avoid an accident
Distribution of merge points	How merging areas are distributed across a motorway
Merge area encroachments	Merge area layouts
Gap-acceptance distributions	Distribution of the gap acceptance of vehicles
Number of vehicles caught in dilemma zones	Number of vehicles waiting in conflict areas in a simulation environment
Speed differential between crossing movements	Speed differences during crossing movements in intersections
Speed variance	Speed variance across and among lanes
Red- and yellow-light violations by phase	Red and yellow light violations by phase in urban road networks
Time-integrated and time-exposed TTC measures	(TET and TIT— duration of time that the TTC is less than a threshold and the integrated total TTC summation during that time, respectively)

Several indicators of other impacts have been proposed. The most detailed catalogue of indicators is provided by Innamaa et al. (2018). To give some examples, the report lists 15 indicators of impact for traffic efficiency (mobility), 6 indicators for impact on public health and 11 indicators of impact for land use. The selection of indicators can be adapted to the use cases and data availability. As long as the indicator can be quantified and changes in its value computed as a function of the level of market penetration of level 5 automated vehicles, it is judged as suitable for use in LEVITATE.

Deliverable 3.2 will show which indicators of impact are most common and whether they produce similar estimates.

4 Taxonomy of impacts and models of their interrelations

This chapter proposes a taxonomy of impacts of connected and automated transport systems, based on the review of taxonomies in Chapter 2 and the discussion of indicators of impact in Chapter 3. Impacts are first listed and described. Models showing the relationship between impacts are then proposed in the form of causal diagrams. An example of how to estimate a relationship and how it can be included in the Policy Support Tool is given.

The review of studies in Chapter 2 shows that many potential impacts of CATS have been identified. In this chapter, these impacts have been classified into three main categories:

1. Direct impacts: These are impacts that are noticed by each road user on each trip and can be observed in traffic.
2. Systemic impacts: These are system-wide impacts occurring in the transport system.
3. Wider impacts: These are wider societal impacts occurring outside the transport system.

The boundaries between these categories are not always clear, and there are many ways of classifying potential impacts, none of which can claim to be the only correct one. Some impacts may be regarded both as direct, systemic and wider.

Consider accidents for example. An accident happens to a road user on a given trip, and may therefore be regarded as a direct impact. It is, however, not an impact that occurs regularly. Quite the opposite, it is, fortunately, extremely rare. Besides, it has an impact not only on the road users involved in the accident, but on traffic in general. There will normally be delays; these can affect a large number of road users not involved in the accident. These characteristics of accidents suggest that they have system-wide impacts and should be classified as systemic impacts.

The effects of accidents do not, however, stop within the traffic system. They have wider societal impacts. The number and severity of accidents influences the health care system, the social security system, friends and relatives of those involved in the accidents, the labour market, and so on. Thus, accidents can be classified as a wider impact.

Impacts on employment are another case. If there is no need for drivers, that is an impact occurring in the transport system, but it is also a wider societal impact. Those who lose their job as drivers, must either find new employment outside the transport sector, or leave the labour force. In either case, a societal impact outside the transport system occurs.

As a general rule, impacts have been classified according to the widest range of their impacts. Quite a few potential impacts are therefore wider impacts.

4.1 List of potential impacts

The list of impacts below is based on the review of taxonomies presented in Chapter 2. The size of the impacts will vary depending on the level and penetration of automation technology. All impacts are indicated as changes compared to a baseline. The words "change in" are not written in Table 2, but it should be understood that, for example, travel time, refers to changes in travel time.

Table 2: 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
Value of travel 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 rate	Percent of trips made sharing a vehicle with others
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 availability	The availability of detailed trip data for transport planning

Table 2: Potential impacts of connected and automated transport systems, continued

Impact	Description of impact
	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

Table 2 lists 7 direct impacts, 12 systemic impacts and 14 wider impacts; in total 33 potential impacts. Some of the impacts form clusters and can be aggregated to larger classes of impacts than those specified in Table 2. It was decided to specify impacts at a quite detailed level, as stakeholders may take an interest in a particular impact even if that impact can be regarded as an aspect of a more general impact.

Thus, generalised cost of travel is a concept that sums up the following impacts: travel time, travel comfort, valuation of time, vehicle operating cost and vehicle ownership cost. Impacts such as propulsion energy, energy efficiency, vehicle emissions and air pollution are also closely related. Models showing how groups of impacts can be formed are discussed in the next section.

4.2 Relationships between impacts

The relationship between impacts can be modelled by means of causal diagrams. Arrows indicate which impacts are assumed to be causally related to each other. Causal relationships can be direct or indirect. A direct relationship goes from A to B without passing through a third variable. An indirect relationship goes from A to B but passes through one or more intermediate variables on the way.

A distinction can be made between primary impacts and induced or secondary impacts (feedback impacts). A primary impact is an intended impact originating in a specific technology and showing the intended function or impact of that technology. Primary impacts will usually occur on a trip-by-trip basis. They may refer to a single vehicle or to traffic in aggregate.

Primary impacts and secondary impacts have been modelled in separate causal diagrams. Figure 4 shows a causal diagram for primary impacts of CATS. In the diagram, impacts are ordered from those that are direct, shown at the top, to those that are more indirect or wider, shown further down in the diagram. The diagram is inspired by the detailed model of Hibberd et al. (2018), shown in Chapter 2 of the deliverable.

Impacts are generated by automation technology. Three aspects of it are identified in Figure 4: vehicle design, level of automation (SAE 1 to 5), and connectivity. These characteristics of technology can give rise to different impacts. To illustrate the reasoning underlying the arrows drawn in Figure 4, take vehicle design as an example. Vehicle design includes aspects such as vehicle size, setup of electronic control units (microcomputers used for operating the vehicle), powertrain (fossil fuel or electric) and ease of getting in or out the vehicle. The technology built into connected and automated vehicles will influence both vehicle ownership cost and vehicle operating cost. Choice of powertrain will influence propulsion energy and energy efficiency of the engine. Vehicle design may also influence infrastructure design and infrastructure wear, depending on, for example, the mass of the vehicle and its facilities for vehicle to infrastructure communication. Finally, vehicle design may influence travel comfort and individual access to transport. As an example, vehicles with high ground clearance and no ramps will be difficult to access for wheelchair users.

To give another example, consider road safety, one of the principal primary impacts of CATS. Road safety is influenced by level of automation, as human operator errors will be eliminated at the highest level of automation (there may still be software errors in computer programmes operating the vehicle, but there will be no driver who can make mistakes). Level of automation may also influence road safety indirectly, by way of trust in technology, in particular before the highest level of automation is attained. However, even fully automated vehicles will have to interact with non-automated road users, who may place excessive trust in the capabilities of the technology to detect them, brake or make evasive manoeuvres. Connectivity will influence safety by reducing or eliminating speed variation between vehicles travelling in the same direction and by shortening reaction times in case of braking. Road safety will furthermore be influenced by potential changes in the amount of congestion, vehicle kilometres of travel, changes in the modal split of travel and optimisation of route choice (even at full automation, it is unlikely that accident rate will be the same on all roads). Changes in road safety will in turn influence public health.

Although very many arrows have been drawn connecting the impacts listed in Figure 4, it is likely that not all relationships have been included. It is hoped that the most important impacts have been included.

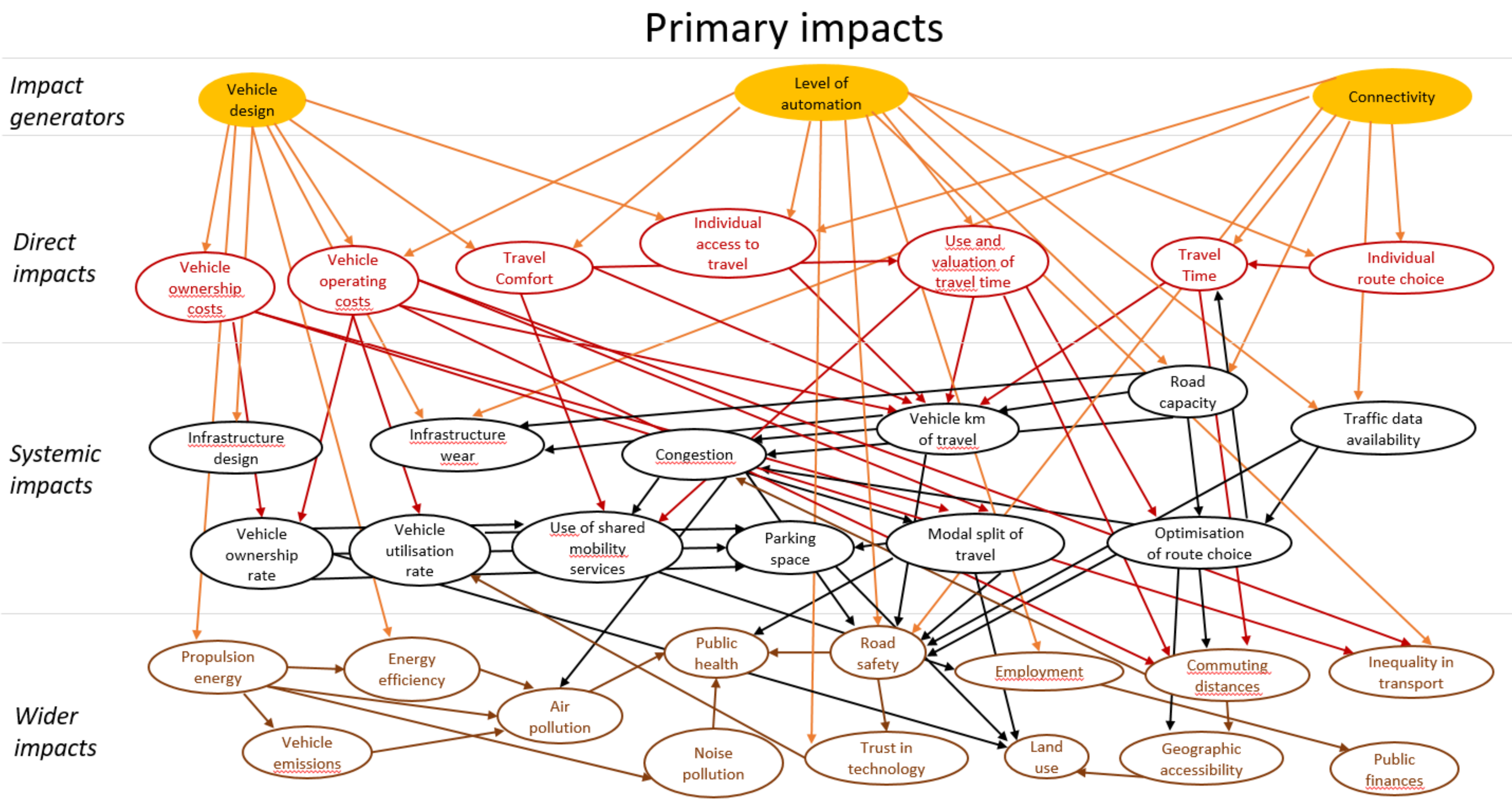


Figure 4 Causal diagram for primary impacts of vehicle automation

It should be noted that some groups of road users will never be automated. Non-automated road users will include pedestrians, cyclists, moped riders and motorcyclists. Although automation technology may prevent most accidents between automated vehicles and non-automated road users, the non-automated road users will have accidents among themselves. These accidents will not be influenced by automation. Table 3 shows the number of injuries among non-automated road users in Norway during 1998-2005 (taken from Elvik 2008).

Table 3: Injuries among non-automated road users in Norway 1998-2005. Highlighted in yellow inside box

Injured as occupant of	Counterpart in accident												
	Truck-trailer	Truck	Bus	Van	Car	Large MC	Small MC	Moped	Cycle	Pedestrian	Other	None	Total
Truck-trailer	73	32	10	5	96	0	1	0	2	0	3	533	755
Truck	80	102	37	40	197	3	0	2	2	1	22	481	967
Bus	120	103	63	43	290	1	0	7	3	8	36	627	1,301
Van	115	214	80	271	1,038	3	0	4	3	8	35	954	2,725
Car	1789	2736	1210	2815	31,355	203	31	59	59	78	543	19,859	60,737
Large MC	41	84	46	128	1,926	107	5	26	25	25	43	2,216	4,672
Small MC	10	14	9	47	474	4	14	21	6	5	10	340	954
Moped	23	68	47	150	2,350	17	26	139	36	51	46	1,036	3,989
Cycle	42	144	105	286	4,388	42	12	82	254	58	83	644	6,140
Pedestrian	54	220	318	409	5,635	61	13	147	167	37	188	185	7,434
Other	17	54	14	20	158	5	0	2	4	2	31	414	721
Total	2364	3771	1939	4214	47,907	446	102	489	561	273	1040	27,289	90,395

There were 6,629 injuries among the non-automated road users, representing a little more then 7 % of the total. The share of injuries among non-automated road users will vary depending on the traffic environment. It will be highest in urban areas, lower on rural roads and lowest on motorways. Thus, all else equal, automated vehicles are likely to have the largest safety effects on motorways.

Primary impacts may give rise to behavioural adaptations that generate secondary impacts. As an example, if the platooning of vehicles utilises road capacity more efficiently, effective road capacity may increase and congestion be reduced. A reduction of congestion can make car travel more attractive and generate increased demand for it. This will in turn increase congestion, although not necessarily back to the original level. The primary mechanisms that are likely to generate secondary impacts are:

1. Changes in travel time and the use and valuation of travel time. All else equal, CATS is likely to reduce travel time and enable it to be used for working or relaxing. This will reduce the generalised costs of travel (the sum of all sacrifices made to travel).
2. Changes in individual access to transport. Individuals without a driving licence or functional impairments will be able to travel in fully automated vehicles. This is referred to as accessibility of transport.
3. Relative changes in the costs of different transport modes. Taxis and public transport are likely to become cheaper as the cost of having a driver are saved. This could make these modes of transport more competitive. On the other hand, the ease of using a fully automated vehicle could make public transport less competitive.
4. Interaction between automated vehicles and conventional vehicles or other road users. Once automated vehicles make up a considerable share of traffic, the

remaining conventional vehicles or non-automated road users may adapt behaviour to imitate automated vehicles.

5. Trust in automation technology. There could be both excessive trust in the technology and a breakdown of trust. In both cases, the potential benefits of automation technology are likely to be reduced. An excessive trust in technology can make drivers ill-prepared to take over control of vehicles at level 3 of automation as well as make pedestrians or cyclists too optimistic about the capabilities of technology to detect them and avoid crashing with them. A breakdown of trust, created for example by cyber attacks, could make people reluctant to use automated vehicles, which would also imply that their benefits would not be realised.

Important secondary impacts are shown in the causal diagram in Figure 5. It is assumed that the secondary impacts are always of the opposite sign of the primary impacts. Thus, if the primary impact of automation is to reduce congestion, the secondary impact is to increase congestion as a result of behavioural adaptation to the initial reduction of congestion. Changes in vehicle kilometres of travel will have a feedback impact on road safety. In addition, there will be feedback impacts on road safety from changes in the modal split of travel. Non-automated road users may adapt their behaviour to automated vehicles, thereby influencing road safety. Non-automated road users may, as an example, take advantage of the defensive behaviour automated vehicles may adopt in interactions with them. Clearly, solutions must be found to situations in which, say, a pedestrian can block an automated vehicle by continuously walking back and forth in a pedestrian crossing. Nevertheless, it is not implausible to suggest that pedestrians and cyclists may count on automated vehicles always giving them way if the rules prescribe so. One cannot count on a car giving way at a pedestrian crossing today. Pedestrians need to calculate the risks they run and let an apparently aggressive driver pass before crossing the road. However, next to nothing is known about potential behavioural adaptation to automated vehicles.

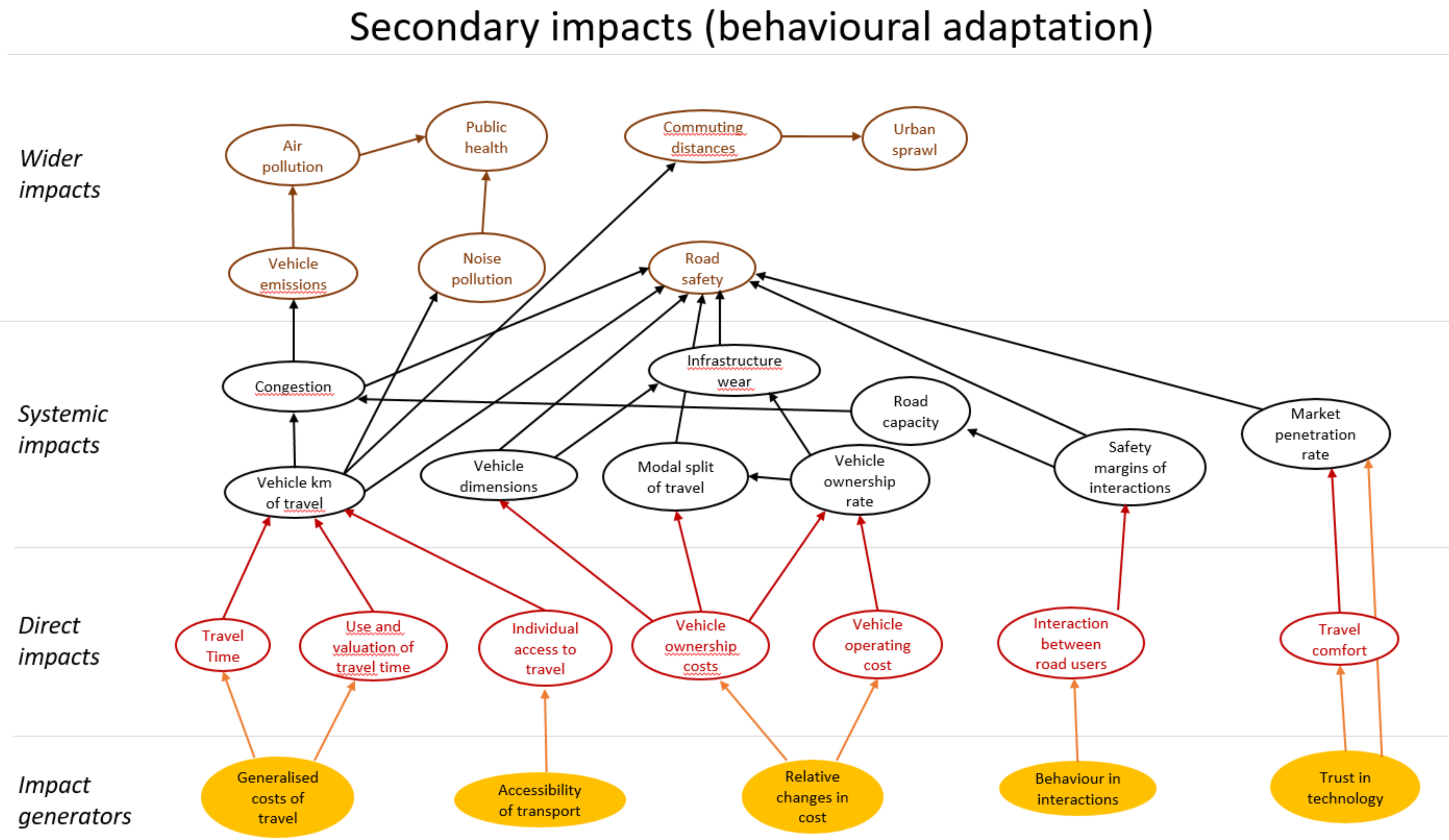


Figure 5: Rebound (secondary) impacts of vehicle automation

As already mentioned, some of the potential impacts of CATS are closely bound together. To make it easier for policy makers to gain an overview of impacts, groups have been formed based on some of the taxonomies reviewed in Chapter 2. These groups are shown in Table 4.

Table 4: Groups of impacts of CATS

Chan 2017	**Chan** 2017	Milakis **et al 2017**	Hoadley 2018	**Innamaa et al l2017**	**Hibberd 2018**
Society	Environment Energy Economy Safety	Energy consumption Safety Social Equity Economy Public Health	Road Safety Socio-Economic	Socio-Economic Safety Energy/Emissions Public Health	Socio-Economic Safety Environment
Vehicle Users	Comfort Convenience Mobility	T ravel costs vehicle ownership and sharing Travel choices Location choices	Travel Behaviour	Travel Behaviour Personal Mobility	Mobility
Transport Operations		Road capacity Land use Transport infrastructure	Spatial Aspects Infrastructure Traffic Efficiency	Land use Network Efficiency Infrastructure Vehicle Operations	Efficiency

Based on the groups identified in Table 4, the causal diagram has been redrawn to form larger categories of impacts that are closely related to one another. The groups are shown in Figure 6.

For some purposes, it may be analytically convenient to form groups of impacts. Thus, in cost-benefit analyses, changes in travel demand can be related to changes in the generalised costs of travel, not to each component of the generalised costs of travel.

4.3 Short descriptions of each impact

For completeness, short descriptions of each of the impacts identified in Figure 4 (primary impacts) will be given. How to measures the impacts is also shortly indicated. The description starts with impact generators.

4.3.1 Vehicle design

Automation may influence vehicle design in many ways. Automated public transport vehicles are expected to become smaller than current buses. On the other hand, the added cost of vehicles, at least in an early phase of automation, could favour large vehicles, as the variable costs of transport (per passenger or tonne km) can then be reduced.

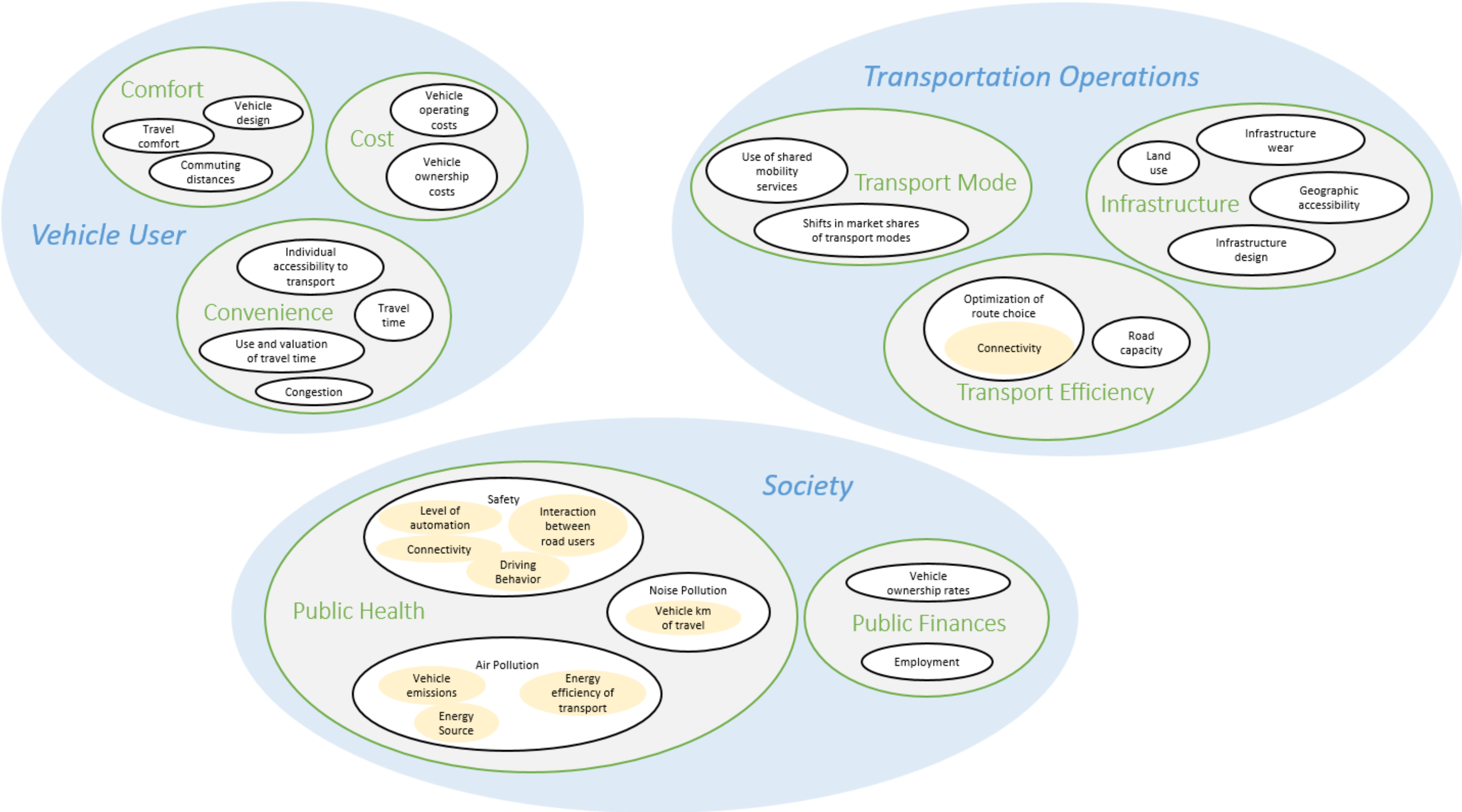


Figure 6: Groups of impacts of CATS

4.3.2 Level of automation

The allocation of driving tasks between a human driver and vehicle automation is a function of the level of automation. Manually performed tasks remain at levels 1 and 2 of automation. At level 3, the vehicle is capable of driving on its own, but a driver is still needed for taking over control in given situations. A vehicle at level 4 of automation can operate without a driver in specific operational domains. A vehicle at level 5 of automation can operate without a driver on all roads in all conditions.

4.3.3 Connectivity

Connectivity is the ability of vehicles to communicate between themselves, for example in order to form platoons. Connectivity can be introduced without making vehicles automated. It is a further development of technology already on the market, such as intelligent cruise control and automatic braking.

The first group of impacts is the direct impacts.

4.3.4 Vehicle ownership costs

Vehicle ownership cost consists of the cost of buying a car and fixed costs of owning the car that do not depend on driving distance. An example of a fixed cost is rent for a garage or an annual lump sum tax on cars. Fully automated cars are expected to be more expensive (to buy) than current cars.

4.3.5 Vehicle operating costs

Vehicle operating cost refers to all costs that are incurred when operating a vehicle. The most obvious item is fuel, but it also includes items like tyre wear, washing the car, replacing worn window vipers, etc. Vehicle operating cost is usually stated per kilometre of driving. Automated cars are generally believed to have lower operating costs than current cars, in particular if they are electric.

4.3.6 Travel comfort

Travel comfort is a multidimensional concept with a large subjective element. Changes in travel comfort associated with a transition to automated vehicles are probably best captured by questionnaire surveys. These will need to be customised to specific use cases. Relevant aspects of comfort are not the same for urban shuttle buses as for private cars. It may be fruitful to treat trust in automation technology as one aspect of comfort. It is uncomfortable to worry about a technology one does not trust.

4.3.7 Individual access to travel

Fully automated vehicles can make individual travel accessible to groups that are currently not allowed to drive. This includes children (at least above a certain age) and those who are denied driving licences because of functional impairments. Estimates of the potential gain in accessibility can be derived from statistics on the percentage of the population having a driving licence.

4.3.8 Use and valuation of travel time

Time spent as a driver has low value, because the time cannot be spent on much else. Hence, travel time savings are highly valued. When cars are fully automated, occupants may be able to spend time on other activities. This is believed to reduce the value of travel time savings. Travel time savings normally constitute the largest part of the benefits of road investments. All else equal, road investments may therefore become less attractive when all cars are fully automated.

4.3.9 Travel time

Changes in travel time for trips with given origins and destinations as a result of connected or automated driving will be the result of a number of other changes:

1. Changes in traffic volume: the most common prediction is that traffic volume will increase, in particular because fully automated transport will reduce the generalised costs of travel,
2. Changes in the utilisation of road capacity: if connected or automated vehicles can utilise road capacity more effectively, a higher volume can be served before delays in travel time arise,
3. Changes in driving speed: it is reasonable to assume that connected or automated vehicles will be programmed to comply with speed limits; if these remain unchanged, there will be a small increase in travel time as a result of the elimination of speeding,
4. Changes in route choice: if connected and automated vehicles have access to real-time data on travel delays on different routes, routes that minimise travel time for given trips may be chosen; to the extent current route choices are suboptimal, this may reduce travel time.

It is not known whether current volume-delay functions apply to connected and automated vehicles (Meyer et al. 2018). Although road capacity may increase, there will be limits to how densely vehicles can be spaced within a platoon and to the lengths of platoons. Thus, even if road capacity increases, it will have a limit.

4.3.10 Individual route choice

Fully automated vehicles are likely to have facilities for vehicle-to-vehicle communication and vehicle-to-infrastructure communication. This enables true-time information about traffic to be collected, supporting individual route choice to minimise delays. Even today, navigation systems (GPS) are capable of calculating travel time with great accuracy, and these capabilities will improve with vehicle automation.

The next group of impacts to be described are the systemic impacts.

4.3.11 Infrastructure design

To prepare for use by fully automated vehicles, it may be necessary to modify infrastructure design, or at least enhance the capabilities of traffic control devices. Suppose, for example, that automated cars will navigate by reading signals delineating lanes. Lane lines and edge lines would then need to have some kind of electronic tagging enabling automated cars to determine their location and memorise it by means of machine learning. This functionality can probably be achieved by adding some material reacting to electric impulses to road markings. It would not be necessary to rebuild the road, just make it electronically readable. We regard it as outside the scope of Levitate to study the modifications that would need to be made to infrastructure.

4.3.12 Infrastructure wear

The benefits of increased road capacity due to automated driving lead to the questions of effects on infrastructure wear. The shortening of the headway distances leads to higher vehicle numbers on road sections. The primary effect on infrastructure wear is expected due to more concentrated loads of heavy vehicles in combination with automated driving. Especially the formation of truck platoons, which would reduce the fuel consumption by using positive aerodynamic effects, will lead to an increased loading of roads and bridges compared to a single vehicle entity. On the other hand, downsizing trucks can become more economically feasible when driving is automated, as the costs of having a driver are saved. Today, economies of scale favour large trucks, as the cost of operating the vehicle then becomes lower per tonne kilometre than for a small truck.

4.3.13 Congestion

Changes in congestion as a result of CATS will be the net result of two impacts pulling in opposite directions. The increase in road capacity brought about by connectivity will, all else equal, reduce congestion. Reduced congestion means shorter travel time. This may in turn generate more traffic, which will increase congestion. The net results depends on which of these two effects is the stronger one.

4.3.14 Vehicle kilometres of travel

The most common prediction is that connected and automated transport will increase vehicle kilometres of travel. This is the expected result of increased travel induced by lower generalised costs of travel. Estimates of the elasticity of vehicle kilometres of travel with respect to the generalised costs of travel are widely available and have been summarised by, for example, Litman (2017).

4.3.15 Road capacity

Connected and automated vehicles are expected to utilise road capacity more efficiently than manually driven vehicles, principally by being more closely spaced and by keeping the same speed. A better utilisation of road capacity will, all else equal, reduce congestion and thus reduce travel time. Effects of reducing space between vehicles and eliminating speed variation can be simulated and quantified.

4.3.16 Traffic data generation

Fully automated vehicles that are equipped for machine learning are likely to continuously record data about the trips made. If these data are made available to traffic planners, they will get access to considerably more detailed data about traffic than today. This may, for example, enable interventions like variable signs to make traffic operations as efficient as possible.

4.3.17 Vehicle ownership rates

One of the biggest advantages of owning a car, is that it is always available and always nearby. However, if connected and automated transport systems are integrated with real-time information systems, delays in getting transport can be minimised, and may perhaps be viewed as acceptable if the costs of travel are reduced. It is not possible to make definite predictions about car ownership rates. Grush and Niles (2018) argue that individual ownership even of fully automated cars is likely to be widespread unless there is a policy designed to discourage car ownership and encourage shared mobility.

4.3.18 Vehicle utilisation rate

Currently, cars are not utilised very efficiently, but are parked for about 23 out of 24 hours. Automated vehicles can be utilised more efficiently, in particular if their use is shared, either in the form of shared use of each vehicle by multiple users (car sharing) or in the form of ride sharing, i.e. a single vehicle taking on board as many passengers as it can carry.

4.3.19 Use of shared mobility services

Car sharing schemes have been introduced in many cities and are slowly becoming more popular. A Danish study (Kristensen et al. 2018) is reluctant in predicting that various forms of shared mobility can replace individual mobility on a large scale. New business models may change this, but definite predictions are impossible to make.

4.3.20 Parking space

If shared mobility becomes common, or if automated vehicles are operated more of the time and parked less of the time, the need for parking space may be reduced.

4.3.21 Modal split of travel

One prediction (Bösch et al. 2018) is that a fully automated transport system will make walking, cycling and public transport less competitive. If individual car ownership remains widespread, this is a reasonable prediction, because a fully automated car will have all the flexibility of a current car, plus the additional advantage that you do not have to drive it. Yet, in a fully automated transport system there are large potential gains to be made by making travel less individualised than it is now. The efficiency of the transport system can be greatly improved by using vehicles more intensely, but this presupposes a larger degree of shared mobility than found today. Some forms of shared mobility resemble public transport and may make current forms of public transport less competitive.

4.3.22 Optimisation of route choice

Information systems monitoring the movement of all vehicles are likely to be part of a fully automated transport system. In closed transport systems (air travel, trains), such monitoring has been possible for a long time. A rail traffic management centre knows the exact location of all trains. Similar knowledge with respect to motor vehicles will enable an optimisation of route choice, although information about the destination of each vehicle may be needed to avoid directing vehicles to large detours.

The third and final category of impacts to be described is the wider impacts.

4.3.23 Propulsion energy

Three main sources of propulsion energy are currently used by motor vehicles: (1) Fossil fuel, (2) Battery supplied electricity, (3) Fuel cells driven by hydrogen. Electric vehicles are gaining ground, and it may be easier to convert to a fully automated vehicle than a fossil fuelled vehicle.

4.3.24 Energy efficiency

The energy efficiency of transport has been improving for a long time and improvement is likely to continue. Yet, there are many sources of uncertainty regarding the impacts of connected and automated transport on energy consumption and efficiency. One important source of uncertainty is whether connected and automated vehicles will continue to have combustion engines or be electric. Electric cars are growing in volume, but are still confined to passenger cars and small vans.

4.3.25 Vehicle emissions

Vehicle emissions, per kilometre driven, have long been declining. This is likely to continue, but a fossil fuelled engine will never become totally clean. It will always have some emissions. Future changes depend to a large extent on whether electric vehicles will replace current vehicles. Emissions from driving will then be minimised, but the production of electricity could still be associated with emissions. It is probably safe to predict that a connected and automated transport system will be associated with lower emissions per kilometre of travel than the current transport system. Quantifying the change is difficult.

4.3.26 Air pollution

Changes in air pollution will be the result of changes in vehicle emissions, see section 4.3.25 above. It is likely that air pollution will be reduced, but it will not be entirely eliminated. Even if an electric vehicle has no emissions, the contact between tires and the road surface will generate microparticles that represent a health hazard.

4.3.27 Noise pollution

Electric vehicles produce less engine noise than combustion engine vehicles. It is not clear how, if at all, CATS will influence traffic noise. It could reduce it, if traffic in general flows more smoothly, with less braking and acceleration, if platoons reduce noise generated by air turbulence, and if vehicles are electric.

4.3.28 Public health

Net impacts of CATS on public health depend on several partial impacts. Less pollution will be beneficial for public health. But if CATS leads to less walking and cycling, that may be bad for public health. Almost nothing is known about how CATS will influence walking or cycling. Some studies speculate that there may be less walking or cycling, but the basis for believing so is not entirely clear. Cycling in cities could, however, become less attractive if there is less congestion and rides in automated vehicles can be hailed on very short notice and with great flexibility regarding origins and destinations for trips.

4.3.29 Road safety

Safety denotes the expected number of accidents or injured road users, preferably specified according to injury severity. In studies of the potential safety impacts of CATS, surrogate measures of safety have been widely applied. This is unavoidable, as simulating accidents remains impossible. One has to rely on the assumption that surrogate measures are a valid indicator of safety.

4.3.30 Trust in technology

CATS must be trusted by users to be used. Trust can be measured by means of surveys, or, once automated vehicles become widely available, the willingness to use them. Threats to trust include unreliability of the technology, cyber attacks and fear of threats to privacy.

4.3.31 Employment

Employment in several sectors can be influenced by the introduction of CATS. The most obvious is that drivers will no longer be needed if all vehicles are fully automated. A decline in accidents may reduce employment in insurance companies and car repair shops. There may be less need for traffic police. However, there is nothing new in the fact that technological changes lead to changes in the labour market. Some occupations may disappear entirely, and new ones will be created. In 1930, there were still many blacksmiths serving horses used in agriculture, but there were no computer experts. Today, there are no blacksmiths, but lots of computer experts.

4.3.32 Land use

Changes in land use occur over the long term. However, one change that may occur in parallel to the introduction of CATS is changes in the need for parking space. City parking may be converted to other uses. Lower generalised costs of travel may also encourage urban sprawl.

4.3.33 Commuting distances

Since automated transport is expected to reduce the generalised costs of travel, one potential impact is longer commuting distances. This is typically a long-term effect, but estimates of the long-term elasticity of trip distance with respect to the generalised costs of travel can be found in the literature. These elasticities have, however, been estimated for a non-automated transport system, and it is not clear if they can be applied to a partly or fully automated transport system.

4.3.34 Geographic accessibility

Meyer et al. (2018) show that full implementation of automated driving can change the accessibility of locations, mostly by making them more accessible (i.e. possible to reach in a shorter time). To assess changes in accessibility, a transport model is needed. The model can then be run with current travel times and with new travel times applying to a fully automated transport system. Comparing the results will show changes in travel time to and from specific locations, thus indicating changes in accessibility.

4.3.35 Inequality in transport

Inequality in transport denotes differences between social groups with respect to access to and consumption of transport. Differences in income is an important source of inequality. If automated vehicles are more expensive than conventional vehicles, their introduction may reinforce inequality in transport.

4.3.36 Public finances

Public finances can be influenced in many ways by CATS. As noted above, there will be changes in employment. If the need for parking space is reduced, income from parking fees may be reduced. These impacts are difficult to predict. Moreover, they can be avoided by policy interventions to create new sources of public revenue to replace those that are lost.

4.4 Quantifying impacts – an example

In order to predict the impacts of CATS, it is necessary to establish a quantitative relationship between one or more variables producing the impacts and the size and direction of impacts. It is possible to do so for some potential impacts of CATS. In this section, an example of how road safety effects can be modelled is given.

The example is based on three studies (Kockelman et al. 2016, Li et al. 2017, Papadoulis et al. 2019) that have used traffic simulation to estimate the effects of CATS-technology on traffic conflicts involving potential rearend and lane change collisions on motorways. Based on these studies, the estimates of effect shown in Figure 7 have been extracted.

One estimate for each of the market penetration rates of 0, 25, 50, 75 and 100 % was extracted from Kockelman et al. (2016) by summing the estimates for low, middle and high volume. Two estimates, applying to market penetration rates from 0, 10, 20, ..., 80, 90, 100 % were extracted from Li et al. (2017). Finally, five estimates for each of the market penetration levels of 0, 25, 50, 75 and 100 % were extracted from Papadoulis et al. (2019).

The predicted number of traffic conflicts at 0 % market penetration was set to 100 for each study; the estimated number of conflicts at higher market penetration levels show percentage changes compared to 0 % market penetration. It is seen that all studies predict a reduction of the number of traffic conflicts. The estimates nevertheless vary considerably. At 100 % market penetration, reductions are between 66.7 % and 99.3 %.

It is not possible to assign statistical weights, as normally defined in meta-analysis, to the estimates. Two studies state the estimated number of traffic conflicts, the third (Li et al. 2017) does not. One may nevertheless get an impression of the consistency and distribution of the estimates by using, for example, stem-and-leaf plots. Two such plots were made. One applies to estimates for a market penetration rate of less than 50 %. There were 14 estimates of effect in total. 2 indicated an increase in conflict, 4 a reduction between 0 and 10 percent, 4 a reduction between 10 and 20 percent, 1 a reduction between 20 and 30 percent, 0 a reduction between between 30 and 40 percent and 3 a reduction between 40 and 50 percent. There were 30 estimates of effect for market penetrations of 50 % or more. These estimates had a skew distribution with 9 indicating an conflict reduction of more than 90 percent and 8 indicating a conflict reduction between 80 and 90 percent. There was a tail of estimates indicating smaller reduction, up to the interval 20 to 30 percent reduction. Thus the stem-and-leaf plots do not indicate a symmetric distribution of estimates of effect, as one would ideally want.

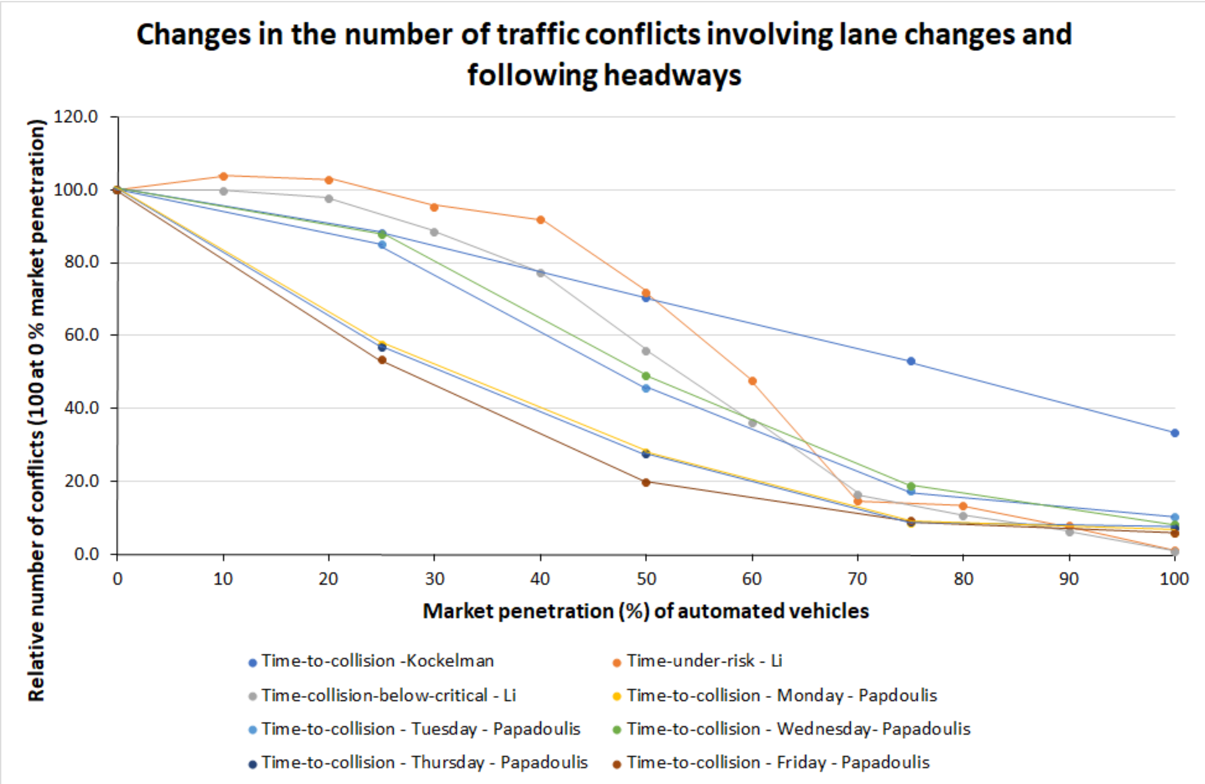


Figure 7: Estimated effects on rearend and lane change conflicts on motorways in three traffic simulation studies

Despite the less than ideal distribution of estimates, a function has been fitted to them in order to indicate the typical shape a function describing the expected changes in the number of accidents as the market penetration of high level automated vehicles increases. Figure 8 shows this function.

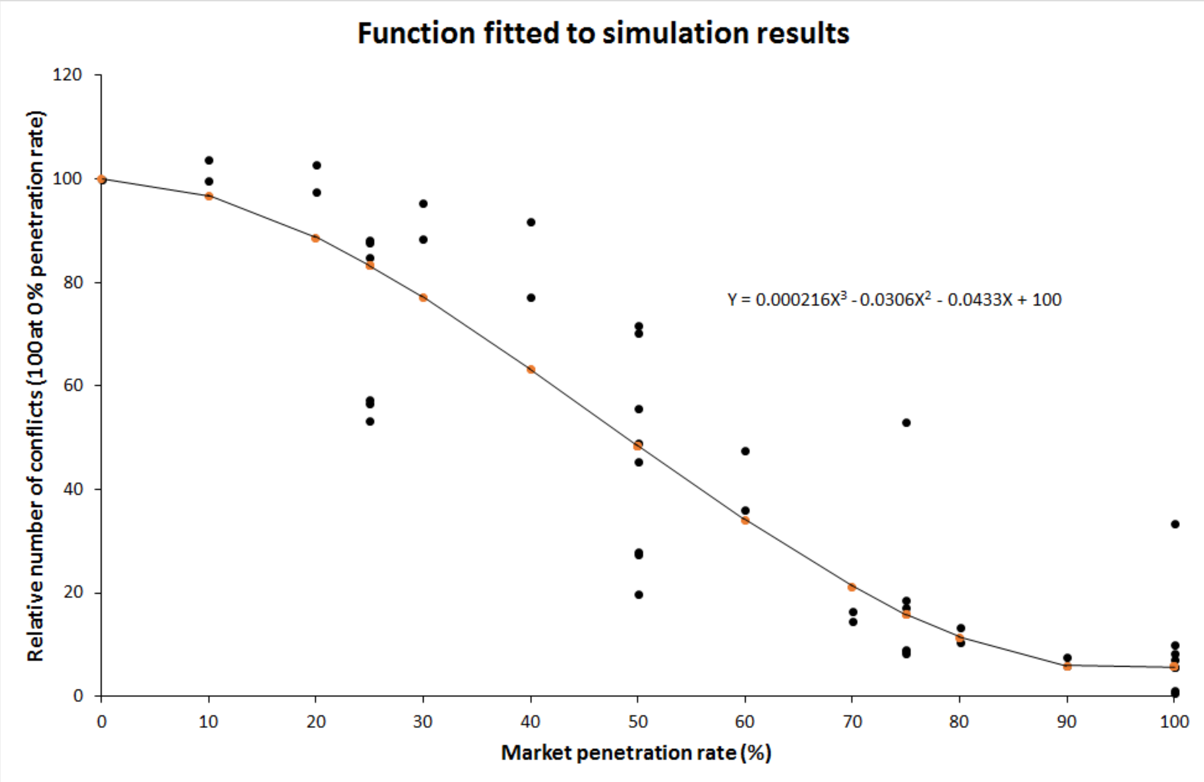


Figure 8: Function describing change in the number of accidents as market penetration of high level automated vehicles increases

The function is a third degree polynomial. This was the easiest function to fit to the data points. In principle, other functional forms may fit equally well or almost equally well, such as various versions of survival functions (used in medicine to describe, for example, survival time following a certain diagnosis or treatment) or a logistic function.

The function has an S-shape. It declines slowly at first, then faster and then the decline slows down again when it gets close to 100 % market penetration. This shape is not unreasonable for a technology that spreads slowly at first, then faster and finally slower again before reaching full implementation. Diffusion curves for new technology often have an S-shape. As can be seen from Figure 8, the data points are widely dispersed around the function. Predictions based on the function will therefore not necessarily be correct in a specific case. Except at 25 % and 50 % market penetration, the positive residual are larger than the negative residuals, i.e. data points predicting smaller effects of CATS than the curve are located farther from the curve than data points predicting larger effects than the curve. However, in estimates of the effect of road safety measures, asymmetric confidence intervals are not uncommon.

Deliverable 3.2 will develop a set of curves intended to support predictions of as many impacts of CATS as possible. It is the availability of studies supporting the development of curves that will determine how many impacts the prediction curves will be able to include.

5 Discussion and conclusions

This chapter discusses the results of the review of potential impacts of connected and automated transport systems and summarises the main conclusions of the review. A preview of analyses to be made at subsequent stages is given.

The actual impacts of connected and automated transport systems (CATS) are unknown and will remain so for a long time. This does not mean that it is impossible to discuss potential impacts of CATS. Based on the capabilities of the technology at various levels of development, a number of likely impacts can be identified and preliminary estimates of their direction and magnitude can be developed.

Thus, most analysts believe that a wide implementation of CATS will improve road safety and the efficiency of traffic operations. Belief in the safety benefits of CATS is based on the fact that automation technology will not make the mistakes, or deliberately run the risks, human drivers do – mistakes and choices that contribute importantly to accidents. It is true that an automated vehicle will not drink and drive, not drive when sleepy, not exceed speed limits, not engage in dangerous overtaking or tailgating, and possibly not start moving until all on board have their seat belts on. Yet, it is easy to forget that the reliability of human operators in terms of avoiding accidents is extremely high. An estimate of risk based on the SHRP-2 naturalistic driving study, 26.8 accidents per million kilometres driven, translates into a per kilometre probability of not having an accident of 0.9999732. This is the benchmark for the reliability automation technology must reach to perform better than a human driver. The reliability of automation technology is currently unknown. While the use of machine learning can make it very highly reliable with respect to regularly occurring events and situations, there will always be unforeseen and very rare events that not even extensive machine learning will have experienced and prepared the system for handling. Even a driver with 40 years of experience may run into an event he or she has never before been involved in.

For this and other reasons, one should not expect CATS to eliminate accidents. It is likely that the technology will improve road safety substantially, but exactly how large the accident reduction will be cannot be estimated precisely. Estimates for motorways reviewed in this report indicate potential accident reductions from 66.7 % to 99.3 %. In the former case, a sizable proportion of accidents are still not prevented; in the latter case, accidents are virtually eliminated. In more complex traffic environments, characterised by informal rules of interaction between road users, the safety potential of CATS is likely to be smaller than on motorways.

Similar points of view apply to potential effects on mobility and efficiency. Sure, vehicles can be connected in platoons that increase the effective capacity of a road. But platoons are probably not feasible everywhere. Urban streets have frequent junctions where road users need a gap in traffic, or need traffic to be stopped, in order to cross the road. Any platoon on such streets must be very short and will experience frequent stops. A major uncertainty is whether individual vehicle ownership continues at or near current levels, in which case congestion may not necessarily be reduced, or is replaced by an increase in shared mobility, in particular ride sharing. The impacts of ride sharing on the number of vehicles in use depend on whether it replaces cars that are currently used as individual means of transport or public transport. Vehicles used for ride sharing are likely to be smaller than buses or other public transport vehicles currently used. A wide use of shared mobility may reduce the number of cars needed to serve a given number of trips. On the other hand, to get the full advantage of the cars, they are likely to be operated more intensely than current privately-owned cars. Some estimates suggest that current travel needs can be served by one tenth of the current number of cars. But if each car travels ten times the current mean distance travelled by a car, overall traffic volume will remain the same and there will not nessarily be any great reduction of congestion.

Environmental impacts of transport are also widely believed to benefit from automation. However, the biggest uncertainty is whether cars will continue to run on fossil fuels or whether automation will go hand-in-hand with switching to electric cars. In the latter case, it is clear that some emissions from cars will be reduced. However, particles from tires will continue to be produced, and in a life-cycle perspective it is relevant to include emissions from the production of the vehicles.

Even the course the process of automation will take is uncertain. It is, for example, not entirely clear whether cars at the intermediate stage of SAE level 3 automation will be developed or whether an attempt will be made to skip this stage and move directly to level 4 or the highest level of automation, SAE level 5.

Given the analytic intractability created by these uncertainties, a decision has been made to model the impacts of CATS as a function of the market penetration of automated vehicles. Within this analytic framework, the impacts estimated will remain relevant for policy makers, as they will span the range from 0 % market penetration of automated vehicles (the current situation, except for trials with small automated buses in many cities) to 100 % market penetration. Thus, the full range of impacts that can be estimated on the basis of current knowledge will be included for as many types of impacts as possible. The only limit on what can be included is lack of knowledge. The relevance for policy making is maintained in that: (1) Highly uncertain or contradictory estimates of impacts may serve as the basis for identifying policy interventions to increase the likelihood that impacts will be in the desired direction (e.g. less urban sprawl rather than more). Uncertainty or contradictory results imply that research has not produced a consensus, which in turn signals to policy makers that there is an opportunity for influencing the direction and magnitude of impacts. (2) Impacts that can be quantified as functions are normally subject to a ceterius paribus condition, i.e. they are valid if all else remains equal. Thus, if traffic volume is widely predicted to increase, knowledge of this has immediate relevance for policy, by informing policy makers about the size of an increase, which in turn indicates the severity of measures that must be taken to counteract the increase (if it is unwanted).

The first step in predicting potential impacts of CATS at the level assumed in this report is to identify potential impacts and indicators that can be used to measure these impacts. To this end, a systematic review of studies identifying potential impacts of CATS has been made. In total, 33 potential impacts have been identified. A distinction has been made between direct impacts (for each road user of each trip), systemic impacts (system-wide impact in the transport system), and wider impacts (wider societal impacts that may originate in the transport system, but also affects society outside the transport system). Furthermore, a distinction is made between primary impacts and secondary, rebound impacts. Primary impacts originate in the automation technology and its functionality and follow a unidirectional causal pathway to the final outcome; rebound impacts originate in one or more intermediate variables in the causal pathway from the technology to the final outcome and may influence the final outcome.

Final impacts will be predicted by means of dose-response curves relating the market penetration rate of automation technology to final outcomes. An example of such a dose-response curve is given in this report. Several such curves will be developed to include as many impacts of CATS as current knowledge allows for.

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