First steps towards a holistic impact assessment methodology for connected and automated vehicles [version 2; peer review: 2 approved with reservations]

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Abstract

Connected and automated vehicles have become more common in recent years, increasing the need to assess their societal level impacts. In this paper a methodology is presented to explore and define these impacts as a starting point for quantitative impact assessment. The many interrelations between impacts increases the complexity of obtaining a complete overview. Therefore, a structured approach is used, which shows many similarities with the modelling of causal-loop-diagrams. Feedback loops between impacts are taken into account at an early stage and both literature review and expert interviews are used to produce a holistic overview of impacts. The methodology was developed and applied in the European H2020 project LEVITATE. The impact taxonomy and interrelations between impacts resulting from this project are presented and further steps needed to perform a quantitative evaluation of the impacts are discussed.

Keywords

impact assessment, automated vehicles, connected vehicles, behavioural adaptation, traffic system, societal impacts

This article is included in the Societal Challenges gateway.
Amendments from Version 1

Based on the reviewer comments adjustments have been made to the article. Detailed information on the exact changes can be found in the responses to the reviewers. In summary the main changes related to the following:

- Adjustments to the article title and abstract to better reflect the content of the article.
- Clarifications regarding the focus on the wide range of different impact areas.
- Clarifications regarding the use of different penetration rates of CAV within the LEVITATE project.
- Clarifications regarding terminology used in the article.
- Clarifications regarding the benefits of using the method presented in the article within the LEVITATE project.

Any further responses from the reviewers can be found at the end of the article.

Introduction

Vehicle automation and connectivity has become more and more common in recent years. Most vehicles on the roads today can take over part of the driving task, such as keeping a constant speed using cruise control or avoiding lane departures using a lane keeping system. Cars with SAE level 2 automation functions, where the driver is only required to monitor the automation, are already being sold and it is expected that conditional, high and full automation functions will become available in the (near) future. While such systems are generally expected to have the potential to increase safety and decrease congestion (Kockelman et al., 2016), the actual impacts of this technology on a societal level depend on many factors (Kockelman et al., 2016; Milakis et al., 2017; Sousa et al., 2018).

The European horizon 2020 project LEVITATE aims to offer policy makers insight into the wide range of impacts that vehicle automation can have on society. The policy support tool that will be developed during this project is intended to enable a wide range of policy makers to select policy interventions and assess the impacts of automated vehicles in the short, mid and long term future under different circumstances. To serve this purpose, the first step is to gain an overview of as many of the potential impacts of connected and automated vehicles (CAVs) as possible. A study was therefore made of previous attempts to identify and classify potential impacts of CAVs and the intricate web of interrelations between impacts (Elvik et al., 2019).

The time scale over which LEVITATE will assess the impacts implies that not only direct, short term, impacts should be considered, but indirect impacts and feedback loops that apply over longer periods should also be included. To obtain such a comprehensive overview of all impacts, a structured holistic approach is needed. E.g., structuring the impact assessment process with the goal of obtaining a holistic set of potential impacts. While many overviews of potential impacts of automated vehicles can be found in the literature (Chan, 2017; Fagnant & Kockelman, 2015; Hörl et al., 2016; Kockelman & Boyles, 2018), structured holistic approaches to impact assessment of automated vehicles are scarce.

This paper presents the approach taken in LEVITATE to explore and define impacts and their interrelations as a starting point for quantitative impact assessment. The modelling approach shows many similarities with the modelling of causal loop diagrams (Bala et al., 2017). In the following sections a brief, non-exhaustive list of existing literature on impact analysis of automated vehicles is discussed after which the approach developed within LEVITATE to explore the impacts is presented. The model developed is then presented, containing both direct and indirect impacts and their interrelations that can be easily adapted and extended for specific uses. Finally, the approach is evaluated for different uses and improvements are discussed.

Review of impact assessment models

Previous projects have proposed overviews of potential impacts of CAVs. Most of these overviews consist of written summaries of impacts discussed in the literature, sometimes enriched with discussions on possible interrelations between these impacts.

In (Fagnant & Kockelman, 2015) impacts are first discussed under four headings: safety, congestion and traffic operations, travel behaviour impacts and freight transport. Subsequently, they present estimates of societal and personal economic benefits based on literature findings of expected changes in vehicle miles travelled, vehicle ownership, technology cost, crash rates, congestion reduction and parking. In (Hörl et al., 2016) the impacts of vehicle automation are categorized as impacts on mobility, city planning, car industry, work organisation, user profiles, delivery of goods and price. Within each category many more specific impacts and some interrelations are mentioned.

In (Chan, 2017) benefits, i.e., positive impacts, of automated vehicles are categorized under vehicle user, transportation operation and society perspectives. Many more overviews can be found in the literature (Herrmann et al., 2018; Kockelman & Boyles, 2018; Polis, 2018) and are a useful starting point for impact assessment. These overviews, however, do not provide the structured holistic approach to exploring impacts needed to eventually perform a quantitative impact analysis as is the objective of the LEVITATE project.

A more structured approach was taken in (Milakis et al., 2017), where a comprehensive literature review is presented on the impacts of automated vehicles. They summarize the impacts in a clear and readable model, consisting of four concentric circles showing vehicle automation technology in the centre. The first order impacts of this vehicle technology on the transport system that are directly noticed by the road users are shown around this centre, followed by the second order impacts on, for example, infrastructure and land use in the third
Innamaa. The feedback relation is then the relation between reduced travel time due to the adoption of shorter time headways, thus including both feedforward and feedback causal relations.

A very structured approach is taken in (Innamaa et al., 2018a; Innamaa et al., 2018b). They define nine impact groups that are displayed on a graph of spatial resolution vs. time frame. The direct impacts, those that have a relatively clear cause-effect relationship with the primary activity or action, are those of small spatial resolution and short time frame. These impacts can usually be measured in a field test and are grouped under safety, vehicle operations, personal mobility and energy/emissions. Indirect impacts, on the other hand, are defined as resulting from these direct impacts and can often not be measured in a field test. They include impacts on network efficiency, travel behaviour, public health, infrastructure and land use and socio-economic impacts.

In a first step of their impact analysis approach they perform a classification of the system and the design domain. In this step they, for example, make clear which automated functions and services will be included in the impact analysis. For the impact evaluation they then propose charts indicating potential impact paths starting from direct impacts on vehicle operations, driver or traveller, quality of travel and transport system and leading to one of the previously mentioned impact areas, such as safety. In addition, they recommend not only investigating these one-way paths to the impact areas, but also the strong links between the impact areas. As a next step, they recommend elaborating further on the proposed impact paths for the system under evaluation by adding direction of change, similar to what is done in causal-loop-diagrams.

**Impact assessment method**

In the LEVITATE project a somewhat different approach has been taken. The focus is put on the system as a whole from the start, thus including both feedforward and feedback causal relations between different impact areas. Examples of such causal relations are shown in Figure 1. Here the feedforward, or direct, relation is the potential impact of CAV regarding the reduction travel time due to the adoption of shorter time headways. The feedback relation is then the relation between increased traffic flow due to this shorter travel time that in turn increases the travel time.

The impact assessment method can be divided into four steps

1. Definition of scope
2. Impact diagram set up
3. Impact diagram elaboration
4. Impact diagram validation

**Initial scoping**

The initial definition of scope defined use cases in terms of type of technology (automation, connectivity, mobility as a service) and area of application (passenger cars, urban transport, freight transport). The LEVITATE project focuses on societal level impacts of CAVs in three areas of use: freight, urban and passenger car transport. In Table 1 the LEVITATE scope in terms of more detailed subsystems and technologies within these three areas are shown.

As the output of the LEVITATE project will be a policy support tool that can be used by municipalities, regional authorities and national governments, impacts on, for example, a European level are outside the impact assessment scope. Finally, the time periods used for the impact assessment are short (five years), medium (10 years) and long term (25+ years). These time periods correspond to the immediate introduction of mobility technologies, the duration of a mixed fleet of non-automated, partial and fully automated vehicles as well as the increase in mobility services based on increasingly ubiquitous connectivity. Within the policy support tool, impacts are estimated for different penetration rates of first and second generation automated vehicles as well as a number of additional policy measures and technologies. The tool will quantify the impacts presented in this paper accordingly.

For example, there are many vehicle-based automation technologies that are close to market. It can be assumed that these will soon enter the vehicle fleet and result in changes compared to current driving. Over the medium term there will be a mixed fleet of vehicles and a range of levels of infrastructure connectivity which may introduce new transport risks, making safety benefits uncertain. Beyond 25 years there will be largely ubiquitous automation with high levels of system integration. Cities are expected to transform as land use, employment and disruptive technologies are expected to cause unexpected changes.

**Figure 1.** Example of causal relations between impacts, containing both feedforward (green) and feedback relations (orange).
Table 1. Example connected and automated vehicles deployment scenarios for each use case.

<table>
<thead>
<tr>
<th>Use case</th>
<th>Automated urban transport</th>
<th>Passenger cars</th>
<th>Freight transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automation</td>
<td>• Point to point shuttle • Anywhere to anywhere shuttle • Segregated pathway operations • On road operations • Intermodal route planning • Street design implications</td>
<td>• SAE L2/3/4 automation • Highway pilot • Autopark • Highway pilot • Cooperative automatic cruise control • Traffic jam pilot • City chauffeur</td>
<td>• Highway platooning • Automated urban delivery • Depot to depot automated transfer • Automated intermodal transport • Synchronized traffic load on bridges • Intelligent access control of infrastructure/bridge</td>
</tr>
<tr>
<td>Connectivity</td>
<td>• Green light optimized speed advisory • System-aware route optimization</td>
<td>• Geo-fencing based powertrain use • Green light optimized speed advisory • Road use pricing • System-aware route optimization</td>
<td>• Geo-fencing based powertrain use • Green light optimized speed advisory • Road use pricing • System-aware route optimization</td>
</tr>
<tr>
<td>Mobility as a</td>
<td>• Multi-modal integrated payments • e-hailing • Automated ride sharing</td>
<td>• Multi-modal integrated payments • Shared ownership models • Urban platooning</td>
<td>Local freight consolidation</td>
</tr>
<tr>
<td>service</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Impact diagram set up

Setting up the impact diagram started with an explorative literature review on the impacts of CAVs within the scope as defined in the previous paragraph. The review was done using the snowball method through Google Scholar, starting from the paper of Milakis et al. (2017) (last search on December 20, 2018). For each study, a list was made of the potential impacts they identified. These lists were then compared. A consolidated list was made from all potential impacts that were mentioned in at least one of the studies that were reviewed. An overview of the impacts described in the found literature (see “ExplorativeLiteratureOverview.pdf” (Cleij et al., 2021)) was sent to other members of the project and their input was requested. The input from project members was used to update the list of potential impacts from literature.

To visualise these impacts and their interrelations, the impact areas were placed in text balloons and the interrelations between these areas visualized using arrows. The arrowhead indicates the direction of the impact relation, i.e., that changes in travel time will likely impact the commuting distance is indicated with an arrow from the former towards the latter.

To structure the diagram and define a holistic set of starting points generating these impacts, the top of the diagram contains the technological changes that drive the impacts; the impact generators. In the LEVITATE project the following impact generators were defined after some iterations: vehicle design, level of automation and connectivity. All impacts could be derived from these impact generators.

An example of such an impact diagram set up including six impact areas is shown in Figure 2. This example shows the influence of automation level on the use and valuation of travel time and the driving behaviour (e.g., shorter headways). These in turn influence the commuting distances and road capacity, respectively. The road capacity in turn influenced the congestion, which influences travel time. Travel time in turn, influences commuting distances.

Impact diagram elaboration

To extend and improve the initial impact diagram, two methods were adopted. Firstly, each impact in the diagram was analyzed for possible further relations to other impact areas in the diagram and impact areas not yet in the diagram. In doing so, additional literature was often consulted. An overview of the most relevant literature used for the development of the impact diagrams can also be found in the underlying data document “OverviewOfMostRelevantLiterature.pdf” (Cleij et al., 2021).

Second, the impact areas were grouped along dimensions commonly found in the literature. The choice for such dimensions was based on a comparison of impact taxonomies from literature (see Table 2).

The main groups in the taxonomy described in (Chan, 2017) was deemed most holistic as it encompassed all others. The impacts in this project were therefore classified accordingly, i.e., affecting vehicle users (direct), transportation operations (systemic) and society (wider). In Figure 3 an example is given of such grouping for the impacts from Figure 2 that can be placed in the vehicle user group. To extend the impact diagram, each of these subgroups was analyzed for missing impacts and newly found impacts were added to the overall impact diagram.
Both steps focus on the analysis of impacts from different points of view, making the impact diagram more holistic.

Impact diagram validation
After several iterations of the impact diagram elaboration step, a final impact diagram was obtained. Whether the diagram includes all potential impacts of CAVs cannot be ascertained at this time. However, the completeness of the diagram is an important objective of the LEVITATE project. Therefore, a validation of the completeness of the diagram was approximated by comparing the impact diagrams to impacts found in additional literature, in combination with a final review by project members. The literature used for this validation (Litman, 2019; Sousa et al., 2018; van Nes & Duivenvoorden, 2017) was not part of the initial explorative literature review. No additional impacts or interrelations were found and therefore
the completeness of the diagram was deemed sufficiently validated.

Ethics statement
The consultations within this work were performed by other members of the LEVITATE project. Following the grant agreement, these project members consented to use their views.

Method output: impact model
The final model of impacts is a large complex diagram. To add structure to the diagram a similar approach to the model presented in (Milakis et al., 2017) was applied. The impacts were classified as direct impacts, systematic impacts and wider impacts. These categories all refer to impacts that originate in automation technology, i.e. are stages of causal chains that start with technology. In addition, this technology could have secondary impacts. These impacts were modelled as behavioural adaptation and presented as a second impact diagram. The secondary impacts originate in changes in behaviour in response to the technology. The diagram showing primary impacts is shown in Figure 4, and one showing secondary impacts (behavioural adaptation; feedback) is presented in Figure 5. The impact generators in the second diagram are the direct impacts in the first diagram.

Figure 3. Example of impact area grouping.

Further steps to impact assessment
The diagrams presented in Figure 4 and Figure 5 show potential impacts and the relationship between these impacts. This first step helps create a holistic overview, but cannot be applied directly for quantitative impact assessment.

Key elements that need further development include a more detailed description of each impact presented in the diagram, specifying the direction of change of the interrelations (positive or negative), and finally identifying the mathematical forms of the relationships between impacts, i.e., estimating dose response curves, indicating how impacts depend on the market penetration rate of connectivity and automation technology.

A first step to be taken is to limit the scope further. The impact diagram can be used to define relevant use cases based on which impacts are relevant among all those included in the diagram. Also, it is possible to focus on specific impacts. For example, one can decide to only look at safety impacts, while taking into account feedback loops caused by other types of impact that became apparent through the original broad scope diagram. In this case, an impact diagram only focusing on road safety is, for example, reduced to the primary impacts shown in Figure 6 and the secondary impacts shown in Figure 7.

Figure 6 shows that automated vehicles affect road safety directly (primary impact) via many routes, for example, they will probably have a lower risk of being involved in a crash than human driven vehicles, with the risk decreasing with increasing the level of automation. This impact is indicated in
Figure 4. Impact diagram with primary impacts from (Elvik et al., 2019).

Figure 5. Impact diagram with secondary impacts from (Elvik et al., 2019).
Figure 6. Primary impacts related to road safety.

Figure 7. Secondary impacts related to road safety.
A logical next step in impact assessment is to quantify as many of the impacts as possible. Within the LEVITATE project this is still work in progress. One can see each interrelation as an open loop system to simplify the development of such algorithms. When doing this, potential time delays between cause and effect should also be taken into account.

**Discussion**

In the LEVITATE project the presented first steps of the impact assessment method helped create a holistic overview of the impacts relevant for the further course of the project. The approach was inspired by the causal loop diagrams and methods adopted by (Innamaa et al., 2018b) and (Milakis et al., 2017). The approach combines the holistic system approach of causal loop diagrams with the structured approaches applied to impact assessment for vehicle automation.

The main difference between the approach presented here and those presented in (Innamaa et al., 2018b) and (Milakis et al., 2017) is the focus on feedback loops. This explicitly recognises the fact that new technology usually has some unintended impacts in addition to the intended impacts. This approach was strongly influenced by the focus of the project on both short and long term impacts. Especially for long term impact assessment, behavioural adaptation is of utmost importance.

It has been assumed (Aria et al., 2016; Arnaout & Arnaout, 2014; Papadoulis et al., 2019), for example, that smaller time headways increase road capacity and therefore decrease congestion and travel time. This assumption, however, does not take into account the well-established fact that decreased travel time creates a feedback loop that in turn increases vehicle km travelled and may increase congestion. In a worst-case scenario, travel time is unchanged, but there are more vehicles on the road creating more pollution.

Another difference with, for example (Innamaa et al., 2018b), is that the project scope is defined in two steps. In the first step a general scope is defined, but the final scope is defined by relying on the insights about relevant impact paths obtained from the first step of the impact assessment method described here. This choice was made to avoid limiting the impact brainstorming too early in the process. By taking many different systems into account, impacts that are not directly obvious for one type of system are still considered and might turn out to, via feedback or direct relations, significantly influence the initially considered types of impact.

Moreover, an example was given of how the impact diagram can be used to define an impact diagram that focusses on one type of impact in particular, while taking all relevant feedback loops from other types of impact into account. This approach would likely provide a more holistic view for the impact assessment of one type of impact than starting from that type of impact and expanding, as many feedback loops are often not obvious initially. Also, this approach can be used to split the work between research groups focusing on different types of impact, as is often done within large projects such as LEVITATE.

Generally, the method presented here has helped structure the impact assessment process within the LEVITATE project, greatly benefitting the efficiency of our work. Furthermore, the relatively large scope in the first phase of impact assessment has benefitted the open exploration of potential impact areas and their interrelations. This strategy of delaying the definition of the final scope resembles the double diamond method often used in design processes (Design Council, 2015; Tschimmel, 2012; ). Here a phase of exploration precedes the scoping phase so that first new insides are gathered and the problem is looked at in a fresh way before the final scoping occurs. This approach to impact assessment has its limitations. While the method aims to be as holistic as possible in defining the impacts, it is not possible to know if true completeness is achieved. Aiming for completeness helps to create insight in all the different factors that are interrelated and together define impacts of CAVs. To achieve this, however, the scope of the assessment is initially kept quite large. This large scope makes it harder to be specific on the exact parameters and dose response curves needed to define each impact. After the scope has been reduced, as is proposed as a next step, many more steps will need to be taken before a quantitative impact assessment can be performed. Defining a smaller scope initially can make the overall process faster, but increases the chances of failing to identify certain relevant impacts and interrelations.

**Conclusions**

This paper presents the first steps of an impact assessment method for CAVs. The focus of this method is to create a holistic overview of impacts that can also be applied for long term impact assessment. The method aims to achieve this by including all feedback loops early in the process and taking different perspectives on how impacts can be classified, as well as including a validation step to assess the holistleness of the final impact diagram.

While the authors do not claim to present the only and best way to assess impacts of CAVs, this method has proven successful for the purposes of the European project LEVITATE and can be expected to help others with similar analysis challenges.
Data availability
Underlying data

This project contains the following underlying data:

- Cleijetal2021_ExplorativeLiteratureOverview.pdf (results of the explorative literature review from the diagram set up phase)
- Cleijetal2021_OverviewOfMostRelevantLiterature.pdf (overview of most relevant literature used during the development of the impact diagrams described in this manuscript)
- Cleijetal2021_IntermediateResultsOfDiagramDevelopment.pdf (overview of the intermediate results of the development process for the impact diagrams described in this manuscript)

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

References


Design Council: Design methods for developing services. 2015. Reference Source


The paper addresses an important topic: how to study the possible impacts of road automation. The problem with studying the impacts is that although the technology is developing, the percentage of automated vehicles on the road is still very low: the first sentence in the abstract is somewhat exaggerated. The use of the term connected and automated vehicles is that it seems to encompass everything from driver support systems to robot-taxis, and this does not help when looking at impacts. The major shift in societal impacts may come from widespread full or nearly full automation and not from driving with systems that perform some driving functions automatically under control of the driver. It is not always clear in the paper about what level of automation and what level of penetration the impacts are discussed.

Some justification for why “as many impacts” is the focus of the work would have been helpful. If we look at wider societal impacts there may be an infinite range of possible changes as it is not only automation in mobility that is changing, but society as a whole is changing as well, which will in turn impact mobility (economic developments, climate change consequences, energy, automation in other sectors, etc.). In order to provide policy support, as is the aim of the project, I'm not sure if “as many” is going to be very helpful.

It would have been good to have some more clarity about the terms used and the differences between a “structured” approach, a “holistic” approach, a “structured holistic approach”, between causal loop diagrams and feedback loops.

Sometimes the text is rather vague, for example, directly under the heading “Impact assessment method” it says “The focus is put on the system as a whole from the start, including feedback and interrelations between different impact areas”. It is not clear to me what “the system as a whole” is, is it traffic, mobility, society….? Also, it is not clear whether the focus is on vehicles themselves or on the wider mobility system. In table 1 both are being described.

I am wondering about “The main groups in the taxonomy described in (Chan, 2017) was deemed most holistic as it encompassed all others.” This taxonomy is the most high-level, simple one, but why call
it holistic? What is the difference between comfort and convenience? In the example in figure 2 commuting distance is comfort and travel time convenience. I don't understand why.

I have doubts about the claim that the project aims to the completeness of the impact diagram, is this ever possible? The claim “Therefore, a validation of the completeness of the diagram was approximated by comparing the impact diagrams to impacts found in additional literature, in combination with a final review by project members. The literature used for this validation (Litman, 2019; Sousa et al., 2018; van Nes & Duivenvoorden, 2017) was not part of the initial explorative literature review. No additional impacts or interrelations were found and therefore the completeness of the diagram was deemed sufficiently validated.” Can you really validate completeness by looking at a few extra literature sources?

The section in the discussion is somewhat confusing: “This approach to impact assessment has its limitations. While the method aims to be as holistic as possible in defining the impacts, it is not possible to know if true completeness is achieved. Aiming for completeness helps to create insight in all the different factors that are interrelated and together define impacts of CAVs. To achieve this, however, the scope of the assessment is initially kept quite large. This large scope makes it harder to be specific on the exact parameters and dose response curves needed to define each impact. After the scope has been reduced, as is proposed as a next step, many more steps will need to be taken before a quantitative impact assessment can be performed. Defining a smaller scope initially can make the overall process faster, but increases the chances of failing to identify certain relevant impacts and interrelations.” Is the model complete or not, as claimed earlier in the paper. Is now the scope too large and has it to be made smaller, which seems to go against the objective of the project. What is then the difference with the other approaches in the literature?

The conclusion states that “this method has proven successful for the purposes of the European project LEVITATE and can be expected to help others with similar analysis challenges.” But not much is said about why it is successful and how that was established.

In summary, in my opinion, the paper needs to provide more clarification of the terms being used. More explanation and justification are needed about the choices being made. More explanation is needed about the limits of the approach and the model, and the way in which they are going to be used and evaluated.

Is the rationale for developing the new method (or application) clearly explained?
Partly

Is the description of the method technically sound?
Partly

Are sufficient details provided to allow replication of the method development and its use by others?
Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
No source data required
[Partly]

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** connected and automated mobility, evaluation methodology for field operational tests, user acceptance, impact assessment

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

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**Author Response 06 Apr 2022**

**Diane Cleij**, SWOV Institute for Road Safety Research, Bezuidenhoutseweg 62, The Hague, The Netherlands

Dear Dr. Barnard,

Thank you for your comments, we feel they have improved the article significantly. In the text below we addressed your comments and indicate corresponding changes to the article text. Your comments are shown in grey, our response is shown below in black and the corresponding adjustments to the article text are shown in red italic. We hope the revisions address your original reservations sufficiently.

Kind regards,
Diane Cleij

**Reviewer Comment 1:**

“The paper addresses an important topic: how to study the possible impacts of road automation. The problem with studying the impacts is that although the technology is developing, the percentage of automated vehicles on the road is still very low: the first sentence in the abstract is somewhat exaggerated. The use of the term connected and automated vehicles is that it seems to encompass everything from driver support systems to robot-taxis, and this does not help when looking at impacts. The major shift in societal impacts may come from widespread full or nearly full automation and not from driving with systems that perform some driving functions automatically under control of the driver. It is not always clear in the paper about what level of automation and what level of penetration the impacts are discussed.”

Thank you for your comment. It is true that the initial scoping is kept rather broad and can therefore be perceived as somewhat vague. As mentioned in the discussion, the scope was initially kept relatively broad, to avoid limiting the impact of brainstorming too early in the process. The LEVITATE projects considers the impacts of different penetration rates of first and second generation automated vehicles which are further specified in the LEVITATE project. In addition, impacts are estimated for a number of Sub Use Cases that can be found
in Table 1. To make this clearer in the paper we added the following text:

“Within the policy support tool, impacts are estimated for different penetration rates of first and second generation automated vehicles as well as a number of additional policy measures and technologies. The tool will quantify the impacts presented in this paper accordingly.”

Reviewer Comment 2:
“Some justification for why “as many impacts” is the focus of the work would have been helpful. If we look at wider societal impacts there may be an infinite range of possible changes as it is not only automation in mobility that is changing, but society as a whole is changing as well, which will in turn impact mobility (economic developments, climate change consequences, energy, automation in other sectors, etc.). In order to provide policy support, as is the aim of the project, I'm not sure if “as many” is going to be very helpful.”

Thank you for this comment. It is true that “many” is not better per se. However, the aim of the LEVITATE project is to estimate all (societal) impacts of developments related to Connected and Automated mobility. This is the core of the project. The policy support tool that is being developed within the LEVITATE project, serves a wide range of policy makers. To serve each of them, as many societal impacts impacts as possible are included in the tool. However, policy makers can select only those impacts that are of interest to them to get a more focussed output. We adjusted the text to emphasize the wide range of policy makers that are the focus group of the LEVITATE project.

“The policy support tool that will be developed during this project is intended to enable a wide range of policy makers to select policy interventions and assess the impacts of automated vehicles in the short, mid and long term future under different circumstances.”

Additionally, including such a wide range of impacts can help uncovering unintended impacts and feedback loops that possibly stay hidden when limiting the scope of your impact assessment. An example of this was given in the discussion: “It has been assumed (Aria et al., 2016; Arnaout & Arnaout, 2014; Papadoulis et al., 2019), for example, that smaller time headways increase road capacity and therefore decrease congestion and travel time. This assumption, however, does not take into account the well-established fact that decreased travel time creates a feedback loop that in turn increases vehicle km travelled and may increase.” Congestion. In a worst-case scenario, travel time is unchanged, but there are more vehicles on the road creating more pollution.

Reviewer Comment 3:
“It would have been good to have some more clarity about the terms used and the differences between a “structured” approach, a “holistic” approach, a “structured holistic approach”, between causal loop diagrams and feedback loops.”

The authors agree that these terms benefit from some additional explanation. We adjusted the text as follows:
“To obtain such a comprehensive overview of all impacts, a structured holistic approach is needed. E.g., structuring the impact assessment process with the goal of obtaining a holistic set of potential impacts.”

Causal loop diagrams contain both feedforward and feedback loops. Where the former is the impact that happens first after the initial change in circumstances (e.g., introduction of CAV) and the latter loop is a consequence of this impact that feeds back to an earlier impact. For example, introduction of CAVs could reduce travel time (feedforward loop) as they might make more efficient use of the road available due to shorter time headways. However, when travel time is lower, more people might use the car which will increase traffic flow and reduce travel time again (feedback loop). To explain this more clearly in the article the following changes have been made:

“The focus is put on the system as a whole from the start, thus including both feedforward and feedback causal relations between different impact areas. Examples of such causal relations are shown in Figure 1. Here the feedforward, or direct, relation is the potential impact of CAV regarding the reduction travel time due to the adoption of shorter time headways. The feedback relation is then the relation between increased traffic flow due to this shorter travel time that in turn increases the travel time.

Figure 1. Example of causal relations between impacts, containing both feedforward (green) and feedback relations (orange).

This on causal relations based approach to impact assessment can be used as an input in the development of specific use cases by focusing on the impacts that are of particular relevance in a specific use case.”

Reviewer Comment 4:
“Sometimes the text is rather vague, for example, directly under the heading “Impact assessment method” it says “The focus is put on the system as a whole from the start, including feedback and interrelations between different impact areas”. It is not clear to me what “the system as a whole” is, is it traffic, mobility, society....? Also, it is not clear whether the focus is on vehicles themselves or on the wider mobility system. In table 1 both are being described.”

The system as a whole here refers to the inclusion of feedforward and feedback loops between impacts. To emphasize this we made the changes as shown in Reviewer comment 3. More generally speaking, the LEVITATE project looks at societal level impacts, but as they are fed by traffic and mobility level impacts these are included as well. To make this clearer we adjusted the text as follows:

“The LEVITATE project focuses on societal level impacts of CAVs in three areas of use: freight, urban and passenger car transport.”

Reviewer Comment 5:
“I am wondering about “The main groups in the taxonomy described in (Chan, 2017) was deemed most holistic as it encompassed all others.” This taxonomy is the most
high-level, simple one, but why call it holistic? What is the difference between comfort and convenience? In the example in figure 2 commuting distance is comfort and travel time convenience. I don’t understand why.”

It is a correct observation that the taxonomy described in (Chan, 2007) is the most high level one. This is likely why it is the most holistic, as it is surely easier to provide a holistic taxonomy defined on a higher level than on a lower level, where more details need to be reported to still be holistic. The difference between comfort and convenience is that the former relates to a physical state of the vehicle user (e.g., sitting in a comfortable chair during a long distance travel) and the latter relates to ease of use (e.g., being at work quicker due to a shorter travel time).

Reviewer Comment 6:
“I have doubts about the claim that the project aims to the completeness of the impact diagram, is this ever possible? The claim “Therefore, a validation of the completeness of the diagram was approximated by comparing the impact diagrams to impacts found in additional literature, in combination with a final review by project members. The literature used for this validation (Litman, 2019; Sousa et al., 2018; van Nes & Duivenvoorden, 2017) was not part of the initial explorative literature review. No additional impacts or interrelations were found and therefore the completeness of the diagram was deemed sufficiently validated.” Can you really validate completeness by looking at a few extra literature sources?”

The authors agree that an exact validation of completeness is not possible. For this reason the paper states that validation was approximated. The authors agree that more papers would of course improve such approximation. For the LEVITATE project, however, this level of validation was deemed sufficient. As this paper mainly aims to describe the method, it is up to those possibly using the method in the future to decide if for their project a more accurate approximation is needed.

Reviewer Comment 7:
The section in the discussion is somewhat confusing: “This approach to impact assessment has its limitations. While the method aims to be as holistic as possible in defining the impacts, it is not possible to know if true completeness is achieved. Aiming for completeness helps to create insight in all the different factors that are interrelated and together define impacts of CAVs. To achieve this, however, the scope of the assessment is initially kept quite large. This large scope makes it harder to be specific on the exact parameters and dose response curves needed to define each impact. After the scope has been reduced, as is proposed as a next step, many more steps will need to be taken before a quantitative impact assessment can be performed. Defining a smaller scope initially can make the overall process faster, but increases the chances of failing to identify certain relevant impacts and interrelations.” Is the model complete or not, as claimed earlier in the paper. Is now the scope too large and has it to be made smaller, which seems to go against the objective of the project. What is then the difference with the other approaches in the literature?”
As mentioned in the previous comment, the validation of completeness is an approximation. As is the case with all approximations, it can be wrong. For this model this would mean that we might miss some impacts that did not turn up in the validation phase, but would turn up if we would use more papers for the validation. However, for the purposes of this project the completeness was deemed sufficiently validated as stated in the article. As for the scope, this is only too large for the further steps in the process of quantifying the impacts, but not too large for the steps described in this article. Keeping the scope large in the initial stages of the process broadens researchers view on potential impacts, making it more likely that also less apparent potential causal relations are uncovered. As proposed in the article, one way of further scoping in later stages of the process is to select one primary impact area of interest. Then use the full scope impact diagram, which now also includes less apparent causal relations and impact areas, to select those impact areas that are of influence on this primary impact (e.g., in Figure 5 and 6 the impact area “Safety” was chosen). To make this clearer in the article we adjusted the text as follows: “For example, one can decide to only look at safety impacts, while taking into account feedback loops caused by other types of impact that became apparent through the original broad scope diagram. “

Reviewer Comment 8:
“The conclusion states that “this method has proven successful for the purposes of the European project LEVITATE and can be expected to help others with similar analysis challenges.” But not much is said about why it is successful and how that was established.”

We added the following text to the discussion to better explain the benefits of the method described in the article for the LEVITATE project:

“Generally, the method presented here has helped structure the impact assessment process within the LEVITATE project, greatly benefitting the efficiency of our work. Furthermore, the relatively large scope in the first phase of impact assessment has benefitted the open exploration of potential impact areas and their interrelations. This strategy of delaying the definition of the final scope resembles the double diamond method often used in design processes (Tschimmel, 2012, Design Council 2015). Here a phase of exploration precedes the scoping phase so that first new insides are gathered and the problem is looked at in a fresh way before the final scoping occurs. “

Reviewer Comment 9:
“In summary, in my opinion, the paper needs to provide more clarification of the terms being used. More explanation and justification are needed about the choices being made. More explanation is needed about the limits of the approach and the model, and the way in which they are going to be used and evaluated.”

Thank you for your review, the authors hope that the previously described changes to the article address your concerns sufficiently.

**Competing Interests:** No competing interests were disclosed.
The article "Impact assessment methodology for connected and automated vehicles" by Cleij et al. presents a methodology to explore and define these impacts (specifically: impact areas) as starting point for quantitative impact assessment. The article presents the outcome of a systematic overview of the impact areas and linkages between them and some examples of how the result can be used.

My recommendation is to approve the article with reservations taking into account the comments below:

- The article is named “Impact assessment methodology for connected and automated vehicles”. However, in your own words “This paper presents the approach ... to explore and define impacts and their interrelations as a starting point for quantitative impact assessment”. Specifically, the paper focuses on “impact areas” rather than on “impacts” as an assessment of the magnitude or even the direction of the impact is not included. Thus, the title does not really correspond to the content as the full impact assessment methodology is not presented but only the potential impact areas affected by CAVs. Therefore, I would suggest to rename the article as something like “Holistic overview of impact areas for CAV”.

- In the abstract, you hint that “Results from the qualitative assessment ... are presented”. However, if not even a direction of the impact is defined, can this be called “results of qualitative assessment”? I see this more as the identification of potential impact areas. Thus, I would recommend to clarify the content of the article for the abstract.

- Terms “non-autonomous, partial and fully autonomous vehicles” are used on page 4. The term “automated” would be better.

- On page 4 you state that “Beyond 25 years... mobility is expected to be “close to perfect”...”. Did you have a reference for this? Or is this a vision by LEVITATE? Such a strong statement would need clarification on this.

- The article uses the taxonomy suggested by Chan, grouping the impact areas under vehicle users (direct), transport operations (systemic impacts) and society (wider) which seems well justified and works well in the outcome.

- On page 7 you discuss “intended and unintended impacts” stating that all direct, systemic and wider impacts are “intended” while behavioral adaptation represents “unintended”
impacts. I am not sure if this can be said. For example, the car manufacturer intends to make the car safe, comfortable, etc. but most likely does not “intend” to affect road capacity. On the other hand, they may intend to build the car such that it increases the trust to technology or provides accessibility to wider demographic groups than traditional cars. Now these items are listed under “unintended impacts”. I agree that it is important to cover both intended and unintended impacts but without knowing whether an impact is positive or negative it is hard to group the areas into these categories. In fact, under one impact area there may be “intended” and “unintended” impacts, for safety there may be an “intended” reduction in many types of accidents but also some “unintended” new types of accidents caused by automation. Thus, I would be cautious in categorizing the impact areas into intended and unintended.

- The article aims for completeness in the overview impact areas potentially affected by vehicle automation. The effort done in compiling the overview was substantial and the outcome was validated with couple of manuscripts not used in the process. Thus, the statement on completeness seems valid. However, there are a couple of items that may have been left outside the model on purpose but I was wondering if they would be needed for impact assessment later anyhow: First, you cannot have impacts without the use of technology. Thus, from the impact diagrams (Figures 3 & 4) I was wondering if “awareness” and “acceptance” should be visible, especially, if the model is aimed at decision makers. People need to be aware of technology and accept it before they start using it. This is an area where many stakeholders can influence the uptake of CCAM. Different levels of awareness and acceptance lead to evolving penetration rates and use of CCAM which affects the societal impacts. Another aspect, which is not included, is the impact on driving behavior (speed, headway, etc., “vehicle operations” in Innamaa et al. 2018b). The effects in these affect e.g. road capacity or emissions. Did you plan to include these in the algorithms of the next phase? Or how did you plan to take these topics into account? Some assumptions for them will be needed in the actual impact assessment phase. (I have a couple of additional suggestions to consider for Figure 4 below.)

- On page 7, in your description of the example in Figure 5, you say that “Figure 5 shows that AVs affect road safety...” and then you give examples that “they will have lower risk of being involved in an accident” but this in fact cannot be seen from Figure 5. Should you set the example with items visible in the graphics?

- On pages 8-9 you tell of “rebound effects”. Without knowing the direction of the impacts, it is hard to know whether they boost the impact or reduce it. Thus, I would reconsider calling it “rebound effect”, or at least I would add the word “potential” there to hint that these may potentially reduce the impact and therefore they are worth checking. It is hard to make a complete list of all potential rebounding effects. Potentially rebounding factors that are now not listed in Figure 4 and which are relevant include at least adaptation of driving style when AV user drives manually outside ODD (for at least users of SAE3 cars) and adaptation of the driving behavior of non-users in traffic with large penetration of AVs. If the driving outside ODD and of non-users are affected, they will have an impact, too.

This article presents the first step of very interesting work. It compiles the current knowledge on potential impact areas of CAV and presents them in structured way aiming to be generic for many CAV use cases. I look forward to seeing the model with quantified impacts.
Is the rationale for developing the new method (or application) clearly explained?
Yes

Is the description of the method technically sound?
Yes

Are sufficient details provided to allow replication of the method development and its use by others?
Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Partly

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** Impact assessment, connected and automated driving, transport, mobility

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

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**Author Response 11 Apr 2022**

**Diane Cleij**, SWOV Institute for Road Safety Research, Bezuidenhoutseweg 62, The Hague, The Netherlands

Dear Dr. Innamaa,

Thank you for your comments, we feel they have improved the article significantly. In the text below we addressed your comments and indicated corresponding changes to the article text. Your comments are shown in bold font, our response is shown below in plain text and if any adjustments were made to the text this is shown in italic, with the exact adjustments underlined. We hope the revisions address your original reservations sufficiently.

Kind regards,

Diane Cleij

**Reviewer Comment 1:**
"The article is named “Impact assessment methodology for connected and automated vehicles”. However, in your own words “This paper presents the approach ... to explore
and define impacts and their interrelations as a starting point for quantitative impact assessment”. Specifically, the paper focuses on “impact areas” rather than on “impacts” as an assessment of the magnitude or even the direction of the impact is not included. Thus, the title does not really correspond to the content as the full impact assessment methodology is not presented but only the potential impact areas affected by CAVs. Therefore, I would suggest to rename the article as something like “Holistic overview of impact areas for CAV”.

We understand the confusion the title might cause and changed the title to:

“First steps towards a holistic impact assessment methodology for connected and automated vehicles”

Reviewer Comment 2:
“In the abstract, you hint that “Results from the qualitative assessment ... are presented”. However, if not even a direction of the impact is defined, can this be called “results of qualitative assessment“? I see this more as the identification of potential impact areas. Thus, I would recommend to clarify the content of the article for the abstract.”

We understand the confusion the terminology might cause and changed the abstract phrase to:

“The impact taxonomy and interrelations between impacts resulting from this project are presented and further steps needed to perform a quantitative evaluation of the impacts are discussed”

Reviewer Comment 3:
“Terms “non-autonomous, partial and fully autonomous vehicles” are used on page 4. The term “automated” would be better.”

Thank you for the suggestion, we corrected it in the text.

Reviewer Comment 4:
“On page 4 you state that “Beyond 25 years... mobility is expected to be “close to perfect”...”. Did you have a reference for this? Or is this a vision by LEVITATE? Such a strong statement would need clarification on this.”

We agree that this is a strong statement needing clarification. The statement indeed referred to an early vision within the LEVITATE project. However, this vision changed during the course of the project. As the statement also does not provide relevant information for this paper, we decided to remove it entirely.

Reviewer Comment 5:
“The article uses the taxonomy suggested by Chan, grouping the impact areas under vehicle users (direct), transport operations (systemic impacts) and society (wider) which seems well justified and works well in the outcome.”
We agree with the reviewer and do not think this comment calls for changes in the paper.

Reviewer Comment 6:
"On page 7 you discuss “intended and unintended impacts” stating that all direct, systemic and wider impacts are “intended” while behavioral adaptation represents “unintended” impacts. I am not sure if this can be said. For example, the car manufacturer intends to make the car safe, comfortable, etc. but most likely does not “intend” to affect road capacity. On the other hand, they may intend to build the car such that it increases the trust to technology or provides accessibility to wider demographic groups than traditional cars. Now these items are listed under “unintended impacts”. I agree that it is important to cover both intended and unintended impacts but without knowing whether an impact is positive or negative it is hard to group the areas into these categories. In fact, under one impact area there may be “intended” and “unintended” impacts, for safety there may be an “intended” reduction in many types of accidents but also some “unintended” new types of accidents caused by automation. Thus, I would be cautious in categorizing the impact areas into intended and unintended."

Thank you for this remark. We agree that the use of the word “intended” does not correctly convey the meaning of primary and secondary impacts as they are presented in the paper. We adjusted the text as follows:

“The impacts were classified as direct impacts, systematic impacts and wider impacts. These categories all refer to impacts that originate in automation technology, i.e. are stages of causal chains that start with technology. In addition, this technology could have secondary impacts. These impacts were modelled as behavioural adaptation and presented as a second impact diagram. The secondary impacts originate in changes in behaviour in response to the technology. The diagram showing primary impacts is shown in Figure 3, and one showing secondary impacts (behavioural adaptation; feedback) is presented in Figure 4. The impact generators in the second diagram are the direct impacts in the first diagram.”

Reviewer Comment 7:
"The article aims for completeness in the overview impact areas potentially affected by vehicle automation. The effort done in compiling the overview was substantial and the outcome was validated with couple of manuscripts not used in the process. Thus, the statement on completeness seems valid. However, there are a couple of items that may have been left outside the model on purpose but I was wondering if they would be needed for impact assessment later anyhow: First, you cannot have impacts without the use of technology. Thus, from the impact diagrams (Figures 3 & 4) I was wondering if “awareness” and “acceptance” should be visible, especially, if the model is aimed at decision makers. People need to be aware of technology and accept it before they start using it. This is an area where many stakeholders can influence the uptake of CCAM. Different levels of awareness and acceptance lead to evolving penetration rates and use of CCAM which affects the societal impacts. Another aspect, which is not included, is the impact on driving behavior (speed, headway, etc., “vehicle operations” in Innamaa et al. 2018b). The effects in these affect e.g. road capacity or
emissions. Did you plan to include these in the algorithms of the next phase? Or how did you plan to take these topics into account? Some assumptions for them will be needed in the actual impact assessment phase. (I have a couple of additional suggestions to consider for Figure 4 below.)

Thank you for your comment. Within the LEVITATE project constructs such as “awareness” and “acceptance” were taken into account when estimating future penetration rates of AVs. For each penetration rate the impacts as shown in the impact assessment schemes were estimated. These constructs are thus indirectly taken into account but not explicitly shown in the impact assessment schemes. These schemes do mention trust in technology, as we expect this to be strongly influenced by AV performance. Trust in technology can in turn influence acceptance and thus penetration rate. Within the project, however, we chose to use penetration rate as an input and evaluate the rest of the impact given this penetration rate. As for the driving behaviour impact, this was explicitly mentioned in the diagrams in earlier versions, but in the current version behaviour as a general category has been replaced by a set of more specific impact generators that refer to specific types of behaviour. Driving behaviour related to a single vehicle (with or without driver) is captured in the impact generator “level of automation”, while driving behaviour related to interaction between multiple vehicles is captured under “behaviour in interactions”.

Reviewer Comment 8:
“On page 7, in your description of the example in Figure 5, you say that “Figure 5 shows that AVs affect road safety...” and then you give examples that “they will have lower risk of being involved in an accident” but this in fact cannot be seen from Figure 5. Should you set the example with items visible in the graphics?”

This example refers in the first place to the arrow from impact generator “Level of automation” to wider impact “Road safety”, here higher levels of automation could be hypothesized to reduce crash risk due to, for example, quicker reaction times. This effect likely increases with increasing level of automation as higher levels of automation could be assumed to, for example, have better situation awareness. This paragraph further mentions that vehicle connectivity influences road safety, which is indicated by the arrow from impact generator “Connectivity” to wider impact “Road Safety”. To make the relation between the example and the figure clearer we adjusted the text as follows:

“Figure 5 shows that automated vehicles affect road safety directly (primary impact) via many routes, for example, they will probably have a lower risk of being involved in a crash than human driven vehicles, with the risk decreasing with increasing the level of automation. This impact is indicated in Figure 5 with the arrow between “level of automation” and “road safety”. Especially if vehicles are able to communicate with each other, i.e. if they are connected (CAVs), the risk of a crash will probably be reduced. This additional improvement on road safety is indicated with the arrow between “connectivity” and “road safety”.

Reviewer Comment 9:
“On pages 8-9 you tell of “rebound effects”. Without knowing the direction of the impacts, it is hard to know whether they boost the impact or reduce it. Thus, I would reconsider calling it “rebound effect”, or at least I would add the word “potential”
there to hint that these may potentially reduce the impact and therefore they are worth checking. It is hard to make a complete list of all potential rebounding effects. Potentially rebounding factors that are now not listed in Figure 4 and which are relevant include at least adaptation of driving style when AV user drives manually outside ODD (for at least users of SAE3 cars) and adaptation of the driving behavior of non-users in traffic with large penetration of AVs. If the driving outside ODD and of non-users are affected, they will have an impact, too.”

We agree that the word “rebound” does not cover all feedback effects shown in Figure 6. We adjusted the text as follows.

In addition, some potential feedback effects can be expected as shown in Figure 6. Such feedback effects can either amplify or reduce the original impact.” The driving behaviour aspects you mention are currently captured under the impact generators “behaviour in interactions” and “level of automation”. We especially endorse the mentioned importance of including adaptive behaviour of non-AV-users to driving among AV, as this is an often overlooked effect. Within the LEVITATE project we have therefore conducted a driving simulation study investigating such effects and will soon publish a paper about the results.

Reviewer Comment 10:
“This article presents the first step of very interesting work. It compiles the current knowledge on potential impact areas of CAV and presents them in structured way aiming to be generic for many CAV use cases. I look forward to seeing the model with quantified impacts.”

Thank you, the quantified model is further developed in the European project LEVITATE. More information on the current status can be found on https://levitate-project.eu/

**Competing Interests:** No competing interests were disclosed.