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System-level impacts of self-driving vehicles: terminology, impact frameworks and existing literature syntheses

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Summary

The intention with this report is to contribute toward the development of systemic and holistic studies of impacts of self-driving vehicles. The report is targeting system-level impacts of self-driving vehicles on the transportation system but also wider societal impacts on factors such as: land-use, public health, energy and emissions, etc. This report is complimentary to two papers that are focused on in-depth literature review of simulation studies (Pernestål Brenden and Kristoffersson 2018) and future scenario studies of impacts of self-driving vehicles (Engholm, Kristoffersson, and Pernestål Brenden 2018).

The first aim of the report is to summarize knowledge to enable future design of a high-level conceptual framework for impacts from self-driving vehicles from a systems perspective. The second aim is to summarize knowledge on impacts from self-driving vehicles in a selection of the available literature. The main contributions of the report are the following:

- A terminology for different types of automated vehicles, connected vehicles and mobility concepts for automated vehicles is presented
- Frameworks for classifying system-level impacts from SDVs in the existing literature are summarized and analyzed
- Existing literature studies on system-level impacts from SDVs are synthesized and common themes and gaps in current research are analyzed

The terminology proposed in this report distinguishes between different types of automated and connected vehicles and is primarily intended as a tool to enable stringent analysis in this report when analyzing literature that apply different terminologies. Two frameworks for classifying system-level impacts are identified and compared. The analysis of the frameworks covers their scope, specification of mechanisms generating system impacts and briefly reviews their applicability as a starting point for developing a systems model of impacts from self-driving vehicles. The review of existing literature syntheses shows that there is a large variation in availability on literature for different system impacts. Impacts on road safety, road capacity and vehicle ownership forms are well studied. Examples of less studied impacts are costs of ownership, public health, infrastructure, air pollution and accessibility. The review identifies several contractionary mechanisms and effects that can affect various system-level impacts. The results of the review highlight the need to approach impact assessments of self-driving vehicles from a systemic and holistic point of view.

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Content

1 Introduction – a systems perspective on impacts of self-driving vehicles

So far, research on impacts from self-driving vehicles (SDVs) to a large extent have focused on direct implications such as traffic flow (Calvert, Schakel, and van Lint 2017; Friedrich 2016), safety (Martinez and Canudas-de-Wit 2007; Dresner and Stone 2008; Hayashi et al. 2012) and energy consumption and emissions (Barth, Boriboonsomsin, and Wu 2014; Wadud, MacKenzie, and Leiby 2016) based on assumptions on future technical capabilities of SDVs. Typically, results indicate that the implications from SDVs might be substantial, but it remains unclear what benefits become realized and how they could be predicted and assessed from a holistic, integrated systems perspective.

Literature on indirect system-level impacts and societal effects from SDVs is more scarce and wider impacts of SDVs is an area where little is known. The majority of the impact oriented literature addresses one or a few impacts in isolation without focus on potential systemic interactions between impacts and their causes (Papa and Ferreira 2018). Even if individual impacts from SDVs could be estimated with relatively high accuracy by studying narrowly defined impacts in isolation it is unlikely that this type of results can be aggregated to get a realistic overview of the holistic effects. Complex sociotechnical systems often have strong internal dynamics that without any exogenous input sets the system's critical limits (Richardson 2011). This means that the internal structure of the system, its endogenous behavior, is of key importance for determining the impacts of a change in the system (i.e. the introduction of SDVs). Shepherd (2014) stresses that the large number of different agents and stakeholders operating in the system results in feedbacks with different dynamics and time-lags. Transport systems are inherently complex thus requiring being studied in ways that takes dynamic system behavior in to account. Thereby the study of system-level impacts requires a holistic systems approach in which systemic interactions are properly accounted for.

The intention with this report is to contribute toward the development of systemic and holistic studies of impacts of SDVs. The report is targeting system-level impacts of SDVs on the transportation system but also wider societal impacts on factors such as: land-use, public health, energy and emissions, etc. There are many topics and approaches that requires attention and this report addresses some of the most fundamental of these. This report is complimentary to two articles that are focused on in-depth literature review of simulation studies (Pernestål Brenden and Kristoffersson 2018) and future scenario studies of impacts of self-driving vehicles (Engholm, Kristoffersson, and Pernestål Brenden 2018).

1.1 Purpose of the report and contributions

The aim of this report is twofold. The first aim is to establish a framework for future studies of impacts from SDVs from a systems perspective. The second aim is to summarize knowledge on impacts from SDVs in a selection of the academic literature. The main contributions of the report are the following:

- A terminology for different types of automated vehicles, connected vehicles and mobility concepts for automated vehicles is presented
- Frameworks for classifying system-level impacts from SDVs in the existing literature are summarized and analyzed
- Existing literature studies on system-level impacts from SDVs are synthesized and common themes and gaps in current research are analyzed

1.2 Scope and delimitations

The focus in this report is on impacts from SDVs as defined and scoped in chapter 2. This means that Automated Road Transport Systems (ARTS), autonomous vehicles, conditionally driverless vehicles and driverless vehicles are included but that impacts of vehicles with lower levels of driving automation (corresponding to SAE level 1-3) are not in focus. Regarding connectivity and collaborative driving functions there are no delimitations made. Hence both highly cooperative SDVs with V2X

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capabilities are included and fully autonomous SDVs operating without practicing any collaborative driving functions are included.

The focus of the research project is primarily to understand impacts from SDVs that directly or indirectly affect the Swedish national transport infrastructure. The report puts no limitations on type of transportation whether passenger or goods are being transported. However, the available literature is to a large extent focused on passenger transportation and thus influences the balance between the emphasis of the two areas in the literature review in this report. Focus in the report is mainly toward mid and long-distance transportation and not on urban mobility.

The literature that is covered in the review in this report is academic literature that contain reviews or synthesis of results from multiple studies. This type of literature is chosen since this report span over many different impacts from SDVs. In this report, academic papers are complemented with grey literature in the form of official reports, however with a systematic approach. There is also a large field of literature with (consultancy) reports about impacts from SDVs that are non-scientific in their approach (e.g. Sweco Society 2018; Digital McKinsey 2017). These are not in the scope of this report.

1.3 Method

The process of creating the report consists of four phases (fig. 1). In the first phase of the project, a brief scanning and reading of existing literature was performed to get an overview of the research area and identifying critical questions and perspective for the report. The insights from the initial reading fed in to the design of the report and the literature selection. The next phase includes setting a terminology for automated driving in order to harmonize terms related to self-driving vehicles that are applied differently in the reviewed literature. In the third phase, classification framework for impacts of SDVs in the academic literature are identified and analyzed. The last phase of the work is a review of existing literature reviews/syntheses.

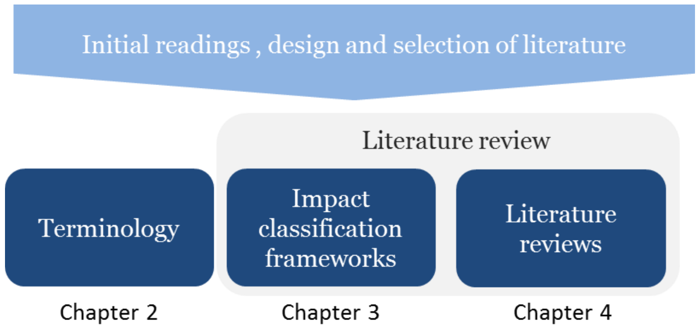

Fig. 1 - summary of the phases in the project of developing this report

The initial readings identified that four categories of academic literature can be distinguised based on their scope and approach:

- Single or isolated impact studies focusing on a specific impact with a narrow focus (e.g. intersection capacity impacts from advanced cooperative cruise control systems)
- Simulation studies simulating a network where SDVs have been introduced in some form. Typically, in these studies new mobility concepts based on SDVs (e.g. self-driving taxi services) are simulated.

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- Societal scenario studies. This type of studies uses expert-groups to identify critical trends, scenarios and societal impacts of SDVs. These studies are broad and speculative in their nature.

- Literature reviews and syntheses. This type of literature aggregates and synthesize results from multiple studies either within one impact category (e.g. safety) or across many impact categories.

In this report the focus is on reviewing literature reviews and syntheses. Since single or isolated impact studies are typically covered by these literature reviews and syntheses, the main results from these types of studies are covered indirectly. By addressing this relatively limited set of literature in-depth reading of the selected papers is possible which would not be feasible if the report were to include papers addressing single and isolated impacts of SDVs for such a wide definition of system-level impacts that is used in this report.

This literature is complemented with literature on impact classification frameworks for SDVs. A visualization of the selection in terms of type of literature scope is presented in fig. 2.

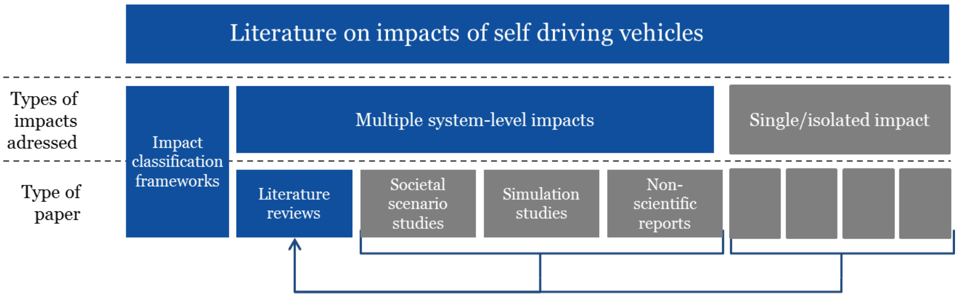


Fig. 2 - Overview of what type of literature that is in scope, and out of scope, for this report. The blue boxes represent literature that is included and grey boxes literature that is not included. Studies on single and/or isolated impacts are not directly included but are indirectly included through the review of systematic literature reviews covering such studies.

A set of high-level literature selection criterion are used. The criterions are different for the different parts of the literature review since the approach and requirements on the literature are different. In table 1 the criterions are presented among with the literature identification method and which papers are included as the main references. Note that the list of paper in the table is not exhaustive but covers the most important literature included in the review.

Table 1 Overview of the selection criterions for literature included in the literature review

	Selection criteria	Identification method	Included papers, main references
Impact classification frameworks	Comprehensive - covering a wide range of system impacts Specifically developed for SDVs and not general road transportation	Identified through initial readings	(Milakis, van Arem, and van Wee 2017; Innamaa et al. 2017)

Literature reviews	Holistic perspective – covering at least one impact category System level perspective Academic and grey literature	Identified through initial readings	(Litman 2018; Milakis et al. 2017; Fagnant and Kockelman 2015; Farah et al. 2018)
		SCOPUS and TRID database search, keywords: “review AND impacts OR effects AND automated vehicles OR SDVs OR driverless vehicles or automated driving”	(2018; Cavoli et al. 2017; Williams et al. 2017)

The SCOPUS search for literature reviews resulted in 20 unique papers of which 3 were considered relevant for this report. The literature search and selection were performed during Q2 2018.

There are some papers identified that might be of interest to the reader of this report but for various reasons were not included in the selection of reviewed literature. There are several non-academic papers that are covering similar topics as the papers reviewed in this report. A few examples of such papers focusing on Sweden that might be of interest for the reader are (Sweco Society 2018; Trafikanalys 2017; Digital McKinsey 2017).

1.3.1 Terminology

The approach for developing the terminology in this report is to relate to the SAE International (2018a) taxonomy for driving automation and making appropriate adaptations and compliments to align it toward the type of terminology commonly applied in the academic literature. Also the terminology is adjusted so that it is in line with proposed terminology by the Swedish investigation on self-driving road vehicles (Utredningen om självkörande fordon på väg 2018).

1.3.2 Impact classification frameworks

The identified papers on impact classification frameworks for SDVs are reviewed with focus on summarizing, comparing and analyzing the frameworks based on what impacts are generated from automated driving, how impact categories are defined and scoped, how impacts are causally generated and are influencing/being influenced by other variables. The identification of papers with impact classification frameworks for the review in this report is based on the initial readings.

1.3.3 Existing literature syntheses

The approach for the review of existing literature review is mainly to provide an overview of the available literature and to summarize the main characteristics and findings of the reviewed papers. Hence no specific analytical methodology is applied in this phase. The review of existing literature reviews and syntheses of system-level impacts does not intend to provide a full inventory of the existing literature but rather introduce the reader of this report to a selection of literature that covers the main topics and knowledge generated by research so far.

1.4 Acknowledgements

This research was funded by Trafikverket under Grant TRV 2017/22806. The report is one deliverable for the research project “Systemeffekter av Självkörande Fordon”.

2 Terminology for connected and automated vehicles in this report

In the literature, a variety of terms are used for different types of vehicles with driving automation and for various mobility services. There is a lack of stringency in the vocabulary sometimes make it difficult to understand and compare various sources of information about automated vehicles. Some papers (e.g. Townsend 2014) on purpose use a variety of terms as a way of highlighting that there might be a wide range of different types of vehicles with driving automation in parallel in the future and those might not be inter-operable (terms such as: autonomous vehicle, SDV, driverless car, robot car, etc. are used).

To make a comparison and analysis of the literature, as in this report, a harmonization of the terminology is needed. The terminology in this report is created in order to be aligned with SAE Internationals proposed taxonomy for driving automation (SAE International 2018a), and the Swedish investigation on self-driving road vehicles (Utredningen om självkörande fordon på väg 2018).

SAE International is a global association focused on developing standards for the vehicle industry. SAE International have proposed a taxonomy for driving automation in road motor vehicles. The SAE taxonomy aims at covering driving automation in the full span from no driving automation to full driving automation by classifying driving automation in six levels (level 0 to level 5) (SAE International 2018a). The SAE levels of driving automation levels are summarized in fig. 3. Those levels will further on in this report be referred to as SAE level [0-5] in this report.

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Fig. 3 - SAE International's levels of driving automation (SAE International 2018a)

SAE International's taxonomy is based on terms describing automation of the driving task, instead of focusing on terms for automated vehicles as such. The reason is that a vehicle might have several automated systems for other purposes than performing parts of, or the entire driving task such as blind spot monitoring or adaptive headlights. Hence, vehicles with such systems could be denoted as an automated vehicle (or similar) without the dynamic driving task being automated. SAE International recommends referring to a vehicle with driving automation capability as "(SAE) level [1-2] driving automation system-equipped vehicle" or "(SAE) level [3-5] automated driving system-equipped vehicle" (SAE International 2018a, 29). Note the different meaning between driving automation system, which relates to systems that performs the driving automation in SAE level 1-2, and automated driving system, which relates to systems that performs the driving automation in SAE level 3-5.

In the scientific literature the nomenclature often differs from SAE International's taxonomy and recommendations. Terms referring to automation of vehicles (and not specifically addressing the dynamic driving task) is often used to describe vehicles where the driving task is automated. Examples of such terms are; automated vehicles, driverless vehicles, SDVs, robotic vehicles, etc. Often these terms are defined in relation to the SAE levels, but the meaning of one term usually differ between different papers. Referring to automation of the vehicle rather than the driving task most often simplifies the language and its practical use compared to applying SAE International's taxonomy. One case is in papers when the focus is on the transportation system (with automated vehicles being one component in that system) and there is a need to describe a type of vehicle rather than specifying vehicles' technical capabilities for driving automation.

The terminology in this report is intended to be consistent with the line of reasoning in SAE International (2018a) but still refering to the vehicle as being automated instead of specifically addressing the dynamic driving task. The defined vehicle terms are not mutually exclusive (e.g. a driverless vehicle is also an automated vehicle and an SDV).

The terminology presented below is separated in three areas: 1) general terms for vehicle automation 2) types of vehicles with driving automation and/or connectivity, 3) mobility services with automated vehicles.

2.1 General terms for vehicle automation

The terms presented below are general terms useful for specifying various aspects of driving automation.

Driving task is the operational and tactical aspects of driving i.e. lateral vehicle control, longitudinal vehicle control, monitoring the environment, maneuver planning, signaling, etc. Strategical aspects of driving such as route planning and timing is in this report not considered as a part of the driving task.

Driving automation is when parts of, or the full, driving task is automated (SAE level 1 to 5).

Automated driving system is the hardware and software capable of performing the driving task. This applies to SAE levels 3 to 5. The automated driving system might be limited to function only within a specific *operational design domain* (SAE level 3 to 4) which is the specific environment or type of situations for which an automated driving system is designed to function within (SAE International 2016).

Automated driving is when a vehicle is being driven by an automated driving system. Hence a vehicle with SAE level 3 or 4 would perform automated driving when the automated driving system is engaged but not perform automated driving when the automated driving system is not engaged. This term is analogous to the Swedish term “automatiserad körning” presented in Utredningen om självkörande fordon på väg (2018)

2.2 Terms for vehicles with driving automation and/or connectivity

This section presents terms specifying vehicles with different levels of driving automation and connectivity. Fig. 4 illustrates the relationships between the terms. A simplified version of fig. 4 is presented together with the below terms to indicate how the term relates to the other terms. First, terms for vehicles with connectivity are presented followed by terms for vehicles with driving automation and finally terms for vehicles with driving automation and connectivity are presented.

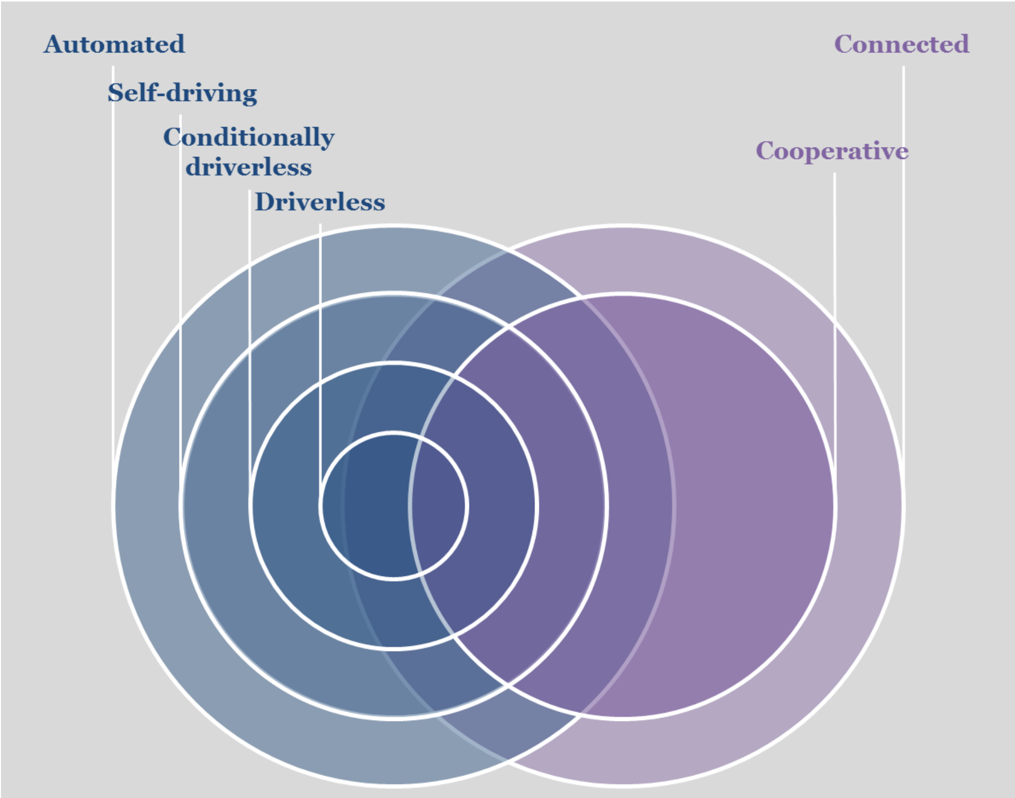
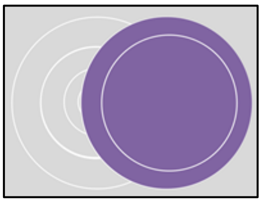


Fig. 4 - Relations between key terms for vehicle types with driving automation. The blue circles represent various levels of automated driving. The purple circles refer to two levels of data communication for vehicles. The fig. is completely schematic and aims to indicate the relationships between the terms.

In this report two terms for vehicles with different levels of communication capabilities are used.



A ***connected vehicle*** is a vehicle that is communicating data to and/or from other entities such as other vehicles, the roadway infrastructure, a central service center (e.g. cloud-services), etc. The purpose of the data communication could be for cooperative purposes and/or for enhancing the operations of the single vehicle. There are three popular terms for different forms of connectivity. *Vehicle to infrastructure (V2I)* is direct or in-direct (e.g. via a cloud-service) communication between a vehicle and some roadway infrastructure. Data from the vehicles could be utilized in a central server for intelligent transport system (ITS) applications such as route optimization or accident identification (Miller 2008). *Vehicle to vehicle (V2V)* is communication for data exchange between vehicles. One application area for V2V is so called cooperative sensing that expands the perception horizons of vehicle by sharing sensor data (Hobert et al. 2015). *Vehicle to everything (V2X)* is two-way communication between a vehicle and any type of other entity related to the vehicle such as, but not limited to other vehicles, roadway infrastructure, charging infrastructure, pedestrians, etc.

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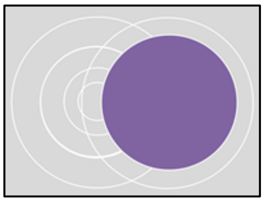
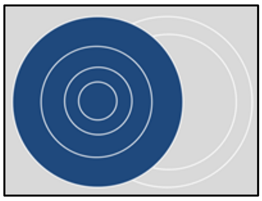
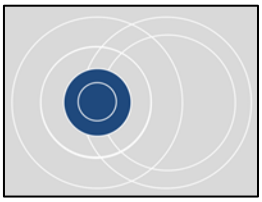


A ***cooperative vehicle*** is a vehicle that collaborates with other vehicles and/or the roadway infrastructure by utilizing V2V, V2I or V2X communication to enhance the performance of several vehicles or the transport system. Collaboration between vehicles might be used for functions such as, but not limited to, cooperative sensing (expanding the perception horizons of vehicle by sharing sensor data) and cooperative maneuvering (coordinated operations of a group of vehicles by a common decision making strategy) (Hobert et al. 2015). One example of cooperative vehicles is when several vehicles are driving in a platoon and using real-time data communication to sustain the platoon.

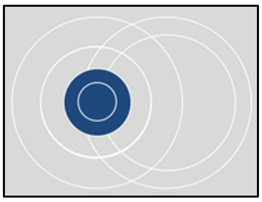
In this report the following terms for vehicles with driving automation are used.



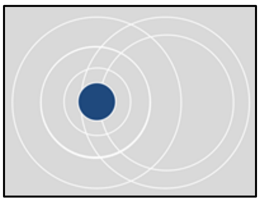
An ***automated vehicle*** is a vehicle where parts of, or the entire driving task is automated. This includes vehicles with automated driving capabilities on any of the SAE levels 1 to 5. A vehicle without any driving automation (SAE level 0) or with driving automation on SAE level 1 to 2 is in this report denoted *conventionally driven vehicle.*



A ***self-driving vehicle (SDV)*** is a vehicle with an automated driving system performing the driving task within a specific operational domain or in all operational domains. SDVs are vehicles with driving automation on SAE level 4 to 5. The term SDV is not dependent on whether it is connected or not. SDVs with SAE level 4 will, when not operating in their operational design domain, be driven by a human driver either located onboard or remotely (e.g. in a control tower or similar). SDVs is in this report abbreviated as SDV.

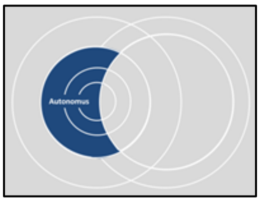


A ***conditionally driverless vehicle*** is an SDV with driving automation on SAE level 4 operated only in its operational design domain. A term sometimes used to illustrate this is "everything somewhere" indicating that the vehicle can operate driverless in some specific environments. A conditionally driverless vehicle could be connected or not. An example of conditionally driverless vehicles is a bus with driving automation on SAE level 4 operating only in a specific environment that equals their operational design domain, for instance a university campus. The bus is driverless within the campus but would not be able to perform automated driving elsewhere. On the other hand, a vehicle that is driven by an automated driving system on highways but requires a human to maneuver and navigate in urban environments and used for both highway and urban driving is an example of a vehicle that is self-driving but not conditionally driverless.

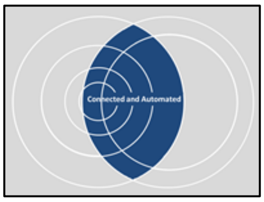


A ***driverless vehicle(s)*** *is* a vehicle capable of automatically performing the driving task in all domains without human intervention from a conventional or a remote driver. Hence a driverless vehicle is a vehicle of SAE level 5. A driverless vehicle is always self-driving when performing its transportation task. A driverless vehicle could be connected or not connected.

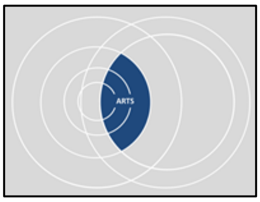
In this report the following other terms for vehicles are used.



An ***autonomous vehicle*** is an *SDV* that is not connected, i.e. does not communicate in real-time with other vehicles and/or the road infrastructure for collaborative purposes, thus operating completely autonomous in relation to other vehicles and the infrastructure. When performing the driving task, the vehicle is only relying on the vehicle's own perception system and is not dependent, or making us of, information acquired via external communication.



A ***connected and automated vehicle (CAV)*** is an automated vehicle that is also connected.



An ***Automated Road Transport System (ARTS)*** is a system of multiple SDVs that are cooperating in a collective operational mode (Madigan et al. 2016). ARTS require the included vehicles to be SDVs and collaborative.

Table 2 summarizes the definition criterion for the above presented terms.

Table 2 - Overview of vehicle types with automated driving and their corresponding SAE levels used in this report.

Type of vehicle	SAE level	Additional definition criteria
Automated	1-5	-
Self-driving	4-5	-
Conditionally driverless	4	Only operated in its operational design domain
Driverless	5	-
Autonomous	4-5	Not cooperative
Connected and automated	1-5	Connected
ARTS	4-5	Cooperative

2.3 Mobility services with automated vehicles

This section presents terms for mobility concepts in which SDVs are used. The definitions in this report are based on concepts described by Pernestål Brenden and Kristoffersson (2018) and Litman (2018). After the main composition of this report was finalized SAE published a taxonomy for shared mobility and its enabling technologies that contain useful specifications and compliments to the below terms (SAE International 2018b).

A ***privately owned SDV*** is an SDV that is owned or leased by a single private person using the vehicle. Privately owned SDVs can be shared within the family, friends or relatives but is not included in a car sharing program, used for ride-hailing services, or similar.

A ***shared SDV service*** is a service using SDVs owned and operated by a fleet operator (public or private) that transport individuals or a private group of individuals (up to 6 passengers) from origin to destination. For instance, a driverless taxi service could be an example of a mobility concept based on shared SDVs. The vehicles are shared whilst rides are not shared.

A ***shared-ride SDV service*** is a service based on SDVs that are owned and operated by a fleet operator (public or private) and were trips are intended to be shared by a group of people with similar transport needs in terms of space and time (e.g. travelling from similar origins and destinations in the same time-period). An example would be a shared driverless taxi service that is a driverless taxi service with shared rides (when there are other passengers to share the ride with). I.e. the taxi might pick-up other users during the ride. Both the vehicles and rides are shared.

A ***self-driving bus service*** is a self-driving bus service that can carry more than 6 passengers. Vehicles and rides are shared. Smaller busses (~6-20 passengers) are referred to as shuttles.

3 Classification frameworks for system level impacts

SDVs might impact the transportation system and society in many ways. Some impacts are directly related to the vehicle themselves, e.g. vehicle operations and emission levels by individual vehicles. Other impacts arise from SDVs interacting with other traffic and the infrastructure, e.g. network capacity and intersection capacities. Furthermore, there are impacts related to wider societal structures, such as impacts on land use, economic development and public health that occur over longer time-periods when SDVs, the transport system and society interacts.

The different types of impacts do not take place in isolation from each other. System impacts are interlinked by directly or indirectly affecting each other. Also, different impacts can have common causes and be influenced by the same variables. This complexity result in impacts that are not simply observable outputs from the transportation system, they are also variables embedded in the system being both affected by, and affecting, other impacts and variables. To make holistic studies of system level impacts of SDVs there is a need to have an overview of how different types of impacts can be classified and how they are related to each other.

To systematically study and model system level impacts from SDV there is first a need to identify and classify impacts into *impact categories*. The number of potential impacts from SDVs is large and without clear definitions of categories for different types of impacts it is very challenging to perform any structured studies of system-level impacts. There is also a need to identify and specify the relationships between the impact categories in to a *conceptual model* that captures the systemic behavior of interrelated impact categories.

This chapter of the report reviews two *impact classification frameworks* for automated driving (Innamaa et al. 2017; Milakis, Van Arem, and Van Wee 2015). Both impact classification frameworks also consist of conceptual models addressing impact mechanisms and the causal links between automated driving and its impacts to some extent. Thus, they both go a bit beyond classifying impacts into categories but in this report, they are denoted as impact classification frameworks. The two impact classification frameworks are first described one by one and are then compared and analyzed.

3.1 Trilateral impact assessment framework (TIAF)

The organization Trilateral Working Group on Automation in Road Transportation is currently developing an impact assessment framework for automated driving. The ambition is to create a global high-level harmonization of impact assessment in the field of automated driving and a methodology for assessing field trials and pilot projects of ARTS. The work with the framework is ongoing but a tentative version of the impact assessment framework has been published (Innamaa, Smith, Barnard, et al. 2018). A book chapter with related material has also been published (Innamaa, Smith, Wilmink, et al. 2018).

The TIAF covers the following topics related to impact classification

- ARTS classification. How the ARTS can be described and classified to enable meta-analysis of results from field trials.
- Impact classification. How different types of impacts from automated driving can be categorized into broad impact categories.
- Relations between impacts. How the different impact categories are interrelated and affecting each other.
- Classification of impact mechanisms. How to categorize the mechanisms causing impacts from automated driving.
- Recommendations for experimental procedure. How field trials should be designed to enable systematic impact assessment.
- Recommendations for data sharing. How data from different field trials should be organized and shared among organizations.

The review of the TIAF in this report focuses on the first four of the above-mentioned topics.

The TIAF is based on a systems' thinking approach where focus is on identifying the main impact categories and causal links between them and the introduction of automated driving. A simplified diagram of a systems thinking approach to impacts of automated driving presented in Innamaa, Smith, Wilmink, et al. (2018) is shown in fig. 5. The arrows between the impact categories indicate causal links and the direction of causality.

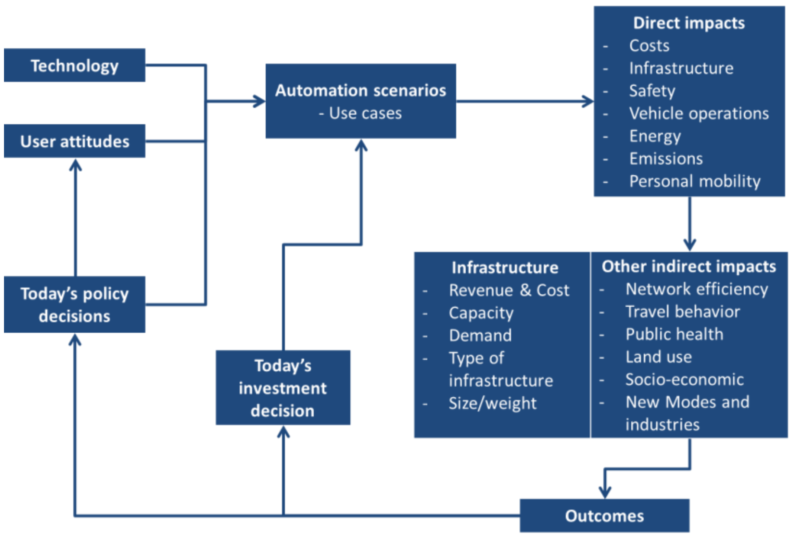


Fig. 5 – An illustration of the systemic approach for impact assessment of automated vehicles in the TIAF (Innamaa, Smith, Wilmink, et al. 2018, fig. 1). The arrows indicate causal relationships. The fig. show that driving automation and its impacts are part of a systemic structure.

The TIAF classifies impacts into direct impacts and indirect impacts. Direct impacts have a relatively clear causal relationship with the introduction of SDVs in the transportation system. Usually these direct impacts are being generated in the short-term and are relatively easy to measure, capture and assess since they are directly observable or measurable. Indirect impacts occur over time as a result of direct impacts in combination with external effects, typically under complex causal interactions with many different variables. Indirect impacts are broader and have longer time lags before they are occurring than direct impacts. Generally, indirect impacts are more challenging to observe and capture than direct impacts. For instance, they are usually more long term than feasible time frames for pilot projects and field tests, which the TIAF was developed for. This usually makes pilot projects and field tests unsuitable for observation of indirect impacts. The relative relations between the direct and indirect impact categories in the TIAF depending on their time frame and spatial resolution are summarized in fig. x, which is a slightly modified version of Innamaa, Smith, Barnard, et al. (2018, fig. 1).

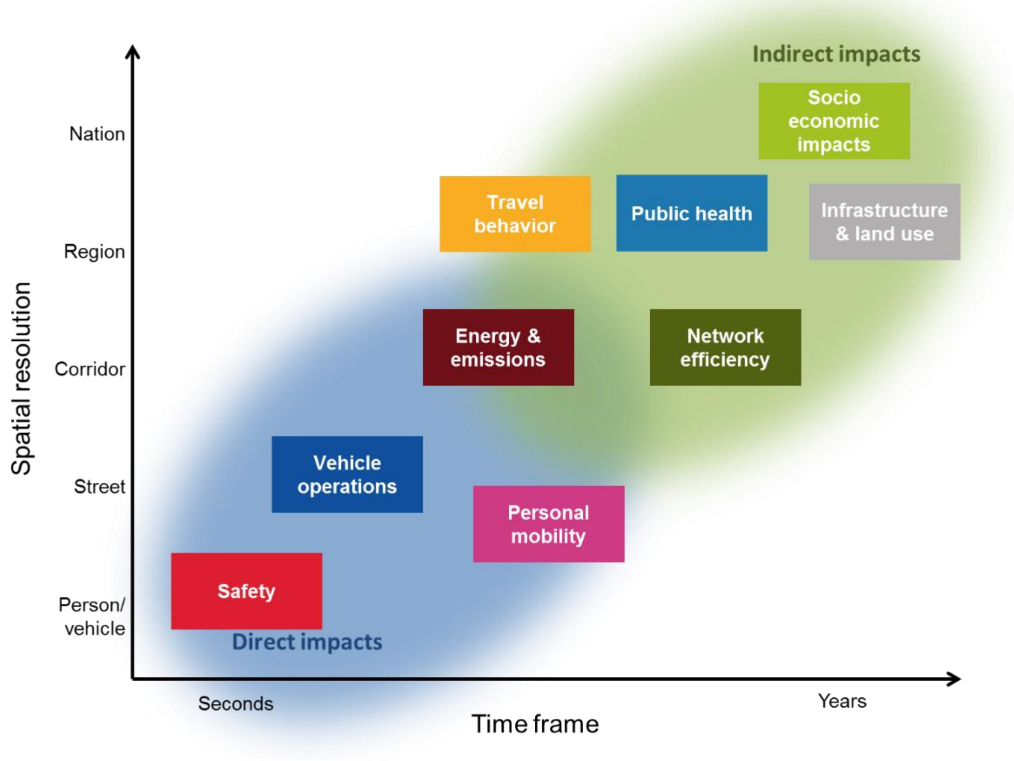


Fig. 6 - A classification of direct and indirect impacts dependent on their time frame and spatial resolution (own editing and interpretation based on Innamaa, Smith, Barnard, et al. (2018, fig. 1). Note that the classification of direct and indirect impacts take place on a gliding scale.

The TIAF provides general definitions of the constitution of each impact category. It gives a brief description and suggestions for KPIs that could be used to represent the impacts. The below descriptions of the impact categories are directly cited from Innamaa, Smith, Wilmink, et al. (2018, 10–13) in order to present their description and classification of the impact categories. Note that there are some differences from fig. 6 in naming and classification of impacts.

Direct impacts

Safety: Ultimately, safety is measured as fatalities, injuries and property damage for vehicle occupants and other road users. Other road users may include pedestrians, bicyclists, slow-moving vehicles, construction workers and first responders. Nearly all automated vehicles applications, ranging from SAE Level 1 collision avoidance systems to SAE Level 5 SDVs, have potential safety impacts. A challenge with safety assessment is that actual crashes are rare events; therefore, proxy measures are often used. These measures may include selected traffic violations, instances where a human driver must take control of the vehicle, exposure to near-crash situations, and responses to near-crash situations.

Vehicle Operations: Vehicle (control) operations include acceleration, deceleration, lane keeping, car following, lane changing, gap acceptance: all affect road (network) capacity. Relevant automation applications include those which provide longitudinal and/or lateral control with respect to the road and other vehicles.

Personal Mobility: Mobility from a user's standpoint includes journey quality (comfort, use potential of in-vehicle time), travel time, cost; and whether the travel option is available to someone (e.g., a non-motorist). It also includes equity and accessibility considerations. The higher levels of automation will have the most significant impacts, by providing mobility for non-motorists and enabling multi-tasking. These include first mile / last mile services and accessibility applications. Challenges in measuring personal mobility impacts include the variety of sub-populations who may be affected in different ways, and the difficulty in assessing the actual value of automation to a person based on survey data. (Travel time indicators are generally evaluated at the network level – rather than the individual level.)

Energy / Environment: The energy and emissions category include both the energy consumption of the vehicle through a driving cycle, and tailpipe emissions of pollutants including greenhouse gases. The direct energy/emissions impacts come from the change in the driving cycle. Changes in vehicle propulsion (e.g., electric vehicles) or an impact on total kilometers/mileage driven may also have a significant effect on tailpipe emissions.

Cost: Once an automation application has moved out of prototyping, and into production, what is a reasonable estimate of the capital and operating cost for the technology? This is important for assessing the future business case for deployment and ultimate usage.

Indirect impacts

Network Efficiency: Network efficiency refers to lane, link and intersection capacity and throughput in a regional transport network. It also refers to travel time, delays and travel time reliability. Improved safety may improve network efficiency via reduced incident delay. Also, changes in vehicle operations (e.g., car following) will affect network efficiency. In addition, changes in transport modes or mileage driven by AVs affect it, too.

Travel Behavior: A traveler may respond to automated transport options, including new service offerings, by changing travel behavior. There may be more or fewer trips. Modes, routes and destinations may change. Higher-level automation applications that have a significant effect on personal mobility or labor could have a significant effect on travel behavior.

Asset Management: Assets include physical and digital infrastructure of road transportation. Automation may affect these infrastructure assets required in several ways, though significant uncertainty still remains in this area. In particular, there may be changes in trip making. If travelers respond to automation by making more trips, more road capacity may be needed. On the other hand, if automation leads to greater use of shared, rather than owned, vehicles, the infrastructure required for parking may be reduced. Changes in trip making may affect the assets required

Public Health: Automation may impact the health (physical and mental) of individuals and entire communities, via safety, air pollution, amount of walking and bicycling, as well as access to medical care, food, employment, education and recreation.

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> *Land Use: Automation may affect the use of land for transport functions (e.g., parking, road geometry) but also in general. These longer-term land use changes may include community planning i.e. location and density of housing, road network design, employment and recreation. The number of factors that contribute to long-term land use changes makes distinguishing those changes contributed by automation a particular challenge.*
>
> *Socio-Economic Impacts: Improved safety, use of time, freight movement, travel options (for motorists and non-motorists), public health, land use and effects of changed emissions (including climate change) will have longer-term economic impacts. Automation may also have substantial impact on labor markets and industries. Assessment in this area continues to evolve.*

In the TIAF some causal relations and interlinks between the impact categories are described (Innamaa et al. 2017, fig. 1). Innamaa et al. (2017) present these on a general level and use a high-level visual representation with arrows indicating the direction of causality between the impacts. There are several causal links both from direct to indirect impacts, but also from indirect impacts to direct impacts. Some impacts have direct interdependencies. One example is safety that affects vehicle operations and safety also being affected by vehicle operations. There are multiple interrelations forming feedback loops. The framework does not provide any explicit information about which time scales the interactions take place on, but it is clear that there is a variety of different time-scales involved which gives rise to complex dynamic feedback behavior in the system. The causal relations between the impacts as presented in the TIAF are summarized in fig. 7 and table 3 below. Fig. 7 provides a holistic overview of all the relationships presented in the TIAF whilst table 3 summarizes what is affecting and affected by the respective impact categories one by one.

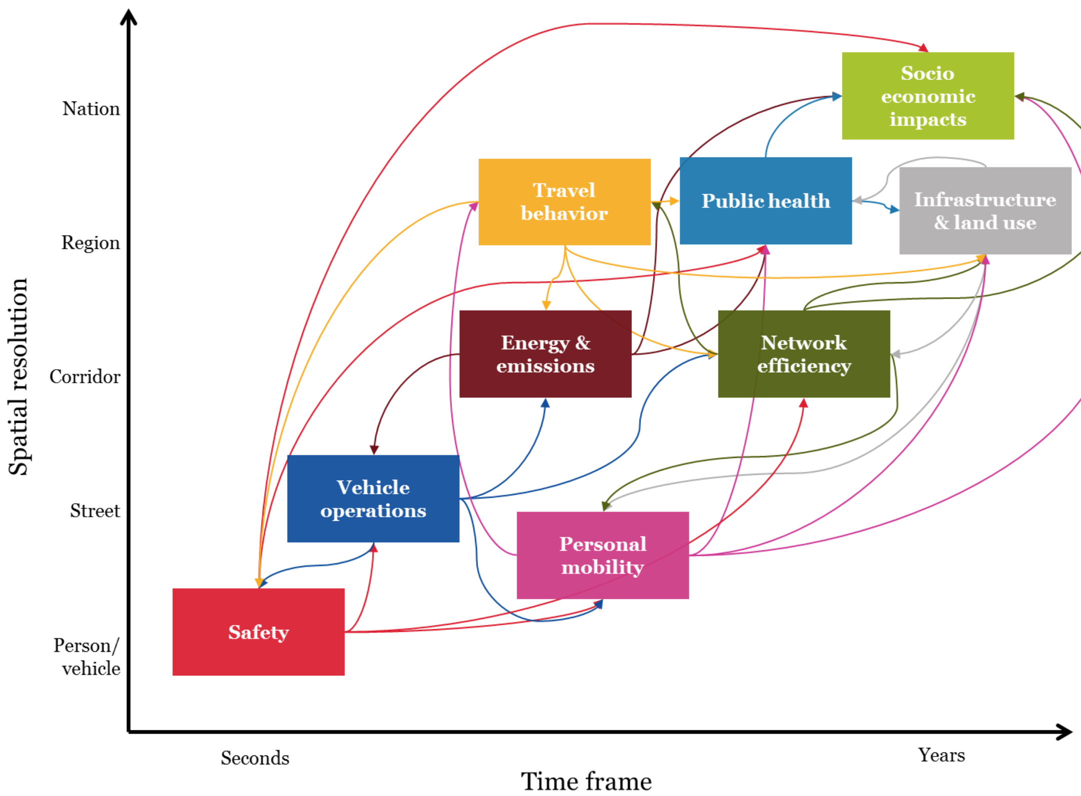
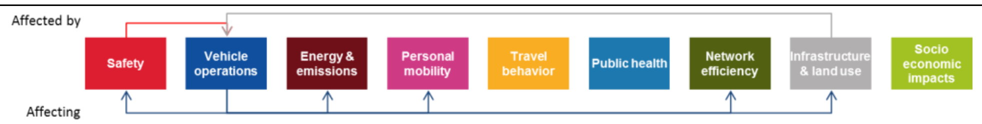
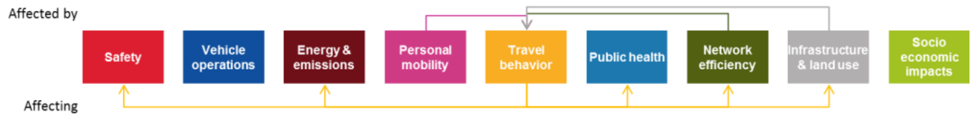
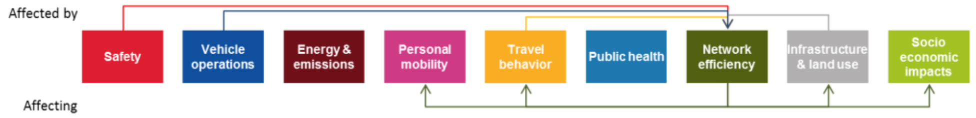
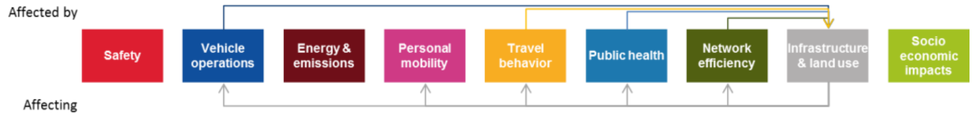


Fig. 7 - holistic overview of the causal relationships between the impact categories presented in the TIAF (Innamaa, Smith, Barnard, et al. 2018, fig. 1). The arrows indicate causal relationships

and the color of the arrow show what impact category the arrow is originating from. The fig. show that there are significant interrelations operating in loops among the impact categories.

Table 3 - Causal relationships between impact categories as outlined in Innamaa, Smith, Barnard, et al. (2018, fig. 1).

Impact category	Impact relationships
Safety	
Vehicle operations	
Energy & emissions	
Personal mobility	
Travel behavior	
Public health	
Network efficiency	
Infrastructure & land use	
Socio economic impacts	

System impacts are generated and affected by multiple individual effects. For instance, safety impacts from SDVs can be composed of several effects from multiple factors caused by changes in vehicle operations, factors caused by changes in travel behavior and so on. To decompose and map the specific factors influencing system impacts, the TIAF to base the assessment on nine impact mechanisms. The idea behind the impact mechanisms is that they represent aspects that are directly affected by automated driving and give rise to system impacts. The impact mechanisms are thereby not impacts as such but they are events causing impacts. An impact mechanism can therefore be interpreted as a root cause for impacts. The purpose of the impact mechanism categories is to have a systematic way of categorizing the cause for the impacts and from the impact mechanisms derive causal links for how the system impacts are generated. A chain of such links is called impact path. By mapping the individual impact paths from their origin to the impact path to the system impact it is possible to systematically identify and analyze individual and specific aspects of the impacts. The proposed impact mechanisms by TIAF are the following.

1. Direct modification of the driving task, drive behavior or travel experience
2. Direct influence by physical and/or digital infrastructure
3. Indirect modification of SDV user behavior
4. Indirect modification of non-user behavior
5. Modification of interaction between SDVs and other road-users
6. Modification of exposure / amount of travel
7. Modification of modal choice
8. Modification of route choice
9. Modification of consequences due to different vehicle design

For a more in-depth explanation of the mechanisms see Innamaa, Smith, Barnard, et al.(2018).

The TIAF stresses that different applications of automated vehicles might have different ways of generating impacts and that the set and combinations of impact mechanisms operating might be very different for different automated vehicle applications and concepts. Therefore, it is not possible to recommend a general approach that can be applied to all types of impact assessments. TIAF recommends that specific applications for automated vehicles are studied separately by systematically mapping potential impact mechanisms and direct and indirect impacts for the specific SDV application. TIAF recommends this mapping to be done with diagrams linking the impact paths which then could be expanded to a causal loop diagram (TIAF does not explicitly call these diagrams causal loop diagrams). These diagrams should contain variables representing the impact mechanisms and the affected impact categorizations along with arrows and symbols (+ or -) representing the causal links and direction of causality between the variables. An example causal loop diagram from the framework is shown in fig. 8.

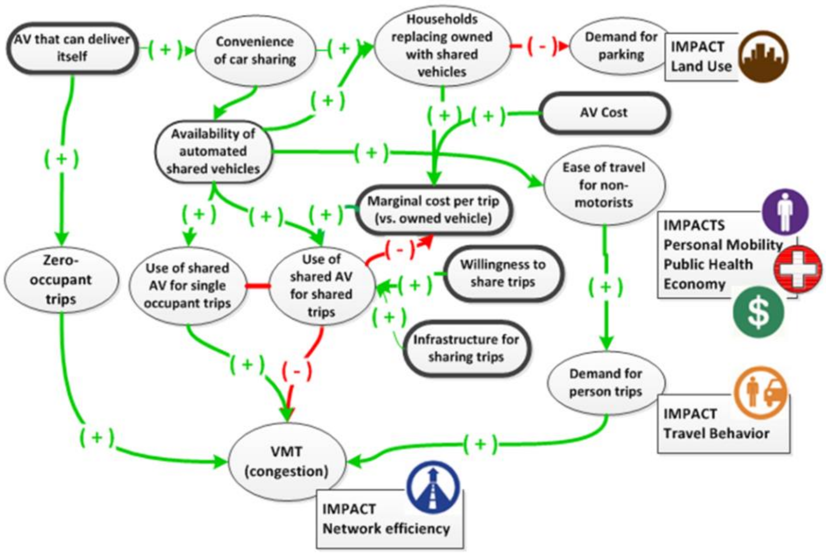


Fig. 8 - causal loop diagram showing potential impacts of a driverless vehicle (Innamaa, Smith, Barnard, et al. 2018, fig. 2).

3.2 The ripple effect of automated driving

Milakis, Van Arem, and Van Wee (2015) present a framework for categorizing impacts from vehicle automation. The impact framework is based on a ripple effect model where events are being spread out in waves from the center cause, just like a rock being thrown into water ripples out. The framework is further discussed and presented in de Almeida Correia et al. (2016). A slightly adjusted framework has also been used as a basis for a systematic literature review that has been performed by the same research group (Milakis, van Arem, and van Wee 2017). The impact framework is built on placing vehicle automation in the center, representing the component from which the impacts are generated, see fig. 9. The level of automation (and thus the capabilities and functionality of the vehicles) is determining what impacts might happen and how drastic the generated impacts will be. From the center, impacts are sequentially spread outwards in the framework from 1st order, via 2nd order out to 3rd order.

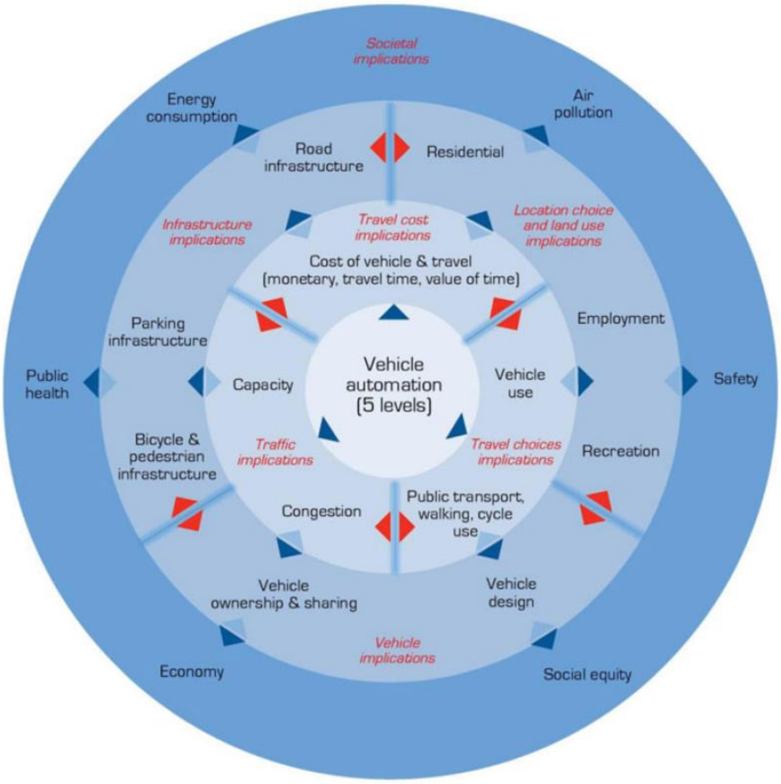


Fig. 9 - the ripple effect of automated vehicles in which impacts from automated vehicles is assumed to propagate over time by a cumulative process (Milakis, van Arem, and van Wee 2017, fig. 1).

The 1st order impacts are the short-term impacts induced by vehicle automation. They are categorized as impacts on traffic, travel cost and travel choices. Traffic impacts include free flow capacity, flow stability, capacity drops, etc. Travel cost includes the value of time, the monetary cost and the effort of travel, i.e. the components of generalized travel cost (de Almeida Correia et al. 2016).

The 2nd order impacts are mid-term and consists of impacts on vehicle ownership and sharing, vehicle design, location choices and land use, infrastructure (de Almeida Correia et al. 2016). For instance, improved roadway capacity might reduce the need for road infrastructure investments. SDVs might also lead to fewer parking spaces in central urban areas due to self-parking capabilities.

3rd order impacts are long term, wider societal impacts. These impacts are usually very complex and are to a large extent the cumulative effect of 1st and 2nd order impacts (de Almeida Correia et al. 2016). This is a similar classification to the one developed in TIAF (compare with direct and indirect impacts) even though the terminology and perspective is slightly different.

In (Milakis, van Arem, and van Wee 2017) a more detailed description of the specific impacts in the framework. The article also presents assumptions on mechanisms for how the listed impacts might be generated and furthermore a literature review with a synthesis of results from existing literature.

3.3 Comparison between TIAF and the ripple effect of automated driving

First of all, it should be acknowledged that the TIAF and the ripple effect of automated driving are developed for different purposes. TIAF has been developed mainly for being a conceptual tool to support the design and assessment of field trials for SDVs. It is also meant as support for policy makers to perform long-term scenario-based planning (Innamaa, Smith, Barnard, et al. 2018). The basis for analysis of impacts in the TIAF is a bottom-up approach where results from initial field trials can be used to analyze potential wider impacts of a large-scale implementation.

The ripple effect of automated driving was developed to fill a gap for a holistic framework regarding categories for impact from SDVs categories in the scientific literature available at the time (de Almeida Correia et al. 2016). The different purposes of the frameworks have implications for what focus they have and thus also their strengths and limitations.

3.3.1 What is causing impacts – the root component

Both impact categorization frameworks are based upon a perspective where (variations of) driving automation or automated driving is placed in the center of the system and being the direct cause of impacts. In this section in the report, this driving automation/automated driving in the center of the system is referred to as the framework's "root component". The two frameworks have different approaches on how to define the root component and the role of the root component the impact classification framework.

The ripple effect of automated driving framework puts driving automation the root component. Different kinds of driving automation are differentiated by using the SAE levels 1-5 (Milakis, van Arem, and van Wee 2017). No further specification of the root component is done.

In TIAF the root component is being described as a system constituted not just of automated vehicles but also other aspects of the mobility concept (or ARTS) that the automated vehicles are a part of. The TIAF states that at least the aspects summarized in table x of the root component should be specified (Innamaa, Smith, Barnard, et al. 2018):

Table 4 domains of the ARTS that should be specified according to TIAF

Domain	Description
Vehicle type(s)	Passenger vehicle (private or shared), mini bus, large bus, small truck, large truck, etc.
SAE level and specific driving automation functions	
Function of the mobility concept	Transportation of people, goods or a combination of the two Long vs. short distance trips Other specifications of the transportation task to be performed by the mobility concept
Operational design domain	Geographical location Level of mapping required Type of road (# of lanes, markings, etc.) Type of intersections Design speed Weather/meteorological conditions Etc.
Penetration rate of the mobility concept	Are operations performed among non-automated vehicles? Relations with other vehicles and mobility concepts
Environment in which the mobility concept is operating within (ODD)	

The TIAF puts more focus on the root component whilst the ripple effect of automated driving does not explicitly emphasize the importance of detailed specification. However, this difference is probably mainly a result of the different purposes of the frameworks. Both frameworks are addressing driving automation on any of the SAE levels 1-5.

It can be assumed that the impacts from driving automation are highly dependent on the mobility concept they are a part of and on the specific conditions for the wider societal scenario in which the mobility concept is operating within. Hence, specifying only the SAE level for an automated vehicle is too general and not a description detailed enough for ambitious impact studies.

3.3.2 Impact categorization and scope

Both impacts are intended to be used for analysis of automated vehicles from a passenger transport perspective. They do not explicitly address how they can be used to categorize impacts from road freight transport.

The two frameworks are to a large extent consistent in terms of scope of what impacts are included and there are no major deviations in types of impacts that are included between the frameworks.

When comparing the explicit classification of impacts in direct/indirect impacts, as in TIAF (Innamaa, Smith, Wilmink, et al. 2018) and 1st, 2nd, 3rd order impacts as in (Milakis, van Arem, and van Wee 2017) there are clear differences between the two frameworks. The two impact categorization frameworks have different approaches for how the categorization is performed. TIAF's classification of impacts is performed on a slightly higher level with broader categories whilst Milakis, Van Arem, and Van Wee (2015) for some categories are defining more narrow and specific impacts in sub-categories.

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In fig. 10 similar impact categories are color matched and then sorted from left to right from direct/1st order to indirect/3rd order impacts.

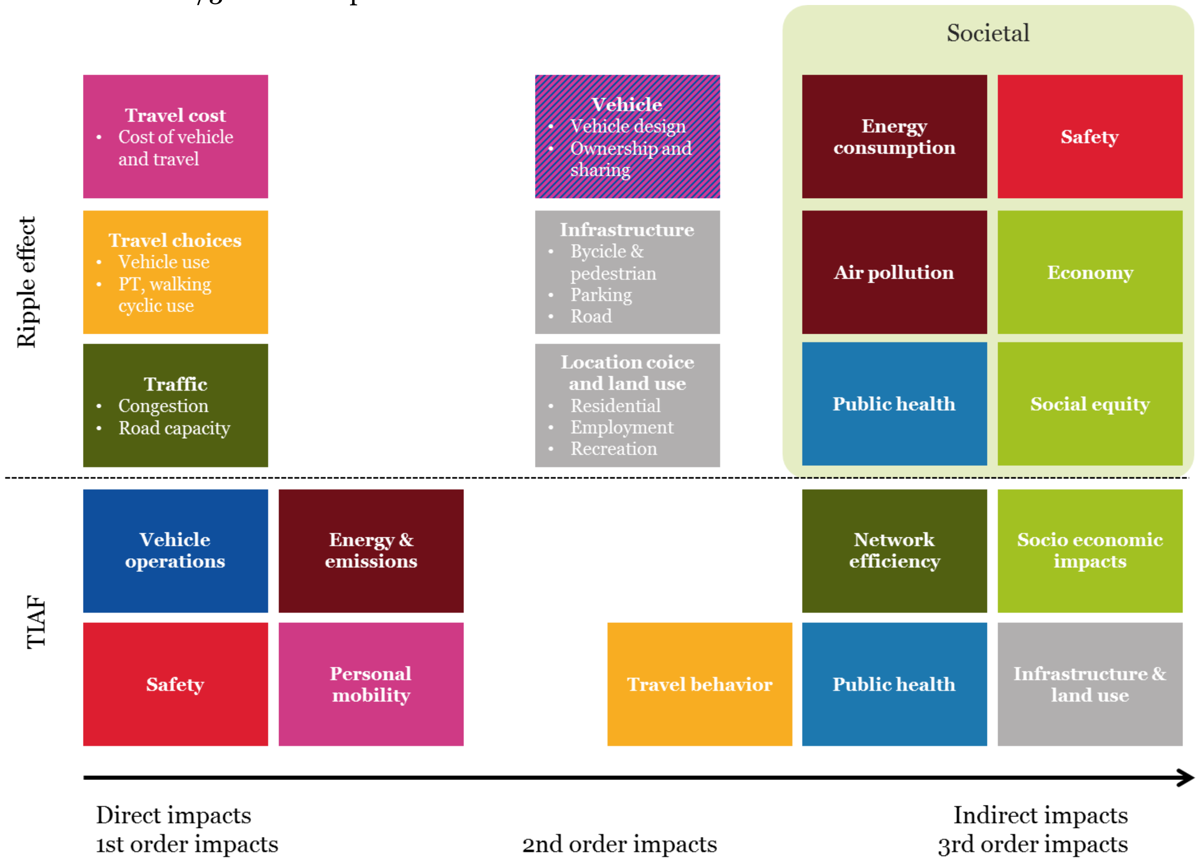

Fig. 10 – Impact categories in the impact classification frameworks and sorted on if they are presented as direct/1st order impacts, 2nd order impacts or indirect/3rd order impacts. The impact categories are color coded so that similar impact categories in the different framework are having the same color.

For instance, safety is classified as a direct impact in TIAF but in the ripple model classified as a 3rd order impact. There a several inconsistencies of this type between the frameworks. One explanation might be that ripple effect model is based on categorizing the ripples in three areas where the impacts have their major impact: 1st order: vehicle user/driver/traveler →2nd order: infrastructure and traffic → 3rd order: wider society.

TIAF does instead focus on the relationship of impacts in terms of time-lag and spatial proximity in relation to the root component which yields a different categorization.

Likely, the different classification of impacts in to 1st/2nd/3rd order impacts compared to in direct/indirect impacts (e.g. if safety is classified as a direct impact or a 3rd order impact) would not influence the result of an impact assessment if the motivation behind the choice of classification is clear. How this classification is to be done is likely to a large extent a matter of taste since it is a purely conceptual differentiation and grouping of different types of impacts. With regards to what impacts are included the two frameworks are more or less harmonized. Based on fig. 10 the two categorizations of impacts have been mapped against each other. The mapping, presented in table 5, show the relationships between the different terminologies for impact categories applied in the two frameworks.

Table 5 - mapping of impact categories from the two frameworks based on what aspects they are included. Slightly different terminology is applied in the different frameworks, but the included

aspects and scope of the impact categories are possible to map against each other in a consistent way.

TIAF		Ripple effect of automated driving
Safety		Safety
Vehicle operations		Vehicle design
Energy and emissions		Energy consumption
		Air pollution
Personal mobility		Vehicle ownership and sharing
		Travel cost
Travel behavior		Travel choices
Network efficiency		Traffic
Public health		Public health
Infrastructure and land use		Infrastructure
		Location choice and land use
Socio economic impacts		Economy
		Social equity

3.3.3 Impact mechanisms and causal relations between impacts

The ripple effect of automated driving assumes that the causal links between the impacts mainly are propagating from the center of the model and then causing higher orders of impacts when accumulated over time. The 2nd and 3rd order impacts are therefore the cumulative result of the impacts of lower order. Milakis, Van Arem, and Van Wee (2015) is problematizing this and discusses that interactions between impacts do occur and that they might impact each other in various ways. Some of these potential effects operating between impacts are discussed by de Almeida Correia et al. (2016). Also, the orders of impacts are not necessarily separated in time. For instance, emission levels are directly affected by of the introduction of vehicle automation if it leads to more efficient driving and thereby be occurring simultaneously as 1st order impacts (Milakis, van Arem, and van Wee 2017). One example of the limitations of the ripple effect model in terms of causal dependencies (and the assumed direction of causality from 1st to 2nd and 3rd order impacts) is the relationship between travel cost and travel behavior (1st order impacts) and vehicle ownership and sharing (2nd order impacts). The impact of the vehicle ownership and sharing form is likely to have significant impact on travel cost and travel behavior, thus there is a strong causal link going from a 2nd order impact to 1st order impacts which is not compatible with the concept of a ripple effect model.

The TIAF approach has a higher focus on making the interactions between impacts and the impact mechanisms explicit. The TIAF authors highlight that the impacts are feeding back to the system in several ways. In the simplified model in fig. 5 this feedback is shown as influence on investment and policy decisions. Without acknowledging and accounting for this type of feedback any impact assessment will only give a limited understanding of the long term of impacts on the transportation system. Having an understanding of these feedback mechanisms is therefore crucial in the study of system level impacts. The TIAF also outlines how the different impact categories are interacting with each other, as illustrated in table 3. Even if the causal interactions are presented on a general level it provides a foundation and line of reasoning that can be further elaborated in further studies on system-level impacts of SDVs.

3.3.4 Strengths and limitations

The two studied frameworks are not two competing or opposing approaches. Rather they are in many ways similar and both are based on a set of shared principles.

- The introduction of (various forms) automated driving is the root cause of any system impacts

- Impacts from automated driving propagates over time with complex causal interactions that are interlinked with more general societal factors

- Many of the impacts are interacting with each other in those causal interactions

- There are some impacts that are more direct and others that arise over time as a result of the propagation and accumulation over time.

- Some impacts are directly influencing the individuals using and interacting with SDVs, while some impacts influence larger groups of people and some impacts influence the whole society.

Both of the impact classification frameworks are conceptual and very general in their nature. Hence, they are, at least conceptually, able to be applicable to many different types of future scenarios with a vast range of potential SDV mobility concepts and societal environments. Any formal modeling or simulation of system-level impacts require significantly clearer definitions of impacts and detailed understanding on the causal links between impacts.

In terms of scope of what impact categories are included in frameworks both frameworks cover the wide span of system-level impacts that are of interest to analyze. The impact categories are to a large extent consistent between the two frameworks and there are only small differences in how the impact categories are specified.

There are some differences between the frameworks that can be summarized in to two main areas:

- **Causal relationships**: The TIAF has a more explicit focus on outlining specific causal interactions between impact categories on a whilst the ripple effect of automated driving uses the more conceptual ripple effect model to explain causal interdependencies between impact categories.

- **Intended application of framework:** The ripple effect of automated driving is mainly a conceptual framework for systematically categorizing impacts. It suitable for research synthesis and literature reviews (as in(de Almeida Correia et al. 2016; Milakis, van Arem, and van Wee 2017). The TIAF is intended to be used as a framework for field trials and pilot projects and, in addition to the impact categorization framework, also recommends, a structure for how to specify the root component, potential KPIs to quantify impacts, study design considerations for field trials, etc.

The identified strengths and limitations with the two frameworks are summarized in table x.

Table 6 - Identified strengths and weaknesses between the TIAF and the ripple effect of automated driving as a tool for creating a conceptual model.

	TIAF	Ripple effect of automated driving
Strengths	• Explicitly addresses impact mechanisms and causal links between impact categories • Provides suggestions for specific KPIs to evaluate impacts from pilots with SDVs and ARTS	• Provides a holistic overview of impact categories • Provides well elaborated qualitative assumptions on impact mechanisms

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	• Practical guidelines for how to collect and analyze data from field trials	
Limitations	• Limited to passenger transport • Some inconsistencies in impact definition within the framework (e.g. cost is sometimes described as its own impact category and sometimes included in other impact categories)	• Limited to passenger transport • Sequential propagation of impacts (as assumed in the ripple effect model) is likely not a realistic causal model • Root component not clearly addressed

4 Review of literature on impacts of SDVs

This chapter summarizes a selection of papers in the academic literature that reviews and synthesize system-level impacts of SDVs from a holistic perspective. The chapter is organized as a summary of the main content of the selected literature paper by paper. The order of the paper presentation in this section is organized so that papers covering many impacts categories are presented first and papers covering a smaller number of impact categories are presented later. Table 7 presents the order of the papers and a summary of their scope in terms of impact categories. The first time a new paper is summarized the reference to it is bolded.

Table 7 - order of presentation and focus areas for the reviewed papers

Paper	Mega trends	Role of public sector	Tech. & market development	Usage & response to SDV	System-level impacts covered								
					Safety	Vehicle operations	Energy and emissions	Personal mobility	Travel behavior	Network efficiency	Public health	Infrastructure and land use	Socio economic impacts
(Milakis, van Arem, and van Wee 2017)					x	x	x	x	x	x	x	x	x
(Litman 2018)			x	x	x	x	x	x	x	x		x	x
(Fagnant and Kockelman 2015)		x		x	x		x		x	x		x	x
(Williams et al. 2017)	x	x	x		x	x	x	x	x	x		x	x
(Cavoli et al. 2017)		x	x	x	x		x	x		x	x	x	x
(Farah et al. 2018)												x	
(Fraedrich et al. 2018)				x				x				x	x

The only identified peer-reviewed systematic literature review covering a wide range of system-level impacts is **Milakis, van Arem, and van Wee (2017)**. They present a mapping of results from existing literature structured according to the impact categorization in the ripple effect of automated driving (see section 3.2 of this report for a summary of the ripple effect of automated driving). The literature review in the paper covers peer-reviewed academic literature published before February 2017 and serves as an inventory of literature. The included literature was identified by searching for indexed literature with a set of general keywords for automated driving (e.g. vehicle automation, SDV(s), etc.) together with specific keywords for each of the impact categories. The keywords used for the literature search for the various impact categories are summarized in fig. 11. There is no selection of literature based on approach or methodology (e.g. simulation, surveys, field trials, etc.).

Implication	Keyword
Travel cost	Cost, travel time, comfort, value of time, travel time reliability
Road capacity	Capacity, congestion, traffic flow
Travel choices	Travel choice(s), mode choice(s), travel behavior, travel distance, vehicle kilometers traveled, vehicle miles traveled, modal shift
Vehicle ownership and sharing	Vehicle ownership, car ownership, vehicle sharing, car sharing, ride sharing, shared vehicle(s)
Location choices and land use	Location choice(s), land use(s), accessibility, residential density, urban form, urban structure, urban design
Transport infrastructure	Road infrastructure(s), road planning, road design, intersection design, parking infrastructure(s), public transport service(s), transit service(s), cycle lane(s), cycle path(s), sidewalk(s), pavement(s)
Energy consumption and air pollution	Fuel, energy, emissions, pollution
Safety	Safety, accident(s), crash(es), risk, cyberattack(s)
Social equity	Social equity, social impact(s), vulnerable social group(s), social exclusion
Economy	Economy, productivity, business(es)
Public health	Public health, human health, morbidity, mortality

Fig. 11 - Keywords used to identify literature for various impact categories in (Milakis et al. 2017 Table 1).

Milakis, van Arem, and van Wee (2017) Impact categories that are (relatively) well-studied with many identified papers are safety road capacity, travel cost (comfort and travel time). Impact categories with few or no identified papers are travel cost (fixed cost of automated vehicles), value of time, location choice and land use, energy consumption (long term), air pollution (long term), economy, public health, and social equity. Thus, the existing literature (as of January 2017) tend to be biased toward direct impacts.

Milakis, van Arem, and van Wee (2017) also present a synthesis of results from the reviewed literature to provide an indication of what impacts SDVs might have. Since the studies included in the review in vary in scope with different types of mobility services, geographies, SDVs, assumptions, different study approaches, etc. it is not easy to draw any general conclusions on the effects from driving automation as a general phenomenon. The results from the included literature was synthesized impact category by impact category. In table 8 the results presented in Milakis, van Arem, and van Wee (2017) are summarized.

Table 8 - potential impacts for SDVs as presented in Milakis, van Arem, and van Wee (2017). + indicates increase/positive, - indicates decrease/negative, ? indicates uncertain or limited evidence

First order implications	Effect	Second order implications	Effect	Third order implications	Effect
Fixed cost of automated vehicles	+	Vehicle ownership	-	Fuel efficiency	+
Travel comfort	?	Location choices and land use	?	Energy consumption (long term)	?
Travel time	-	Transport infrastructure	-	Emissions	-
Value of time	?			Air pollution (long term)	?
Highway capacity	+			Safety	+
Intersection capacity	+			Social equity	?
Vehicle kilometers travelled	+			Economy	?
				Public health	?

Litman (2018) covers a broad range of topics related to automated driving such as: market introduction and diffusion of SDVs, benefits and costs associated with automated driving, impact on travel demand and planning considerations related to land-use, road infrastructure investments and public transport interactions. The paper is oriented towards passenger transport and reviews both academic and non-academic literature. The paper is written with mainly decision makers and transport planners as the intended audience to highlight some of the key concerns related to driving automation. Litman (2018) stresses that there is a wide range of potential problems associated with driving automation that are not discussed properly since the public discussion on the topic is focusing almost exclusively on the potential benefits with automated driving.

Regarding market introduction two main factors are assessed: technology development for SDV and the market demand. Litman (2018) highlights the fact that the fleet turnover rate for motor vehicles is usually rather slow. It is likely to expect that SDVs probably will not constitute a major share of the vehicle fleet until 20-30 years after the initial market introduction of SDVs. To give a rough estimation of potential deployment rates of SDVs, a comparison with experiences of the deployment of existing vehicle technologies (automatic transmission, air bags, hybrid drivetrain vehicles, subscription vehicle services and vehicle navigation services) is presented in the paper. With the assumption that SDVs become available on the market at 2020 an estimation of the rate of sales, travel and vehicle fleet penetration is presented. The results of this estimation are presented in fig. 12.

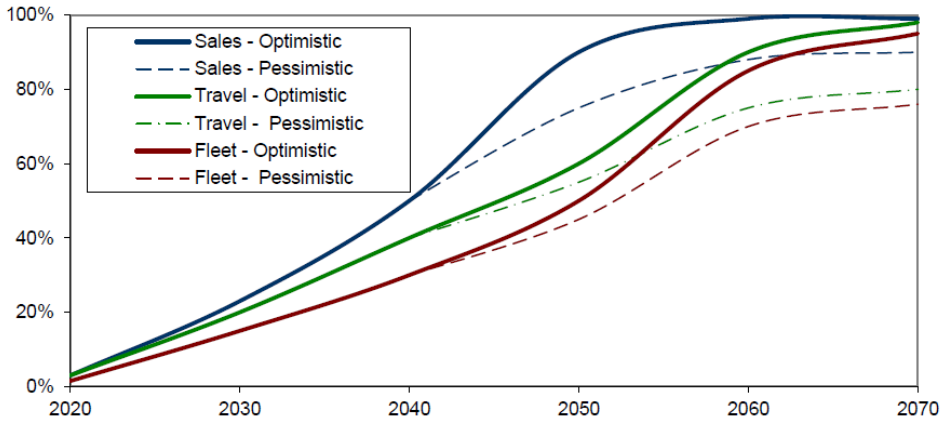

Fig. 12 - estimated penetration rates of sales, travel and vehicle fleet composition for SDVs in (Litman 2018, fig. 1) given that SDVs become available on the market in 2020.

On the topic of benefits and costs of SDVs Litman (2018) separates the discussion in internal (benefits and costs that the user of the SDV is exposed to) and external (benefits and costs that others are exposed to). Some of the internal benefits presented are reduced stress of drivers/users which can be translated to a lower value of time for road travel, mobility (and accessibility) for non-drivers and reduced driver costs for shared SDV services and shared-ride SDV services which reduces the financial cost of traveling.

Regarding internal financial costs Litman (2018) discusses that SDVs will have high purchase prices relative to conventionally driven vehicles due to the increased amount of technology in the vehicles. SDVs that are not privately owned but operated as a part of shared SDV service or a shared-ride SDV service will induce additional costs such as: increased cleaning, fleet management, business overheads and empty trips that ultimately need to be covered by the users of the service. However, these costs are most likely countered by the increased vehicle utilization. By summarizing findings in the literature regarding potential costs for various types of SDV services Litman (2018) presents the following estimation (with numbers calculated based on the average exchange rate from USD to SEK 2017).

- For privately owned SDV, the average cost will initially be in the range of 4,3 SEK to 6,4 SEK per vehicle km driven. This number will likely drop to around 3,2 SEK to 5,3 SEK per vehicle km over time.
- Costs for shared-ride SDV services will when introduced likely be around 4,5 SEK per vehicle km driven with the potential to be reduced to around 1,9 SEK per vehicle km at 2035 (Jonhson and Walker 2017). In the literature estimates as low as 0.5 SEK per vehicle km can be found (Kok et al. 2017).
- As reference, the cost for other, existing, mobility services are: conventionally driven privately owned cars is in the range of 2,1 SEK to 3,2 SEK per vehicle km, taxi services 10,7 SEK to 16 SEK per vehicle km, ride-hailing 8 SEK to 13,4 SEK per vehicle km and public transport 1,1 to 2,1 SEK per km.

Without putting stress on the absolute numbers but rather the relative difference between them, Litman (2018a) concludes that results indicate that that the cost for privately owned SDVs will be higher than for a conventionally driven privately owned cars but lower than ride-hailing and taxi services. The cost for shared-ride SDV services will likely be significantly lower than for privately owned SDVs and might be in the same range as today’s cost of private car usage.

Internal costs which are not financial that Litman (2018) discusses are new types of safety risks and crashes such as system failure, platooning risks, higher travel speed and larger exposure to car travel. Also, the risk of personal data (e.g. location data) that are generated and used by SDVs being compromised by hacking or other security breaches is a highlighted factor. Another internal cost is the concept of *access anxiety* (a concept introduced by Grush, Niles, and Baum (2016)). Access anxiety is the stress that SDV users feel about the uncertainty of whether the automated driving system will be able to perform automated driving of the vehicle during the whole trip from origin to destination. It is similar to the concept *range anxiety* in the electrical vehicles sector where users are stressed about whether the battery capacity will be enough to reach the destination or next charging stop. This is a factor that might induce new types of stress for SDV users and reduce the rate of market uptake of SDVs.

Traffic safety is a very important aspect of the internal implications of automated driving which might bring both benefits and costs to automated driving. Litman (2018) stresses that the claims in some literature that SDVs will lead to a net reduction of traffic accidents 90% by eliminating all accidents where the human factor is contribution are overly optimistic. First, it is likely that SDVs will add new types of accidents that does not happen with conventionally driven vehicles. Secondly, if automated driving induces more traveling and vehicle kilometers travelled, the absolute number of accidents might increase even if the relative accident rates are reduced.

The external benefits and costs presented by Litman (2018) spans over several areas but can be summarized as follows:
External benefits

- Increased safety can reduce insurance costs and crash risks
- Increased road capacity due to coordinated traffic and more efficient traffic flow
- Reduce parking costs because of reduced need for parking close to destinations
- Increased fuel efficiency as a result of improved vehicle operations and collaborative driving
- Supports vehicle sharing since SDVs and driverless vehicles might reduce barriers to implement attractive vehicle and ride sharing services

External costs

- Additional risks to others due to new accident types occurring (e.g. automated driving system failure)
- Increased traffic problems because of increased vehicle travel volumes and sprawl related to reduced generalized travel cost
- Reduced security due to new IT system-related threats, e.g. hacking and IT-terrorism
- Social equity concerns if the adaptation and associated direct benefits and indirect benefits are distributed unevenly among social groups
- Reduced employment for professional drivers (e.g. truck and bus drivers)
- Reduced focus and support for other transport options, e.g. public transport, due to an (overly) optimistic debate on the benefits of SDVs

There are significant uncertainties regarding which of the potential impacts of SDVs that will be realized and how large these impacts will be. There are two important factors determining the direction of development. The first one is how SDVs will interact with travel volumes. There are several potential mechanisms that could make SDVs both induce and reduce travel. Table 9 summarizes some of the implications automated driving might have on travel volumes.

Table 9 - summary of potential mechanisms generating impacts on total vehicle travel related to SDVs. Based on (Litman 2018)

Increased vehicle travel	Reduced vehicle travel
Travel by existing non-drivers	Shared vehicle services reduce fleet size and vehicle use
Reduced value of time and generalized travel cost	Self-driving bus services can improve public transport services and induce modal shift from car travel
Empty rides due to pick-ups and re-positioning	Reduced traffic risk and parking spaces in city centers can create a more attractive urban environment and denser cities
Increased sprawl → longer trips	Reduce some auxiliary vehicle travel, e.g. roaming for parking
Reduced congestion and operating costs induced more travel	

The other important factor highlighted by Litman (2018) relates to the operating model of SDVs, i.e. the mobility services that they are utilized within. The question of mobility services is also coupled with the impacts on vehicle travel volumes. Many of the benefits associated with automated driving requires a shift from privately owned vehicles to shared SDV services or shared-ride SDV services.

Fagnant and Kockelman (2015) discuss the potential impacts of SDVs on the transportation system and society based on existing academic and non-academic literature. The paper is mainly focusing on passenger transport but briefly addresses freight transportation and it covers impacts on areas such as safety, congestion and traffic operations, travel-behavior impacts, changes in VKT and vehicle ownership, fixed costs for SDVs, congestion and parking infrastructure.

The most distinguishable contribution in the paper is an order of magnitude estimation of potential socio-economic benefits from driving automation in the U.S. Three scenarios with varying levels of market penetration rates of SDVs (10%, 50% and 90%) are used. The estimation is based on SDVs' impacts on safety (crash cost savings), congestion (fuel cost savings), and land use (parking savings). The paper estimates the annual direct economic benefits and annual socio-economic benefits per SDV to be $2000/$2960, $1610/3320 and $1760/$3900 for 10%, 50% and 90% market penetration respectively. However, the assumptions behind the calculation are rudimentary and the results are highly indicative.

Williams et al. (2017) present an extensive assessment of potential impacts of CAVs. The paper is the final report from a research project investigating planning considerations for Texas' highway infrastructure with regards to CAVs. The work is based on a literature review of state of the art and future development for CAVs which formed the basis for further analysis of impact of CAVs on:

- Passenger travel
- Commercial and freight transportation
- Travel forecasting
- Transport planning process

The main findings and discussions in the paper for the first two of these topics are summarized in the following paragraphs.

With regards to passenger travel, Williams et al. (2017) highlight the importance of assessing CAVs in the light of concurrent societal and transportation trends. Sharing economy and the gig economy are stressed as trends that could be highly influential on passenger transportation. Shared SDV services and shared-ride SDV services could impact areas such as: auto ownership rates, vehicle utilization and parking requirements, generalized travel costs and number of short-trip making. The impact from CAVs on modal shifts and VKT is likely to a large extent dependent on whether these SDV services are embedded in a multi-modal mobility as a service concept or not.

Williams et al. (2017) examines how travel behavior could be impacted by the introduction of SDVs. Several potential impacts on various aspects of travel behavior are presented in the paper. These impacts are summarized in table 10 indicating that SDVs generates impacts that can lead to both increased and decreased number of trips, changed timing of trips and inducing new trips by people previously not having access to vehicles.

Table 10 – Summary of potential impacts from SDVs on travel behavior presented in (Williams et al. 2017)

Cause	Mechanism	Impact on travel behavior
Improved safety of SDVs compared to conventionally driven vehicles	Fewer accidents on the roads lead to less non-recurrent delays. This will improve the capacity in the network and increase reliability.	People tend to make more trips due to increased road system performance (rebound effect). Enables optimal route planning.

Improved safety of SDVs compared to conventionally driven vehicles	Increased feeling of safety during road travel and trust for the SDV. This can be interpreted as a reduction of the generalized travel cost.	People tend to make more and longer trips
Shift from privately owned vehicles to shared SDV services	Higher exposure to actual monetary travel cost. Private vehicle ownership to a large degree consist of capital costs which are seen as a sunk cost by the owner, hence not being perceived as a cost related to specific trips. With mobility services with SDVs it is likely that the user of the service will be exposed also to capital costs during usage of the service.	Reduced or modified trips due to higher perceived generalized travel cost.
Shift from privately owned vehicles to shared SDV services	Vehicle access with SDV is not dependent on vehicle ownership. Hence vehicle access and mobility will increase for elderly, children, etc.	New trips made by new vehicle user groups.
Shift from privately owned vehicles to shared SDV services	Shared SDV services operated as ARTS enables system level optimization of traffic flows which could enhance the actual capacity in the transportation network. This can be interpreted as a reduction of the generalized travel cost.	People tend to make more and longer trips
Driverless vehicles eliminate the need of chauffeuring (e.g. parents driving their kids to activities)	Without the need of negotiated time use for vehicles, driverless vehicles might be utilized to serve non-drivers during times when a driver is not available.	Timing of trips can be influenced. However, this impact requires concurrent other factors of societal and location-based behavior.
Removal of human driving task for SDVs	Reduced value of time hence reduced generalized travel cost	People tend to make more and longer trips

The potential impacts from SDVs summarized in table 10 might contribute to further impact on location choices and urban form. Williams et al. (2017) discuss that reducing generalized travel cost, mainly by increased comfort and performing productive tasks in the vehicle instead of driving, might induce sprawl. On the other hand, the more “transparent” exposure to costs directly associated with specific trips because of a shift from privately owned vehicles to shared SDV services could have the opposite effect and lead to densification.

Another topic covered by Williams et al. (2017) is the operational domain for SDVs. The implementation of SDVs will be highly dependent on the operational domain since it influences the required sophistication of the driving automation system in the vehicles and how the required levels of safety and system performance can be met. The paper presents four different mobility services with automated vehicles that highlights how the operational domain and different types of SDV can be combined to create different mobility services.

Regarding road freight transportation, Williams et al. (2017) stress two important trends to consider in relation to SDV implementation. The first one is the increased demand for freight transport. For the US, predictions state that freight transport movements will increase with 42% by 2040 to facilitate the predicting population growth and economic growth. The second is the changing delivery patterns of consumer goods mainly driven by the increase of e-commerce. Increasing volumes together with higher requirements on fast deliveries and higher flexibility regarding time and location for delivery create a more complex distribution system. This influence both long-haulage and last mile logistics. It might also impact land use, for instance with large-scale distribution center owned and operated by a consortium of multiple companies or by the public sector. Another factor highlighted is the pressing lack of professional drivers which is a potential key driver for introducing driving automation in the freight sector.

Williams et al. (2017) summarize state of the art of automation in several phases of the supply chain. The deployment of driving automation has so far almost exclusively been in parts of the supply chain where the operating domain is in a closed, private, environment. There are driverless mining trucks, driverless trucks in warehouses and driverless drayage tractors pulling containers in harbor terminals. SDV applications for long-haulage and last mile logistics that takes place on public roads in open operational domains are not as mature yet. The paper presents a summary of several solutions for automated vehicles that are not SDVs for long-haulage such as platooning and advanced driver assistance systems. For last-mile logistics three potential applications are presented in the paper: an SDV for mail and parcel delivery with an operator (i.e. driver) walking outside of the truck managing the deliveries, a driverless parcel delivery vehicle with some form of delivery boxes traveling to the customers' home or other preferred delivery location, unmanned aerial vehicles for small parcel deliveries.

System impacts from automated vehicles in freight transport are discussed briefly in (Williams et al. 2017). There are several factors that can have different implications for road network capacity. Platooning could potentially free up road space because of the reduced headway between trucks. However, it might be that SDVs for freight transport requires separated lanes which might reduce the available road capacity for other vehicles. Platooning also has a positive impact on fuel consumption and fuel related emissions. Regarding safety impacts, the potential benefits if driving automation reduces the likelihood of accidents might be larger than for cars and smaller vehicles. Due to higher masses involved, accidents involving trucks have higher odds of resulting in fatalities and severe injuries than accidents between cars. Also, accident sites with truck-crashes often take longer time to clear and return to normal traffic operations compared to car accidents thus causing worse non-recurring delays.

The Department for Transport in the UK have let perform a scoping study to identify questions regarding social and behavioral aspects of SDVs to address in further planning work (Cohen, Jones, and Cavoli 2017) . One part of the study is an extensive literature review by **Cavoli et al. (2017)** that is published as a separate paper. The review covers many topics related to SDVs ranging from underlying trends, technology and market development, usage & diffusion, impacts from SDVs, the role of the public sector, etc. The approach for the review was to identify both academic and grey literature by searching five literature databases. The literature selection process yielded a final set of literature of 432 papers focusing on social and behavioral aspects. Cavoli et al. (2017) coded these sources on a topic basis to get an overview of the frequency of the studied topics. Fig. 13 show the frequency of the topics in the included set of literature. Road safety, legal issues and public perception seem to be the most studied topics while mobility as a service, accessibility and public health seem to be less studied.

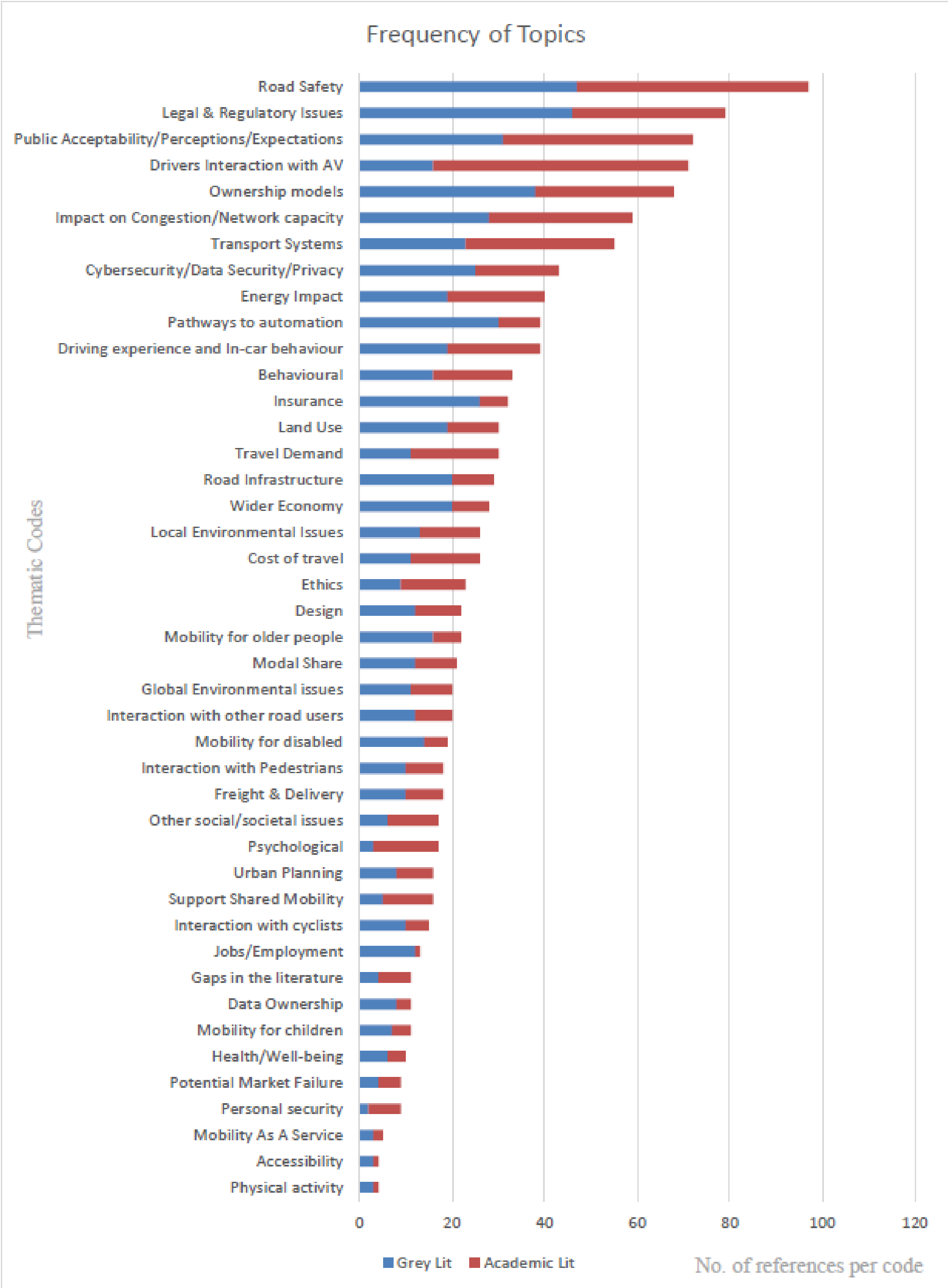

Fig. 13 - Frequency of topics in the reviewed literature by (Cavoli et al. 2017, fig. 6)

The findings regarding system level impacts of SDVs that are presented in Cavoli et al. (2017) are broad in scope but on a relatively shallow level of analysis.

Regarding the impact from SDVs on traffic flow, two critical opposing forces are described in the literature according to Cavoli et al. (2017). One force is the potential increase in travel demand and vehicle kilometers travel due to reduced value of time and generalized travel cost and the potential for new user groups to travel by car. On the other hand, ARTS have the potential of increasing road capacity if efficiently utilized. Cavoli et al. (2017) state that the knowledge regarding actual net effects on traffic flow is very limited and likely very scenario-dependent making it difficult to draw any general conclusions.

Impacts from SDVs on economy and employment are the most evident on SDV and transport related industrial sectors (i.e. not socio-economic benefits in a wider sense). The positive impacts as stated by Cavoli et al. (2017) are crash savings, new jobs in the automotive and adjacent technology industries, new jobs in the electronics manufacturer sector. Four sectors are expected to be negatively influenced by SDVs: sectors specialized in road accident prevention and recovering, the public sector (lower parking revenues and less demand for traffic enforcement officers), traditional car manufacturers and sectors dependent on current mobility system (e.g. car repair centers, parking industry, etc.).

Cavoli et al. (2017) highlight two impacts on land use from SDVs. One is that in scenarios with high levels of shared SDV services there are drastic potentials for reduced land use for parking. The other one is that the reduced value of travel time for SDV trips might in long-term lead to urban sprawl with several potential negative secondary effects (increased VKT, emissions, congestion, etc.).

The findings from the literature presented by Cavoli et al. (2017) indicate that impacts on energy and emissions from SDVs are very different depending on what level of the system being studied. Papers focusing on the capabilities of single SDVs or ARTS have identified several potential positive impacts on energy consumption and emissions because of driving automation, especially with high penetration rates of SDVs:

- Driving automation enables improved eco-driving which can reduce energy consumption
- Improved safety with driving automation can enable lighter vehicle constructions with reduced energy consumption as one consequence
- Improved traffic flow due to collaborative driving enabled by V2V communication
- Reduced need to search for parking space reducing the energy consumption
- Reduced need for street lighting

Studies with wider system delimitations that spans beyond individual SDVs or ARTS indicate that the net impact on energy and emissions depends mainly on changes in VKT induced by SDVs. Potential increases in VKT will likely outweigh the positive impacts discussed in the previous paragraph. Cavoli et al. (2017) use two archetype scenarios two broadly describe the two main underlying assumptions in the reviewed papers. One is a “business as usual” scenario where private vehicles persist as the main usage form of conventionally driven vehicles as well as for SDVs. The other is a “shared mobility” scenario where car-ownership rates have declined and been replaced by emerging on-demand shared services with SDVs. In the business as usual scenario several factors contribute to increase road travel volumes: reduced GTC for travelling with SDVs, the ability for new user groups to travel with road vehicles, empty rides by SDVs, etc. The “shared mobility” scenario might mean a smaller increase, or even a decrease, in travel volumes compared to today. Another highlighted factor is the matter of fuel and propulsion system for SDVs which obviously will have a large influence on impacts on energy consumption and emissions. Many of the papers covered in the review assume that SDVs will be electric vehicles.

Road safety is, as shown in fig. 13, a well-studied topic and is in the literature in general highlighted as one of the major benefits from SDVs. The potential improvements in safety with SDVs mainly stem from that most road accidents are attributed to human error. There is a consensus in the scientific literature is that safety will most likely be improved by introducing SDVs, the question debated is on how large the improvement will be. Another topic with uncertainty is regarding what penetration rates of SDVs are required in order to realize significant safety benefits. Several scholars also stress that new types of accidents will emerge due to the so far unknown interaction with SDVs and other road users.

Farah et al. (2018) review the scientific literature with the purpose of summarizing the state of the art and gaps for research on physical and digital infrastructure for CAVs. The reviewed literature was selected by database searches and literature published in English after the year 2000. The main conclusion regarding the current research status is that physical infrastructure is much less studied than digital infrastructure. The review of literature on physical road infrastructure is presented in two main categories: geometric road design and structural pavement design.

Regarding geometric road design, Farah et al (2018) presents impacts and features SDVs might have and enable on future roads:

- When all vehicles are SDVs and cooperative, lane width and road width could be reduced. In some cases, additional lanes could be created, potentially to be used for platooning. In areas with managed lanes (e.g. high occupancy vehicle lanes) these could be used as pilot and initial deployment lanes as dedicated lanes for SDVs to achieve separation between SDVs and conventionally driven cars.
- For highways, SDVs might enable new designs. One example is lanes for SDVs with higher speed allowances (e.g. 160 km/h) with dedicated off-ramps. Medians could be used for other transport modes or other purposes (e.g. park space) since SDVs are assumed to have drastically smaller risks of experiencing lateral steering incidents.

Farah et al. (2018) also present some features of the physical road infrastructure required to enable SDVs:

- Lane assistance system factors seem to be the most important. These include lane markings and their visibility and harmonization.
- For collision avoidance systems, infrastructure-based warning systems, including required V2I communication systems, is the most important feature, especially in complex urban environments. Pedestrian and cyclist protection should be prioritized.
- Regarding speed control systems, lane markings and clear and consistent traffic signs are important factors.

On structural pavement design, the discussion is focused on increased rutting because of decreased lane width and improved lateral control. There are simple ways of preventing this by programming SDVs to distribute among the width of the road which. However, this would compromise the potential reduction of lane and road width.

Farah et al. (2018) cover the digital infrastructure required for connected SDVs and particularly for cooperative SDVs in three topics: sensors, connectivity and cloud; digital maps and road database; exact positioning of the vehicle.

Regarding sensors, connectivity and cloud services and computation it is discussed that data from existing infrastructure sensors (e.g. traffic cameras) could provide SDV’s perception system with information omitted by the on-board sensors. For instance, this information could be used to identify other vehicles or pedestrians hidden by objects blocking the range of the sensors. Other infrastructure support system that might be used, but that are probably not necessary, for SDVs and driverless vehicles are: V2I communication with roadside units for speed limit signaling and assisted merging and lane changing, magnetic striping for lane keeping, and information on ques and traffic signal information.

Digital maps and road database are regarded as crucial to support the operations of SDVs. Farah et al. (2018) presents some of the required features such as: highly detailed lane geometry information that is highly accurate and richly attributed. There are proposals on how digital road databases for SDVs could be designed (e.g. Moon Lee (2016)). Other papers have explored the potential of improving the in-vehicle driving automation by V2I communication providing information about pavement surface quality and other road information, weather conditions, and information about physical, static objects to reduce in-vehicle processing for sensor data interpretation.

To enable cooperative SDVs, exact geo-positioning of vehicles in relation to the infrastructure is a key challenge. There are several approaches on how to achieve this. One approach is to use fixed gantries along the road infrastructure for the in-vehicle sensors to calibrate against. A more novel approach is to use GPS for vehicle positioning (see Knoop et al. 2017).

Farah et al. (2018) highlight that in most research on infrastructure implications of SDVs the penetration rate of SDVs is assumed to be 100%. The requirements on the infrastructure to facilitate mixed traffic between conventionally driven vehicles and SDVs are barely researched. Some of the specific research questions identified by the paper authors are:

- Could SDVs enable shorter merging distances and shorter on/off ramps? And would mixed traffic require longer merging sections and ramps compared to today?

- What is the trade-off between decreased lane width and increased rutting?
- What is the required level of road pavement for SDV sensors and other equipment to function properly and should road authorities guarantee a certain level?
- What are the requirements of digital maps and should national road authorities provide digital maps?
- Are infrastructure-based sensors crucial for safe operations of SDVs? If so, which infrastructure-based sensor data is crucial?
- How should communication between vulnerable road users and SDVs take place? When and how does is it required?

Fraedrich et al. (2018) present a systematic review of the literature on how SDVs could affect urban planning and the built environment. Existing research show that mobility and the built environment are closely interconnected and mutually influencing each other. However, the research on SDVs have so far to a little extent investigated the link between SDVs and land use. Most studies on this topic has been in the form of consulting experts in the field. Fraedrich et al. (2018) identify five topics in the existing scientific literature that are summarized below:

Changes in road infrastructure and signage. Studies indicate that the requirements on planning of the physical road space will change due to the introduction of SDVs. One example is the need of drop of zones near housing and work-places. The requirements for physical signage might reduce considerable due to V2I capabilities. With high penetration rates of connected SDVs some intersections might not need any physical signage.

Effects on parking infrastructure. Self-parking abilities for SDVs could reduce the need for parking spaces near passenger trip destinations. Self-parking could also improve efficiency in parking houses, but it is unclear if these efficiency gains will prove economically relevant. A potential development highlighted by several studies is that parking spaces over time will be relocated from dense urban areas to more sparsely populated areas. Some studies reason that since parking spaces in urban areas are expensive it might be more economically reasonable for an SDV to roam around empty than parking. Shared SDV services resulting in increasing utilization rates might significantly reduce parking requirements. Simulation studies indicate that reductions of parking space of around 15% might be possible if privately owned conventionally driven vehicles are replaced by shared SDV services.

Interactions with pedestrians and cyclists. Some studies suggest that when SDV technology have matured the trust of pedestrians and cyclist will be higher towards SDVs than for conventionally driven vehicles under the assumption that SDVs will always be driven correctly. This could improve the situation for cyclists and pedestrians. On the other hand, intersections with less physical signage and more drop of zones for SDVs might worsen the situation

Potentials for redevelopment of land-use. The possible impacts from SDVs on road infrastructure design and parking space creates opportunities for redevelopment of urban space. Examples from the literature include broader and better sidewalks and bike paths, green areas and more dedicated space for public transport.

Land-use and relocation. Long-term impacts of SDVs could be associated with the relocation of residential locations. Economic research has studied how mobility, accessibility and location choices relates. Findings suggests that the location of households to some extent could be understood as a trade-off between generalized travel cost (consisting of the travel time, financial cost and marginal cost for a trip) and other economic factors (e.g. wages, house prices and living costs). One implication is that reduced generalized travel cost for households by improvements in the transportation system, i.e. by the introduction of SDVs, can be exchanged by relocating further away from urban centers where living costs might be lower. This mechanism exemplifies how the introduction of SDVs in the long run could induce more vehicle kilometers driven with associated emissions, energy consumption and congestion because of complex interactions with land use patterns.

5 Concluding discussion

5.1 General observations regarding the research area

In this section, observations based on the literature review about the current status of research area of system level impacts of SDVs are presented.

Most of the existing literature is oriented towards passenger transport applications of SDVs. Impacts from driving automation in freight and commercial transport is not studied to a large extent. Most of the research in the freight and commercial transport area is focusing on applications and barriers and benefits for adoption. Impacts, and the modelling of impacts from driving automation of freight and commercial transport have barely been studied. Another observation is that urban applications of SDVs are studied to a much larger extent than rural and long-distance travel applications. This is especially the case for simulation studies where mobility services with SDVs in urban centers is the typical case that is studied (Pernestål Brenden and Kristoffersson 2018).

A topic that is discussed to some extent but almost not studied in any detail is the relation between SDVs and physical and digital infrastructure. Within this topic a few common perspectives (although yet without clear answers) can be outlined: how will the physical infrastructure be impacted by the introduction of SDVs? What requirements on the infrastructure are there for (different types and variations of) SDVs to enable them to operate? What communication technologies and infrastructure are required for different applications within V2V and V2I?

Regarding which types of impacts that are more and less studied, both the systematic literature reviews by Milakis, van Arem, and van Wee (2017) and Cavoli (2017) indicate the same results. Road safety, road capacity and vehicle ownership forms are well studied. Less studied impacts are costs of ownership, public health, infrastructure, air pollution and accessibility.

Another area with a lack of knowledge is regarding the market adaptation and dynamics and mechanisms generating demand for the sales and diffusion of SDVs (in different type of ownership models). The gap exists both regarding passenger, commercial and freight transport. One promising approaches is to apply theories of innovation diffusion with system dynamics modelling for SDVs for personal use that has been applied by Nieuwenhuijsen et al. (2018). Regarding freight transport applications the mechanisms for implementation are yet to a large extent unexplored. Kristoffersson and Pernestål Brenden 2018 (2018) provide an indication on what the opportunities and barriers for adoption of driving automation in the freight sector are.

5.2 Methodological challenges and approaches for studying system impacts

The reviewed classification frameworks for system impacts can serve as a point of departure for further studies of system-impacts using various modelling approaches. Although the frameworks are conceptual and on a high-level of detail they can be used for (at least) two important purposes: a) as a classification of what system-impacts are relevant to consider when studying SDVs and b) as a conceptual model for outlining causal relationships between impact categories and how they influence each other.

One aspect of importance highlighted in TIAF is the need of clearly and systematically defining the study object when performing system impact assessments (Innamaa, Smith, Barnard, et al. 2018). This is an important but difficult task that requires further work. Unless when speaking in broad terms on an aggregated level it is not meaningful to talk about system-impacts of driving automation as such. Studies of system-impacts need to be performed with a specific SDV use case and scenario in focus (in itself being a sub-system consisting of driving automation technology, vehicles, users, business models, etc.). For instance, the system-impacts of driving automation on SAE level 4 is very different when used in privately owned SDVs or in a fleet used for shared ride SDV services. Fig. 14 illustrates a high-level concept for how such a classification can be made being inspired by Innamaa, Smith, Barnard, et al. (2018). The three grey boxes represent various levels of the sub-system of which system impacts that are of interest to study. On the lowest level (the darkest of the grey boxes) describes the SDVs, their driving automation capability, their drivetrain and other technical features and their intended use (passenger, goods, etc.). On the middle level the ARTS consisting of the SDVs and required physical and digital infrastructure is described. On the highest level the mobility concept that the ARTS is embedded within is described in terms of factors as: business model, service design, user aspects, market share, etc.

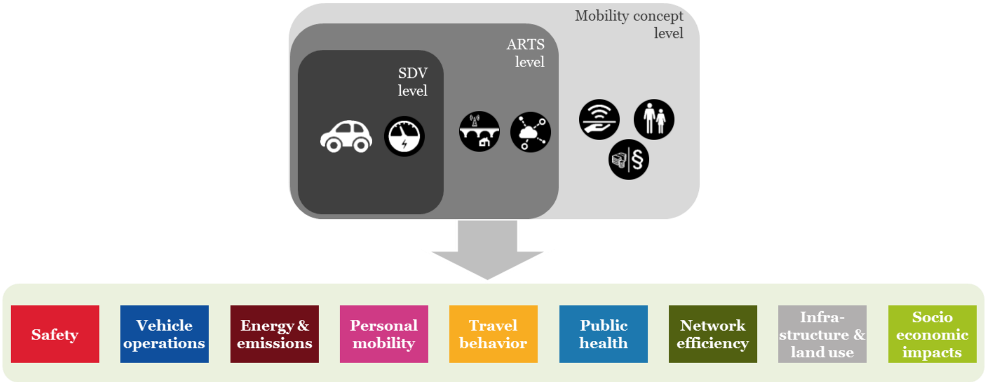

Fig. 14 - illustration of high-level concept of how the system under study can be described

The potentially most difficult challenge for assessing impacts of SDVs is to estimate net-effects on system-level. This has two main reasons. The first is the systemic behavior of impacts in the transport system. Since the introduction of SDVs on public roads will have several impacts that will affect other variables over time and be influenced by feedbacks many different opposing forces might operate on the variable of interest. This make the task of evaluating specific impacts challenging. As an example, let's consider a (over-) simplified model of the impact on traffic flow efficiency due to the introduction of connected and automated vehicles for passenger travel (fig. 15). In this simple example three different impact categories are involved (vehicle operations, network efficiency and travel behavior). Driving automation enables shorter headways between vehicles (at least at high penetration rates) and thus improving the effective capacity on the road. Collaborative driving may also improve the traffic flow efficiency by avoiding shockwave jams, coordinated braking and acceleration, etc. When the traffic flow efficiency increases, travelling times will decrease thus leading to a decrease in generalized travel cost (GTC). The reduced GTC over time likely leads to a rebound effect where travel volumes will increase which yields more vehicles on the road. The increased traffic might saturate the capacity of the road and thus reducing the traffic flow efficiency. Assessing the net impact on traffic flow efficiency thus require (at least) an assessment of the direct impact on network efficiency due to changed vehicle operations but also the indirect effects due to changes in travel behavior.

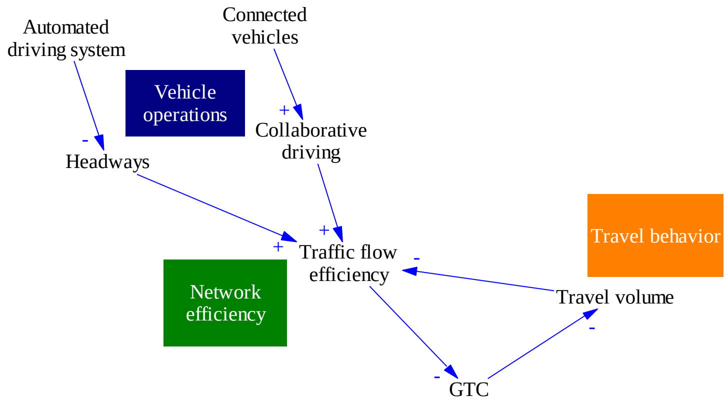

Fig. 15 - simplified model of the impact on traffic flow efficiency due to changes in vehicle operations and travel behavior

The second reason why net impacts are difficult to assess is that it requires the system boundaries for any impact assessment model to be efficiently defined. This is challenging since impacts on system level (e.g. on a national level) in the transport system to a large extent is determined by endogenous system behavior (Shepherd 2014). This mean that the system's critical levels are mainly a result of the dynamics within the system and not a result of exogenous variables (Richardson 2011). What is exogenous and endogenous in a model depends on the model structure and the defined system boundaries. Therefore, any system impact model needs to include critical dynamics within the model without growing the model complexity and scope in absurdum. In the literature, studies based on modeling methodologies assessing net impacts are scarce. However, one example is Wadud, MacKenzie, and Leiby (2016) which assess energy consumption by considering several direct impacts from driving automation on vehicle operations and long term impacts on vehicle design, changes in mobility services and travel demand. Although the study omits many potential endogenous feedbacks it still involves the understanding of and formal specification of several integrated complex causal relationships in several disciplines.

5.3 Examples of impact paths from the literature

In the literature there are a vast range of potential impacts and impact mechanisms from SDVs being discussed. Many of the holistic papers on SDV impacts confirm the systemic behavior of system impacts of SDVs that is stressed in TIAF. Based on impacts and impact mechanisms presented in one of the papers (Milakis, van Arem, and van Wee 2017), a causal loop diagram were developed to illustrate how impacts from automated driving are generated (see fig. 16). The illustration highlights that many effects are interconnected and that impacts should not be studied in isolation but must be understood as a sociotechnical system.

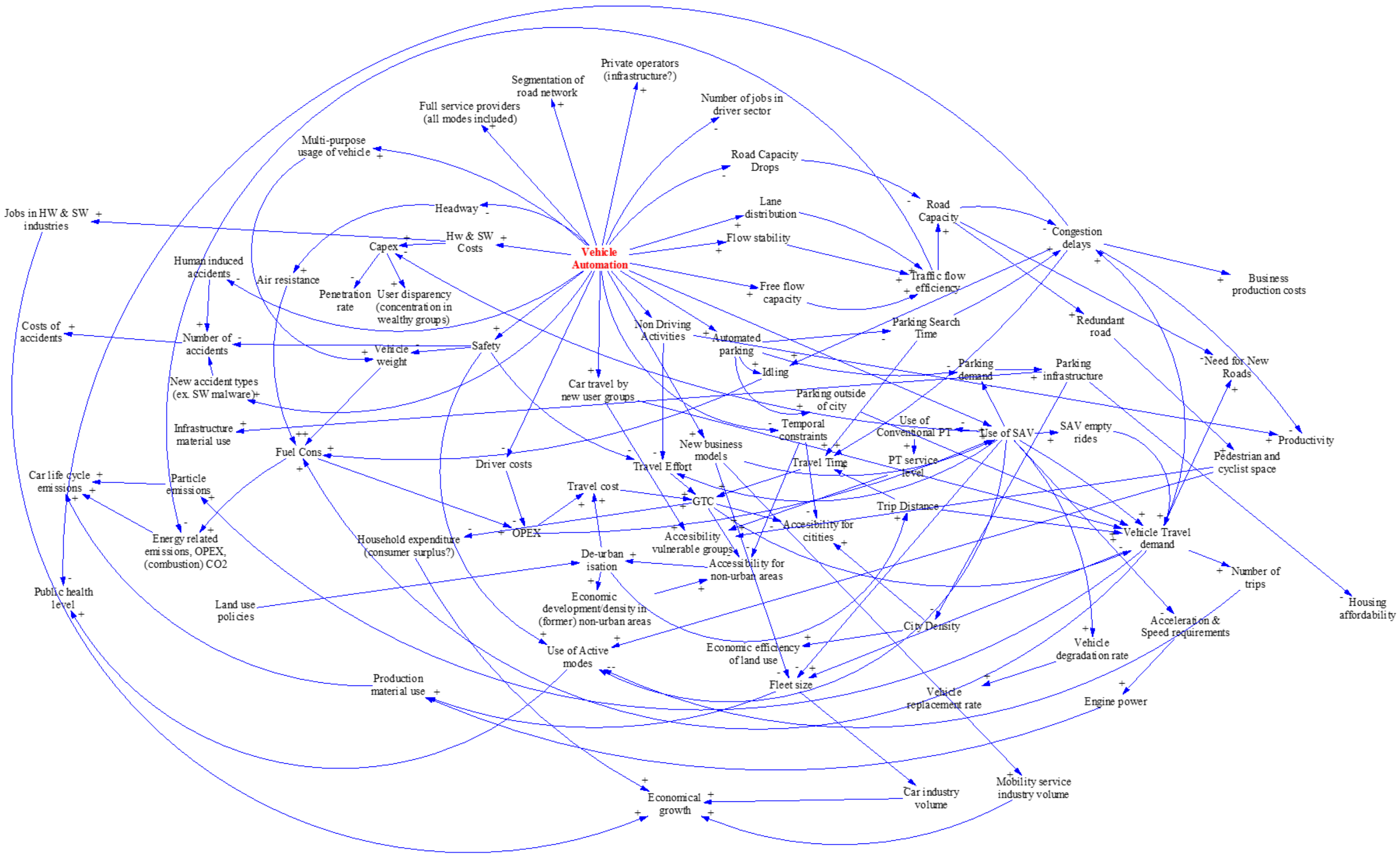

Fig. 16 - Variables and causal links explicitly described in Milakis, van Arem, and van Wee (2017a)

5.4 Main findings

This concluding section presents the main findings and their implications for further studies on system-level impacts of SDVs.

5.4.1 Terminology for connected and automated vehicles

The terminology proposed in this report is primarily intended as a tool to enable stringent analysis in this report when analyzing literature that use different terminologies. However, it might also serve as a basis for further elaboration and could be applied in forthcoming studies and papers as a broad classification tool. The main novelty of the terminology is that it differentiates between conditionally driverless and driverless vehicles.

There are some additional improvements that would be useful going further:

- Specify terms for vehicles that are: connected but not collaborative, automated but not self-driving or self-driving but not conditionally driverless, etc.

- How to account for remote operations by a human operator driving a vehicle via teleoperations. Is a remotely operated vehicle to be regarded as self-driving?

- Combine the terminology with specific use-cases for driving automation to better capture the practical implications of various types of vehicles are use cases. There are examples in the literature that can serve as a starting point for this work (Wachenfeld et al. 2016). The importance of specifying the use case for assessing system impacts is highlighted in TIAF.

5.4.2 Classification frameworks for system-level impacts

Two conceptual frameworks for classifying system-level impact were identified and compared, the Trilateral Impact Assessment Framework (TIAF) (Innamaa, Smith, Barnard, et al. 2018) and the ripple effect of automated driving (Milakis, Van Arem, and Van Wee 2015). Regarding the scope of the framework in terms of what types of impacts are considered relevant: safety, vehicle operations, energy and emissions, personal mobility, travel behavior, network efficiency, public health, infrastructure and land use and socio-economic impacts. Within these impact categories numerous sub-categories can be derived and there are impacts that are difficult to categorize as only one impact type. The impact categorizations in these frameworks could in future studies be used as a guiding definition for system-impacts. The frameworks are slightly different in how impact categories are classified. TIAF uses a gliding scale from direct to indirect impacts that depends on the automated driving activity's closeness to the impacts in space and time. For instance, this classification mean that safety is regarded as a direct impact (since an accident is an immediate consequence of the driving activity) and socio-economic impacts are regarded as indirect impacts (since the impacts are a cumulative result of many direct impacts taking place over long time and in a widespread geographical area). The ripple effect model categorizes impacts in 1st, 2nd and 3rd order impacts. The impacts in the higher orders are a cumulative result of the impacts in lower orders. A comparison highlighting the differences in the classification of impacts is presented in fig. 10.

Both frameworks highlight the importance of making explicit, understanding and evaluating the relationships between the impacts and how they propagate over time in a kind of "system of impacts" (see fig. 7). However, this impact system contains complex causal relationship that are not possible to specify in any detail on a general level since they are use-case and context specific. TIAF suggest that so called impact-paths are used where the causal mechanisms for how system impacts are generated are mapped step by step to create a detailed model of the system of impacts (Innamaa, Smith, Barnard, et al. 2018, 15–24).

For future system-impact studies the TIAF approach to use impact-paths to model the system of impacts is a useful starting point. The TIAF is presented as mainly being intended as a tool for evaluating field trials of SDVs but the approach in TIAF could also be used to perform conceptual model of system-impacts based on results from SDV simulations.

5.4.3 Review of existing literature

The review has a focus on existing literature reviews to give a broad overview of the status in the field. Regarding which types of impacts that are more and less studied, both the systematic literature reviews indicate the same results (Milakis, van Arem, and van Wee 2017a; Cohen, Jones, and Cavoli 2017). Fig. 6 present an overview of topics covered in the literature from Cohen, Jones, and Cavoli (2017). There are major uncertainties on what the net impacts of introducing SDVs will be. The lack of real data and uncertainties in predictions about adoption rates and usage of SDVs and the dynamics for the market introduction make it challenging to create realistic scenarios to study. Many existing studies on the impacts of SDVs are based on studying the potential impacts in extreme cases, for instance with 100% market penetration of SDVs. Also, there are many parallel opposing mechanisms induced by SDVs that determines the net impact and estimating this form of systemic behavior with high accuracy is challenging. See section 5.2 for a more elaborated discussion on some of the reasons for these uncertainties.

The main findings of the literature review in terms of what impacts and impact mechanisms are discussed along with topics that requires further studies are presented in table 11. The presented impacts are not necessarily likely outcomes and some of the listed impacts are mutually exclusive.

Table 11 - summary of key findings in the literature review. The table is non-exhaustive and more elaborated descriptions of potential impacts are presented in chapter 4.

Impact category	Positive impacts	Negative impacts	Neutral/other impacts	Uncertainties and topics for further research
Safety	• Human induced accidents drastically reduced with high levels of automation	• New, technology- and driving mode (e.g. platooning) related, risks and failure modes	• Increased travel volumes give higher exposure and can lead to higher accident rates in absolute terms although relative risks are reduced	• Safety risks with mixed traffic – behavior of human drivers in relation to SDVs • Net impact (effect from increased travel volumes) on absolute accident rates • Cyber and IT security risks • New risk mechanisms from automation
Vehicle operations	*Not applicable to categorize vehicle operations impact as positive/negative*		• New collaborative driving modes (e.g. platooning, automated intersection management, etc.) • Reduced headway between vehicles • Smoother acceleration and breaking (enabled by V2V) • Increased homogeneity in traffic flow • New vehicle designs enabled by no need for driver seats and improved safety (reduced weight of vehicle)	• Headway limits for passenger comfort • V2V technology standards • SDV penetration rates to realize benefits • Relation to network efficiency and energy and emissions

Energy and emissions	• Platooning reduces aerodynamic drag • Improved traffic flow and reduced congestion • Automation catalyzing transition to electrical vehicles • Automated driving systems can be designed to optimize energy efficiency of driving • Potentially SDVs will be lighter than non-SDVs thus reducing energy consumption	• Increases in VKT due to the introduction of SDV increases energy consumption • Increased energy consumption due to on-board computers and sensors		• Net impact (effect from increased travel volumes) • The relationship between SDVs and electrification, trends in the industry and market response • Studying driving automation impacts in isolation from electrification • Impacts from new vehicle designs (aerodynamics and weight)
Personal mobility	• Road vehicle travel enabled for new user groups (previous non-drivers) • Reduced (monetary) costs of travelling due to increased asset utilization with shared SDV services • Improved availability of mobility services and thus improved individual accessibility • Changes in vehicle ownership, potential shift from private ownership to usage of shared SDV services • Increased public transport service level due to reduced operating costs when SDVs are used in the public transport system	• “Access anxiety” • Social exclusion due to high costs of ownership of private SDVs or lack of access to shared SDV services • Reduced public transport service level due to competition from SDV	• Exposure to full cost of travelling when using shared SDV services (compared to privately owned vehicles where the investment is usually interpreted as a sunk cost by the vehicle owner).	• Market penetration dynamics and scenarios, especially for shared SDV services • Sensitivity of travelers to exposure of full cost of travelling • The impacts of access anxiety on travel behavior • The impacts on public transport • Will elderly and children be able to use SDVs on their own?

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Travel behavior	*Not applicable to categorize travel behavior impact as positive/negative*		• Increased travel demand and VKT due to reduced value of time, new users and empty SDV driving • Value of time (for the driver) reduced by eliminating human driving • Value of time reduced due to new vehicle interior designs enabling other activities to be performed • Generalized travel cost decreased due to reduced value of time, reduced (monetary) costs and reduced travel time	• Travel demand impacts • Value of time and generalized travel cost impacts from SDVs and various forms of mobility services with automated vehicles • The use of SDVs in relation to (and as a part of) public transport • Travel behavior in scenarios with competing mobility services with automated vehicles
Network efficiency	• Improved longitudinal and lateral control enables reduced lateral separation and headway thus improving road capacity • Coordination of driving enabled by V2V leading to smoother traffic flow	• Increased VKT due to new type of trips (e.g. empty driving) and induced travel demand from SDVs	• Impacts likely to vary heavily under various scenarios (penetration rates of SDVs, road type, driving modes, etc.)	• Net impact (effect from increased travel volumes)? • Interplay between SDVs and conventionally driven vehicles in mixed scenarios • V2V requirements and impacts for reduced headways • Impacts from (potential) new infrastructure designs

Public health	• Reduced energy consumption and particle emissions due to reduced congestion • Reduced accident rates • Reduced noise levels • Usage of active modes enhanced by redevelopment of urban space (due to reduce parking demand and road width)	• Reduction in usage of active modes		• Large knowledge gap, few or no systematic studies published • Will SDV replace active modes, in what cases and to what extent? • Impacts on noise emissions • Particle emissions due to automated driving
Infrastructure and land use	• SDVs might enable new geometric road designs (e.g. reduced lane width, no need for medians) • Improved lateral control might increase pavement rutting • Reduced need for urban parking space in scenarios with high penetration of shared SDV services	• Urban sprawl due to reduced value of travel time (people willing to commute longer) and improved accessibility in non-urban areas	• Potentially automated vehicles need to be separated from conventionally driven cars in mixed traffic scenarios	• Digital infrastructure requirements (V2X infrastructure, digital maps, etc.) • Infrastructure requirements during initial phases of SDV introduction • Data formats and standards for V2X communication • Impacts in scenarios with various degrees of SDV penetration • Should SDVs adjusted to current infrastructure or the current infrastructure adjusted for SDVs
Societal costs and benefits	• External costs of road transport (accidents, CO_2 emissions, noise, particle emissions) etc. could be reduced by more efficient driving and new vehicle designs • Wider economic benefits due to improved performance of the transport system • Accessibility improvements	• Losses of jobs for drivers and in “traditional” vehicle sector • Benefits and external costs of SDVs will likely have uneven distribution		• Social equity and distribution effects (of both benefits and costs) • In what type of future scenarios are socio-economic benefits maximized? • Impacts on labor markets • Methods for cost benefit analysis for SDVs and SDV related infrastructure • Impacts on tax revenues due to electrification and reduced vehicle fleet size due to shared SDV services)

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		among social groups		

As table 11 indicates, there are many open research topics and questions related to SDVs. Some of the reviewed papers present specific open research questions and topics: social issues (Cohen, Jones, and Cavoli 2017, sec. Appendix F), infrastructure issues (Farah et al. 2018), and general topics related to system-level impacts of SDVs (Milakis, van Arem, and van Wee 2017a).

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