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Towards a method for getting a grip on societal impacts of automated driving

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Abstract

Impact assessment of automated driving is challenging due to uncertainties in how automated driving will develop as well as a lack of evidence of the system level impacts based on real conditions in the real world. Especially, there is a lack of realistic on-road field operational tests of long-term impacts on how automation will affect our lives. Therefore, other approaches need to be used in order to assess potential impacts on the society and quality of life. This paper proposes a systematic methodology gathering and combining data from different sources: limited pilot tests, online surveys, expert and stakeholder interviews, focus groups, literature and modelling. The impact path framework developed by experts from the EU, US and Japan was used as a basis. Future studies can use the methodology to help determine the sizes and directions of impacts.

Keywords: impact assessment; automated driving; quality of life; methodology

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1. Introduction

Automated driving (AD) is being commended as a promising solution to the major problems of today's transport system: congestion, accidents and air pollution. Indeed the potential impacts of automated driving on the transport system and society as a whole can be wide-ranging. However, assessing the potential impacts of automated driving in a realistic way is a very difficult undertaking for several reasons:

A. There is a lack of clear understanding how automated driving will develop in the near future both from technical and user viewpoints, relating to technical performance, operational design domain (ODD), human-machine-interaction (HMI), time scale to the introduction, etc.
B. There is a lack of realistic scenarios for a transport system in which automated driving is the norm, due to point A above as well as parallel trends affecting the transport system.
C. There is a lack of evidence how automation will affect our behaviour coming from real-world data based simulations, user tests with ordinary drivers or even expert judgments of the direction or magnitude of the expected impacts.

And above all, there is a lack of realistic on-road field operational tests of the long-term impacts of automated driving in daily use. As automated driving has the potential to change the transport system, our daily mobility, cities and society as a whole, the potential implications are far-reaching. Therefore, it is important to be aware of these implications to ensure that implementation of automated driving concepts, and services that base on it, can be done in a way to reach the most benefit for society as a whole.

The FESTA methodology (FESTA 2018) provides comprehensive guidance for impact assessment for field operational tests (FOTs). It states that data should be gathered from vehicles that are driven in a more or less naturalistic way (i.e. in everyday life by ordinary drivers) for longer periods on real roads and in real traffic. From these data, effects are estimated for driver and travel behaviour, and then the implications that these effects have on other areas such as traffic safety and efficiency are assessed. Impact assessment is carried out by extrapolating the impacts to the wider transport system, scaling up the effects to a national or even European level. This has been done in large European projects in the past, e.g. on the potential impacts of large-scale deployment of ADAS systems, such as Adaptive (2017), or cooperative systems, such as DRIVE C2X (Schulze et al. 2014).

As this kind of FOT data is not (yet) available for automated driving, and the first large scale pilots are only now on-going in Europe, e.g. L3Pilot (2019), other ways have to be found to address the impact question. To complicate things even further, impacts of automated driving will not be restricted to the transport system but will be broader, such as in long-term on land use (e.g. if there are less cars that need parking space due to more care sharing), public health e.g. (if people use a shared automated vehicle instead of cycling), and equity (e.g. if people who cannot drive due to disabilities start to use automated vehicles). In addition, the impacts of non-users e.g. via behavioural adaptation and changes in the interaction between them and the automated vehicles (AVs) are still unknown.

There are few studies to date that have systematically mapped potential impact mechanisms of AD on the transport system. Most are based on literature reviews together with expert assessment and/or simulations. Milakis et al. (2015, 2017) in their "ripple effect" framework describe different levels (or ripples) of impacts. Taiebat et al. (2018) study interactions and mechanisms between system levels (Vehicle, Transportation System, Urban System, Society) forming impacts on energy and the environment. To the knowledge of the authors, the most comprehensive picture to date of potential impacts of automated driving on the transport system and society, showing also the potential impact mechanisms and pathways leading to the different impacts, was developed by the Trilateral Working Group (between the EU, US and Japan) on Automation in Road Transportation (ART WG). The framework describes impact mechanisms through which automated driving in general is expected to affect our lives, covering both direct and indirect impacts (Innamaa et al. 2018).

In the AUTOPILOT project (AUTOPILOT 2019), automated driving was investigated with a specific focus, namely the role of Internet of Things (IoT) in enabling, enhancing and accelerating the deployment of automated driving. In this study, IoT is considered as an enabler of connected automated driving (CAD), where automated vehicles can communicate with other vehicles and/or infrastructure and other elements in order to exchange information e.g. on the current traffic conditions. As part of the evaluation, the potential effects of connected automated driving on the “quality of life” or in other words, on the societal impacts such as personal mobility, traffic safety and efficiency, the environment and well-being, were assessed. However, the same handicaps as described above for studies on automated vehicles in general were encountered. There are uncertainties around the impacts of automated driving alone, so determining the added value of IoT posed challenges.

Five AD modes were piloted at five European pilot sites under the AUTOPILOT project: Automated valet parking (AVP), Urban driving – Signalised intersection, Urban driving – VRU (vulnerable road user) mobile device detection, Highway Pilot – Hazard detection and Platooning. Most of these AD modes have a specific, limited focus area addressing specific user groups and/or problems, such as the parking process or driving in signalised intersections.

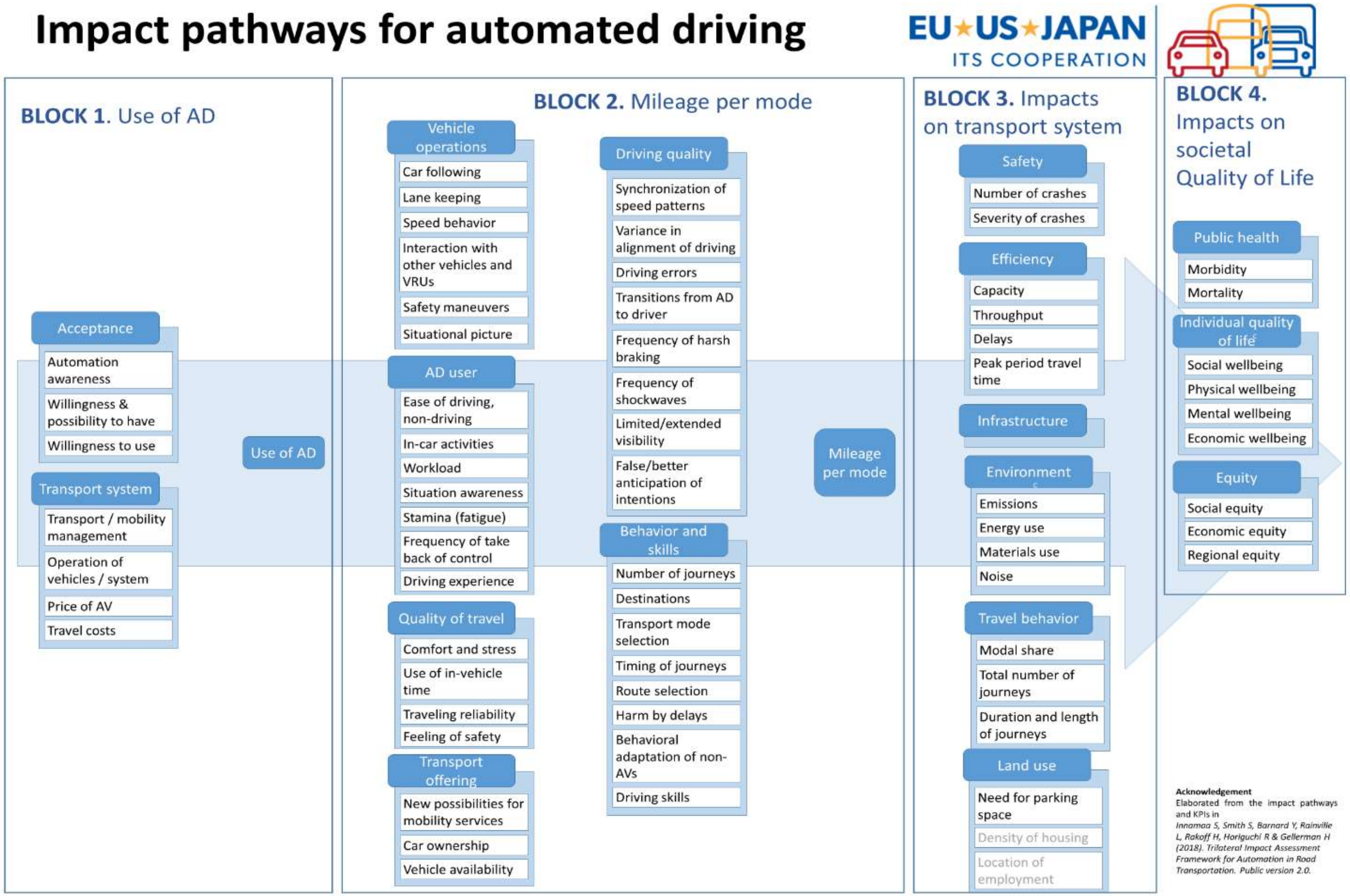
Although several use cases of IoT and automated driving were tested in the project, also with users, these tests usually had more the character of demonstrations. They took place in dedicated areas, with low speed, and using safety drivers who are still necessary behind the steering wheel, so that users could only get a glimpse of what the automated functions would be capable of. This means that there is a lack of a large meaningful body of data from these tests. However, there is more knowledge available beyond the test data. Therefore, the work took another approach, trying to combine everything that is known, in order to move forward, even if a full-blown impact assessment was not possible.

The objective of this paper is to describe the methodology that was developed for assessing the potential impacts of the AD modes on societal quality of life, given the limitations and uncertainties described. The results of the assessment itself are described in Aittoniemi et al. (2020, forthcoming).

2. Methodological framework

The impact assessment framework by the Trilateral Working Group was used as a basis for the work described in this paper. This framework was chosen because it provides to the knowledge of the authors the most comprehensive picture of potential impacts of automated driving on the transport system and society, showing also the potential impact mechanisms and pathways leading to these impacts. Innamaa (2019) elaborated the pathways further from the ones in the original framework, as seen in Fig. 1.

The framework was applied to the five AD modes tested in the AUTOPILOT project. This approach, using the assessment framework as a basis, ensured that the potential impacts were considered systematically, including different potential impact mechanisms and both direct and indirect impacts.



Acknowledgement
Elaborated from the impact pathways and KPIs in
Innamaa S, Smith S, Barnard Y, Rainville L, Rakoff H, Horiguchi R & Gellerman H (2018). Trilateral Impact Assessment Framework for Automation in Road Transportation. Public version 2.0.

Fig. 1 Impact pathways for automated driving (after Innamaa 2019, Innamaa et al. 2018.)

The impact assessment framework shown in Fig. 1 consists of four main blocks:

Block 1: Forming the *Use of AD*: *Acceptance* and *Transport system*
Block 2: Forming *Mileage per mode*: *Vehicle operations, AD user, Quality of travel, Transport offering, Driving quality*, and *Behaviour and skills*
Block 3: Forming the impacts on the transport system level: *Safety, Efficiency, Infrastructure, Environment, Travel behaviour* and *Land use*
Block 4: Based on all previous areas, forming the impacts on societal Quality of Life: *Public health, (Individual) quality of life*, and *Equity*

The *Block 2* ***Mileage per mode*** is in the main focus of this study, as it determines the scope and size of impacts on personal mobility, traffic safety and efficiency and the environment, and therefore the implications of AD and IoT on societal quality of life. This *Mileage per mode* block consists of the following areas.

Vehicle (control) operations include the driving behaviour of the AV itself, consisting of its acceleration, deceleration, lane keeping, car following, lane changing and gap acceptance. *Car following* describes the longitudinal driving behaviour of the AV when following another vehicle, e.g. the time headway to the vehicle in front. *Lane keeping* encompasses the lateral behaviour of the AV, meaning how well it stays inside a lane and whether there are oscillations in lateral movement. In presence of other vehicles in the adjacent lane, the *gap acceptance* of the AV defines the time gaps needed on the adjacent lane for the AV to change lanes. *Speed behaviour* describes the speed choice of the AV (target speed) and its potential changes in different situations (like speed variation). *Interaction with other vehicles and VRUs* refers to all kinds of interactions between the AV and other road users, such as overtakings, cut-ins, stopping behaviour at intersections, gap forming at ramps, etc. The category *safety manoeuvres* includes behaviour programmed into AVs for situations where the driver does not take back control when requested (minimum risk manoeuvres), as well as manoeuvres carried out by the driver, e.g. manual braking or steering if the AV does not seem to handle some situation. The term *situational picture* refers to the interpretation of the situation around the vehicle (the current traffic situation, the road and the environmental conditions) formed based on information available to the vehicle (or driver) from its sensors and via IoT.

The items under ***AD user*** address the perspective and experience of the user and the change from being a driver (in manual driving) with increasing automation to being a user (in full automation). *'Ease of driving, non-driving'* indicates driver's experiences on how easy it is to take care of all the dynamic and other tasks of driving but also the possibilities for doing other things than driving during the trip. *Non-driving* refers to these periods of time which the AV enables by taking control of the driving task. The length and frequency of non-driving periods are critical for ease of driving. AV may change the nature and extent of *in-car activities* carried out by the user while riding/driving. The term *workload* refers to the interaction between the task demands and capabilities of the driver in a certain driving situation.

Situation awareness incorporates the driver's perception and understanding of the driving situation as a whole, including e.g. the traffic and weather conditions, and of AV behaviour at any given time of the trip. The focus (relevance) of situation awareness depends on the level of automation: With full automation, it is not necessary for the user to be aware of the driving situation (but s/he may still like to have the information), whereas in partial automation it is very important. Situation awareness is closely related to the HMI through which the AV and its user communicate. *Stamina (fatigue)* describes the energy level or vitality of the driver/user. In long monotonous driving situations, e.g. on a motorway with little traffic, drivers may become tired, which has implications on their driving capabilities.

The term '*Frequency of take back of control'* relates to situations in conditional automation where drivers are requested to take back control in the end of ODD (system initiated), or they can themselves request to take back full control of the driving task when preferring to drive by him/herself (driver initiated). From the user perspective, this term relates to how often and in which situations the driver needs to take over control. As this take over control situation is potentially risky, its frequency is of interest. The frequency also affects the possibilities for secondary activities during the drive.

Driving experience concerns the experience (mileage) of the user of the AV that s/he drives manually in different conditions and road types. If the AV drives automatically e.g. always when on motorways, the human driver does not get experience of driving on motorway, etc. In the long run, the lack of driving experience affects the driving skills and capabilities.

Quality of travel concerns the characteristics of AV use from the users' point of view. *Comfort* describes whether the ride feels comfortable or uncomfortable (e.g. due to harsh braking or fast longitudinal or lateral acceleration). *Stress* refers to the user's emotional stress (uncertainty, fatigue, distress, worry) related to the trip with an AV (e.g. stress due to uncertainty of AV behaviour or take-back-control situations). *Use of in-vehicle time* refers to possible non-driving related secondary tasks in the vehicle, which can be allowed if the driver is not constantly in charge of monitoring the environment. The actual in-vehicle activities depend also on the user choices and preferences, e.g. their proneness to motion sickness. The use of in-vehicle time is related to the value of time when traveling. *Traveling reliability* in this context means primary how well the trip duration can be predicted, travel time reliability but it may also concern other aspects of the trip such as costs of the journey, reliability of automated services and accessibility. *Feeling of safety* refers to subjective safety when traveling, i.e. whether the driver feels or experiences that the automated vehicle is driving safely, and also ensures the safety of other road users.

Transport offering refers to the potential changes in mobility options available to users. Completely new mobility services can develop due to the introduction of AVs (*New possibilities for mobility services).* If useful new services arise to meet people's mobility needs (such as car sharing service, robotaxis, automated shuttles), this may lead to changes in car ownership. *Vehicle availability* means certainty that there is a vehicle available for a user when (s)he needs it. This is linked to the mode choice and traveling reliability.

Driving quality relates largely to the changes in driving behaviour on a vehicle level (*Vehicle operations).* It concerns the translation of impacts of single vehicle operations to the road network in a wider scope. Changes in individual behaviour of vehicles, such as choice of headway and speed, have consequences on the speed patterns of a group of vehicles traveling in the same direction, reflected e.g. as shock waves within the traffic flow. These behaviour changes depend on the capabilities of the AV, and the extent of impacts in specific situations depends, among others, on the penetration rate of AVs as well as the traffic volume on the road.

Synchronisation of speed patterns may occur with higher penetration rates of AV, or in situations where overtaking is not possible and a platoon/group of vehicles drives with close to equal speed. With manually driven vehicles, keeping a constant speed is not easy, and the speed of individual vehicles typically oscillates around a certain speed (depending on e.g. the state of the driver, possible distracting factors and the surrounding traffic situation). AVs are better capable of keeping a certain set speed. This is especially true for connected vehicles, which can better anticipate upcoming traffic situations. Synchronised speed patterns lead to a smoother traffic flow with less disturbance, especially relevant for situations with high traffic volume and/or bottlenecks (e.g. accidents, lane closures).

Variance in alignment of driving refers to the lateral alignment of a group of vehicles traveling in the same direction. Lateral position in the lane can affect the abrasion of the pavement and e.g. rut formation, if a platoon of vehicles drives exactly on the same track in a lane. *Driving errors* refer to mistakes in driving behaviour by individual vehicles/drivers. On the one hand, automation can reduce driving errors (e.g. by preventing unintended lane departures or by obeying the speed limits), but on the other hand new driving errors can occur. For example, an early stage AV may not park exactly between the markings of a parking place or an AV may misinterpret the road markings.

Transitions from AD to driver refers to the situations when the driver is required to take back control of the driving task. This may have implications for the traffic flow, e.g. the vehicle may lower its speed temporarily until the driver is in the loop. *Frequency of harsh braking* can increase or decrease with AV compared to manual driving, largely depending on AV capabilities to perceive certain events such as stopped vehicles downstream. This is closely related to *Frequency of shockwaves*, which may change depending on AV capabilities and the current traffic situation. *Limited/extended visibility* of AVs compared to manual vehicles refers to the sensor systems implemented in the vehicles and visibility they provide to the driver or vehicle. How well the vicinity of the car is perceived, at which distances and in which angles the sensors work, and how reliable they provide information in different conditions (weather conditions, in case of an obstacle etc.). *False/better anticipation of intentions* is related to interpretation of information received by any sensors. The machines (AVs) may not be equally good as a human actor (the driver) in perceiving and interpreting all weak signals, or at the least AVs may not be capable to cover the huge variety of situations in road traffic. Specifically, this can be seen in anticipating intentions of other road users, pedestrians and cyclists in particular.

The topic ***Behaviour and skills*** is largely related to the personal mobility behaviour of individual users (and non-users) and the skills required for that. With the introduction of AVs, the daily mobility choices of the AV users may change in terms of *Number of journeys* made, choice of *Destinations*, *Transport mode selection*, *Timing of journeys* and *Route selection*. For example, automated valet parking may lead to driving more by car into the city centre instead of using public transport, as finding a parking space is often difficult in city centres (and some people do not like to park in narrow parking garages etc.), highlighted in busy hours. If car travel is more convenient, more people may choose to use a car instead of public transport or active modes. In partial automation, route choices may change e.g. to favour longer routes to travel on motorways and take use of a motorway pilot function. *Harm by delays* describes the perceived harm by travellers resulting from delays in traffic, addressing both emotional and practical aspects. This may change with AD, for example some delays may not be considered as harmful if the time spent in the car can be used in productive ways. *Behavioural adaptation of non-AVs* may occur if manually driven vehicles start to imitate driving behaviour of AVs, for example by using smaller or larger headways or by strictly obeying the speed limits. Behavioural adaptation may also happen to VRUs who start trusting that all vehicles will stop for them if AVs are likely to do so and may change their behaviour e.g. when crossing roads.

Driving skills may be affected when ADF are mature enough to take over a large part of the driving. Driving skills refer not only to manoeuvring the vehicle at the operational level but also to higher level skills such as focusing attention to the relevant, anticipating driving situations, interacting efficiently and safely with the other road users etc. It is expected that ADFs will at least in the short-term work only in good conditions. Therefore, drivers need to drive themselves in bad conditions, which have a higher accident risk, especially when accompanied with less driving experience overall. (This may lead also to personal mobility impacts, e.g. less travel or less car travel during adverse conditions.)

The impacts of CAD on the Infrastructure and Land use (except *Need for parking space*) are not included in the scope of this study. We assume that the AD functions are already in place and therefore the two boxes on the left (*Acceptance* and *Transport system*), which deal with the prerequisites for AV use, are not explicitly considered. The boxes in the framework and the mechanisms within them are not independent, and the purpose of the framework is not to find all possible causal relationships, but to determine the most relevant impact mechanisms for each impact area. Therefore, when determining impacts of the boxes in *Block 2* on the impact areas (personal mobility, safety, efficiency and environment), those boxes were considered pairwise, neglecting possible overlaps or interactions with other boxes of *Block 2* as well as other impact areas.

3. Evaluation method

3.1. Application of the framework

The methodology for systematic assessment of potential impacts of CAD, based on the piloted AD modes in AUTOPILOT, included the following steps:

Step 1: Mapping of mechanisms for the impact areas personal mobility, traffic safety and efficiency & environment to the impact pathways figure. The mapping was done based on previous work, where available:

- Personal mobility: TeleFOT mobility model (Innamaa et al. 2013), expert workshop
- Traffic safety: Impact mechanisms (Kulmala 2010, Innamaa et al. 2018), expert workshop
- Efficiency & Environment: literature, expert workshop

Step 2: Mapping of mechanisms where IoT is expected to have an effect, per AD mode, when compared to the baseline, automated driving without connectivity (IoT).

Step 3: Merging of Step 1 and Step 2 results to find the relevant impact mechanisms of IoT for each AD mode and impact area

Step 4: Collecting evidence on the potential impacts of CAD on the considered impact areas through the available data sources, including pilot tests, other evaluation tasks of the project, stakeholders, experts and literature.

Step 5: Integration of the collected information from different available sources (step 4) with the results from step 3 to identify the most relevant impact mechanisms and potential impact directions.

Step 6: Defining general implications of CAD on societal quality of life based on the results per AD mode.

Most of the work in *Steps 1–6* was carried out in expert workshops. In *Step 4*, all available kinds of information from the pilot tests, stakeholder interviews as well as relevant literature was collected for each of the mechanisms described in *Block 2* of Fig. 1. The following information sources are distinguished:

- Results from the literature (utilising reviews such as Alonso Raposo et al. (2019), Rämä et al. (2018))
- Data from the AUTOPILOT online questionnaire about user acceptance in which 852 respondents from five countries were presented with three scenarios and asked about their potential interest and concerns
- Data from AUTOPILOT technical tests with Automated valet parking, Urban driving, Hazard detection and Platooning
- Data from AUTOPILOT user tests, mainly questionnaires filled in by some 150 participants involved in short rides in the automated vehicles in the AD mpdes described above, on experiences, expectations, concerns and future potential
- Reports from AUTOPILOT focus groups and individual interviews with:
    - Participants from the general public
    - Stakeholders from public authorities and industry, on quality of life and on business models
    - Experts on topics such as IoT, security and privacy, potential impacts and future developments
- System dynamic modelling of impact pathways

The system dynamic modelling allowed for causal loops to be modelled, extending the linear framework described above. System dynamic modelling was applied to gain more understanding of the formation of societal quality of life impacts, and explore sensitivities related to uptake of highly automated vehicles.

Several assumptions apply to the assessment. It was assumed that automated driving enhanced with IoT is in place and IoT based services are used in AVs, hence the elements in *Block 1* of Fig. 1 were not explicitly considered. The specific technologies used to implement AD and IoT were also out of scope – it was assumed that they work and provide the intended functionality. The baseline in the assessment, meaning the status quo that the changes induced by IoT were based on, is non-connected automated driving.

3.2. Illustrative example

The mechanisms affected by IoT (results of *Step 2* of the method) for the box *Behaviour and skills* (see Fig. 1) for all AD modes are shown in Fig. 2. For mechanisms coloured in orange, IoT is expected to have a direct impact when compared to the baseline, whereas for the mechanisms outlined in orange the impact is assumed to be more indirect.

For the example of Automated valet parking (AVP), when compared to the baseline (automated parking with user supervision, user needs to assign free parking space), IoT is expected to have direct impacts on *destinations* of journeys, *transport mode selection*, *timing of journeys* and *route selection*, and secondary or less direct impacts on the *number of journeys* and *driving skills*. These changes then have implications for the three impact areas (in *Step 3*): The first five impact all three areas (mobility, safety and efficiency and environment), while *Driving skills* is relevant only for traffic safety. On the other hand, the AD mode Highway Pilot – Hazard warning is expected to only have minor impacts to *Harm by delays* when compared to the baseline of non-connected automated driving, due to the limited scope of the function.

From the results of the data collection (done in *Step 4*), it was then concluded in *Step 5* that AVP may lead to a mode shift favouring the personal car and may increase the number of trips made by car. This is likely to have a negative impact on traffic safety. On the other hand, AVP decreases the amount of driving looking for a parking space, therefore decreasing exposure to traffic, which leads to a positive impact on traffic safety. These mechanisms work in opposite directions, and more information is needed on demand of AVP in order to determine, which impact will be larger.

For efficiency and environmental impacts of AVP, the results are similar. Traffic flow and emissions can be improved from removing the need to search for a parking space, but this impact can be offset by an increased number of vehicles driving into city centres due to the AVP service making it more convenient. Regarding personal mobility, increased accessibility in terms of reaching destinations is considered positive.

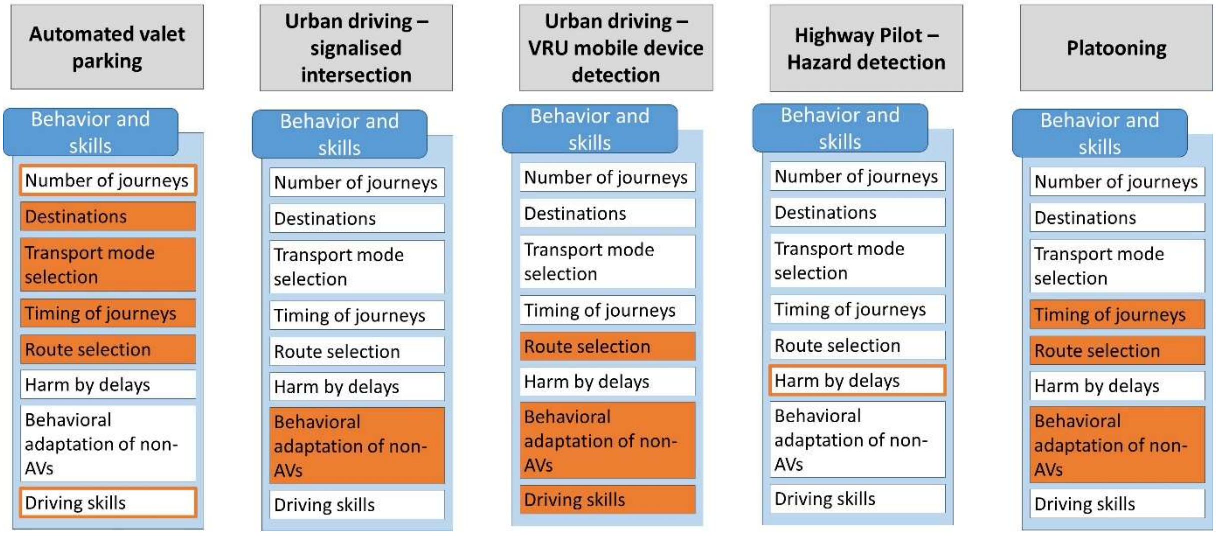


Fig. 2 Illustration of mechanisms directly (orange background) and indirectly (orange outline) impacted by IoT for each AD mode when compared to the baseline of non-connected automated driving

Results for the remaining five boxes in *Block 2* of Fig. 1 were defined in a similar way. In the last step (*Step 6*), overall potential impact mechanisms on the quality of life (health, well-being and equity) were then deduced. For example, AVP can lead to increase in social well-being due to increased accessibility of locations, but on the other hand lead to decrease in physical well-being if active travel modes such as walking and cycling are replaced by personal car use.

4. Discussion

This paper proposes a systematic method for studying the potential impacts of (connected) automated driving on societal quality of life, given the restricted information available from real world studies and the many uncertainties remaining around the development and deployment of automated driving on a large scale. Due to the complexity of the transport network and interdependencies between mechanisms and impact areas, the study takes into account impacts on different levels, e.g. short- and long-term impacts, local and regional levels, direct and indirect impacts. The work takes a flexible approach, combining all available information from different data sources. The impact path framework developed by experts from the EU, US and Japan was used as a basis of the work.

The proposed method allows for all the available, rather fragmentary, information on potential impacts of CAD, based on the piloted AD modes in AUTOPILOT, to be utilised without losing sight of the big picture, that is the complex system formed by the several interrelated impact mechanisms, where changes to one mechanism can have both negative and positive impacts on others. All available fragmentary information is brought together in a systematic way. This allows starting to form the bigger picture, learning more about the *Blocks 3* and *4* of Fig. 1, where the impacts on the transport system and quality of life are described. The method also allows for following the paths back, from impacts towards factors that play a role in positive or negative impacts.

In the study it was assumed that the AD modes considered are in use and work well. Therefore, the results can be said to apply to a best case scenario, disregarding potential challenges in uptake and deployment of the services. However, as the objective of the work was to identify the most relevant impact mechanisms, rather than try to produce numerical estimates, which would have to be uncertain, this does not pose a limitation to the study.

The methodology developed and presented in this paper can be applied to future automation pilots as well. It is indeed recommended that more real-world data be collected in future pilot tests and FOTs in order to gain more insight on the size and direction of potential impacts in the different impact areas identified, and complete gaps in the fragmented data.

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