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Impact assessment of cooperative intelligent transport systems (C-ITS): a structured literature review

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Abstract
In recent years, the number of connected vehicles has been steadily increasing. Vehicles that can exchange information with each other or with infrastructure elements enable services for cooperative manoeuvring and address central problems related to road traffic (e.g., growing traffic volume, sustainability, traffic safety, etc.). The development, standardisation, and implementation activities of Cooperative Intelligent Transport System (C-ITS) services have been advancing in recent years in numerous projects and research efforts. Impact assessment plays a central role in this process, whereby the approaches and methods used can differ significantly. This paper aims to review existing related work and future directions related to C-ITS impact assessment in the form of a structured literature review. Within this scope, it is elaborated which C-ITS services have already been the subject of past studies and under which conditions the respective impact assessment studies have taken place. Furthermore, the methods used in the individual studies as well as the impact categories and KPIs used to quantify the impacts are explained and summarised. Finally, potentials for future research are derived based on the literature analysed. This paper is the first review of its kind to focus specifically on the impact assessment of C-ITS. The results of this paper provide a comprehensive overview of current research efforts in the field of C-ITS impact assessment, provide input for future research directions, and thus contribute to further development in the direction of cooperative connected and automated mobility.

Keywords Cooperative intelligent transport system, C-ITS, Impact assessment, CCAM, V2X

1 Introduction

In recent years, vehicles have increasingly been equipped with sensors and Information and Communication Technology (ICT) capabilities for data collection and inter-vehicle communication [1]. With more than 100 million connected vehicles expected to be on the road by 2023, there is a huge opportunity to address traffic-related issues [2, 3].

The number of vehicles on the road is one such problem. The vehicle population in Europe increased by approximately 1% to 2.4% annually between 2016 and 2020, leading to a growing number of congestions and higher travel times [4]. Growth in traffic volumes may also increase emissions. As a result, the transport sector alone is responsible for 16.2% of global greenhouse gas emissions. At 11.9%, road transport accounts for the largest share of these emissions [5]. Moreover, traffic safety is still a major issue. The EU is actively addressing traffic safety with its 'Vision Zero', aiming to reduce deaths related to road traffic to zero by 2050 [6]. There is a general trend of decreasing road fatalities in the EU, however, in 2019 there were still almost 930.000 crashes recorded, with an injury rate of 1.3 people per crash, and a mortality rate of 4% [7].

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Connected and automated vehicles (CAV) are a potential solution to counteract said problems, by enabling individual traffic entities to communicate and cooperate with each other. Cooperation means that vehicles can autonomously warn each other in case of potentially dangerous situations or communicate with the local road infrastructure [3]. The information exchange between vehicles and other entities participating in traffic is referred to as Vehicle-to-Everything (V2X) communication. Due to the cooperative nature of the vehicle manoeuvres such services are referred to as Cooperative Intelligent Transport Systems (C-ITS).

The technologies and standards behind C-ITS have been available for several years. Accordingly, there are already projects and initiatives for the development, implementation, and standardization of C-ITS [8–13]. In addition, several collaborations of stakeholders in the field of connected, cooperative and automated mobility (CCAM) are dealing with C-ITS, such as C-Roads and the Car-2-Car Communication Consortium (C2C-CC) [14, 15]. Despite having different objectives and focuses with respect to C-ITS services, these projects and initiatives share a common issue, namely the assessment of the impact and effectiveness of C-ITS services.

Impact assessment (IA) can be defined as the process of identifying future consequences of a current or proposed action on different impact categories, whereby the impact being the difference between what would happen with or without the action, respectively. The term IA is distinguished from impact evaluation. The latter evaluates the effects of actions that have already been implemented, whereas the former focuses on the possible future consequences of actions that have not yet been taken [16].

IA is considered an essential part of the development of C-ITS. Accordingly, in regulation 2010/40 on the deployment of ITS in road transport, the EU stipulates that ITS solutions must be effective, i.e. they must make a significant contribution to solving the key problems in the transport sector (e.g. congestion avoidance, improved safety, less emissions) [17]. The assessment of effectiveness, however, is not trivial. It is therefore necessary to know which methods and tools are available to measure the impact of C-ITS services.

Some authors have already summarised recent developments in the field of C-ITS and reviewed CCAM from different of perspectives. However, as detailed in Sect. 2, there is yet no work that specifically addresses and summarises research regarding IA of C-ITS. Accordingly, this paper provides a comprehensive review of methods and tools used for evaluating and assessing the impact of C-ITS. The following research questions will be addressed:

1. How can the impacts of cooperative intelligent transport systems on relevant impact categories be assessed? (see Sect. 4)
    a. What are the existing methods used in impact assessment of cooperative intelligent transport systems? (see Sect. 4.2)
    b. What are relevant categories and performance indicators for measuring the impact of cooperative intelligent transport system services? (see Sect. 4.3)

2. What are current issues and needs for further research related to impact assessment of cooperative intelligent transport systems? (see Sect. 5)

This paper is structured as follows. Section 2 reviews the related work by discussing studies that conducted literature reviews of CCAM. Section 3 describes the methodology used in this literature review, before Sect. 4 discusses the selected literature in terms of study focus, IA method and impact category. Derived from the findings, Sect. 5 identifies future research directions in the field of C-ITS IA. Section 6 closes with concluding remarks.

2 Related work

Multiple authors have published review papers in the field of C-ITS. A general review of CAV systems was provided by Shladover [18], where the author gave a historical overview of the development of CCAM, identified potential synergies between connected and automated driving and highlighted technological challenges in their implementation.

Similarly, Rana and Hossain [19] provided a review regarding the development of CCAM. Various roadside communication infrastructures as well as the associated issues in assisting CAVs with wayfinding were summarised. The authors addressed the impact of C-ITS on highway road geometry and explained various techniques for minimizing stresses on the road surface using CAVs.

A detailed review about wireless communication technologies in connected driving was published by Sharma et al. [20]. The authors provided a comprehensive insight into the field of vehicular ad-hoc networks (VANETs), describing advantages, limitations, applications, routing protocols, security risks and simulators for testing VANETs.

Another review focusing on the technical aspects of VANETs was conducted by Soto et al. [21]. The authors described various cellular-based technologies used for V2X communication and classified them according to a self-developed scheme.

Cunha et al. [22] conducted a systematic literature review on traffic control systems using VANETs. The authors analysed a total of 115 papers between 2010 and 2019, and clustered them according to their general focus, the IA methods used, and type of communication used.

Zoghlami et al. [23] conducted a review of V2X communication architectures and technologies for safety applications of vulnerable road users (VRU). The authors described different message types, data processing methods, and communication architectures for data exchange, and developed requirements for C-ITS services for VRU safety.

Li et al. [24] conducted a survey on simulations of vehicle group behaviour among CAVs. In addition to simulation-based modelling approaches, Li et al. [24] also described specific application scenarios on highways, on- and off-ramps and intersections, and suggested ways to assess the models' performance.

Zhu et al. [25], Wu and Qu [26], Hrica et al. [27], and Li et al. [28] conducted reviews about specific types of C-ITS services each. Zhu et al. [25] summarised 44 research papers concerning merging control strategies of CAVs on highway on-ramps. The authors described different control approaches for single-lane and multi-lane highways under 100% CAV conditions and mixed traffic. A review on control of CAVs in intersection areas was conducted by Wu and Qu [26]. The authors described past studies on planning single- and multi-lane trajectories as well as papers on joint control of signalised intersections. Hrica et al. [27] conducted a review of collision warning technologies for mining haul trucks, and evaluated them based on their technology readiness level. Li et al. [28] examined studies dealing with planning and decision-making processes as well as possibilities for cooperation between CAVs in (un)signalised intersections.

The papers described cover current research directions in the field of C-ITS from different perspectives. The scope ranges from general reviews of CCAM to the underlying technical basis and reviews of research on specific types of C-ITS services. However, it is also evident that the issue of IA is a complementary issue. None of the work described focuses specifically on methods, tools, or performance indicators to determine the impact of different C-ITS services. Furthermore, to the authors' knowledge, there is no other work that explicitly focuses on the IA of C-ITS. Accordingly, this paper reviews research on CCAM conducted between 2012 and 2022 with a focus on IA.

3 Methodology

The methodology used in this literature review is based on the PRISMA approach [29], which consists of the four phases

- identification,
- screening,
- eligibility, and
- included.

Figure 1 provides a summary of the adoption of the PRISMA method in this paper, and describes the step-by-step selection of relevant research papers, which are subsequently analysed in detail in this literature review.

As illustrated in Fig. 1, the database search alone yielded more than 50,000 results, which could subsequently be reduced to 104 relevant papers after further selection steps. A detailed description of the procedure using the PRISMA approach can be found in the Annex (see Sect. 7.1). Furthermore, a list of the included papers along with their classification can also be found in the Annex (see Tables 4 and 5).

Although more than 100 relevant papers regarding C-ITS Impact assessment were identified by applying the PRISMA approach, caution must be exercised when interpreting the results. Especially within the phases Screening and Eligibility, bias might occur due to having only one reviewer carrying out the literature review. However, the co-authors tried to mitigate the risk of bias via alignment meetings and random validation of the paper eligibility.

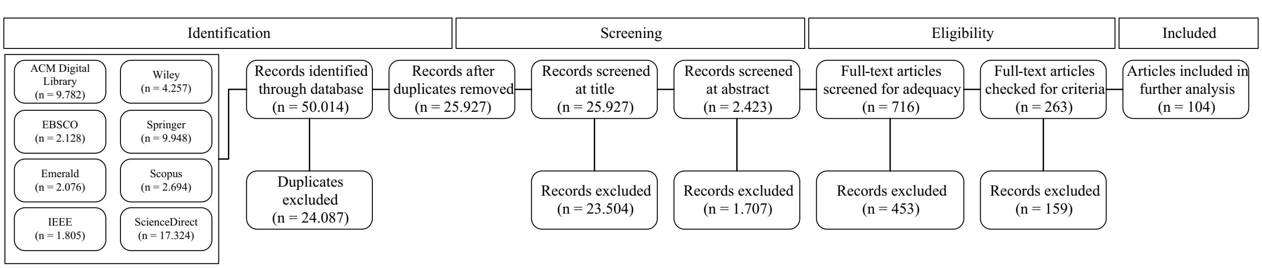

Fig. 1 Literature search and selection – Flowchart

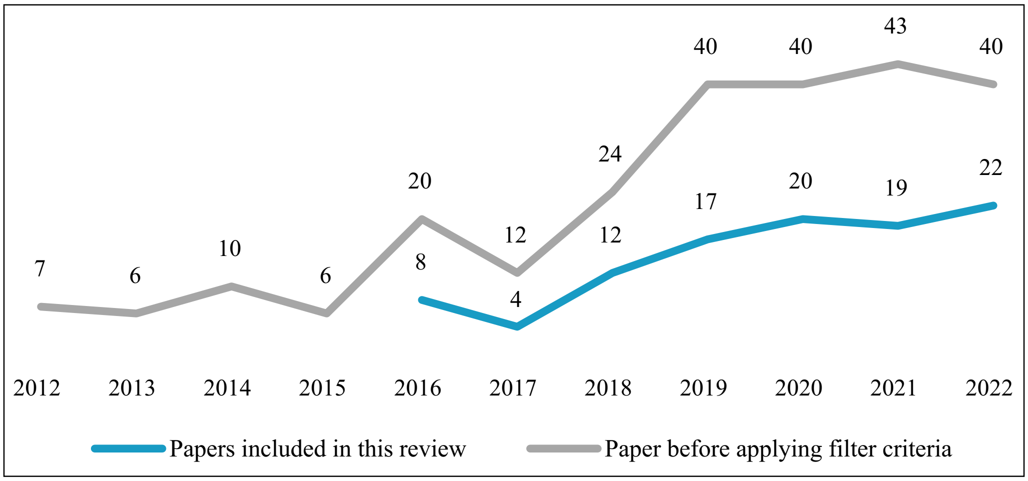

Fig. 2 Number of publications per year

4 Discussion

When looking at the development of the number of publications in the field of C-ITS IA, a steadily increasing research interest can be observed (see Fig. 2).

The development of publications considered in this literature review is similar to the general development of publications regarding C-ITS IA. Additionally, apart from 2017 and 2021, continuously increasing research interest can be observed. This development again underlines the relevance and timeliness of the topic of CCAM.

4.1 Focus of past research on C-ITS impact assessment

The following subsections describe the general scope of the selected papers in terms of IA. The focus is laid on the C-ITS services that were the subject of the respective works. Additionally, the underlying conditions of the IA studies are described.

4.1.1 C-ITS services

A total of 34 different types of C-ITS services were tested in the 104 papers. Figure 3 illustrates which services were assessed in the analysed works and how often they served as the basis for IA studies.

A description of the individual C-ITS functionalities is not provided. For a detailed explanation, please refer to the respective papers (see Tables 4 and 5) or the summarised descriptions of the use cases in [30–33].

Figure 3 shows an overall very comprehensive picture of the tested use cases in the selected journal papers. A closer look at the papers considered reveals that services designed specifically for road safety have low test frequencies due to methodological challenges (see Sect. 5). A comparison with the defined use cases by the C2C-CC, C-Roads and ETSI reveals that a lot of the defined services (Day 1, Day 2 and Day 3+[1]) were already covered in the papers analysed. A list of C-ITS services that have not yet been assessed in highly ranked journal papers can be found in Sect. 5.

4.1.2 Spatial conditions

The papers analysed can also be differentiated according to the underlying spatial conditions. Overall, seven categories of road types could be identified in the studies (see Fig. 4). Furthermore, a distinction was made as to whether the underlying road network is based on a real road network (e.g., certain highway sections) or whether it is artificially generated.

Figure 4 shows that highways are the most frequently used road type followed by intersections. Studies on urban or suburban road sections, on test tracks and based on road networks were conducted less frequently. In three cases, only the length and the number of lanes of the road sections under consideration were given, but it was not specified which road type was used. It is also noticeable that in 24 cases no information was given on road characteristics.

Looking at the sub-categorization of network realism, it can be observed that for highways and intersections the share of artificially generated traffic networks is relatively high. This is most likely since highways as well as intersections are easier to replicate than suburban roads or larger networks because of their simpler topologies.

It is also noticeable that investigations on test tracks are conducted 100% based on real-world networks, because

[1] The C-ITS services of the C2C Communication Consortium are categorized into Day 1, Day 2, and Day 3 + services, based on the complexity of the message exchange and the necessary coordination. [30]

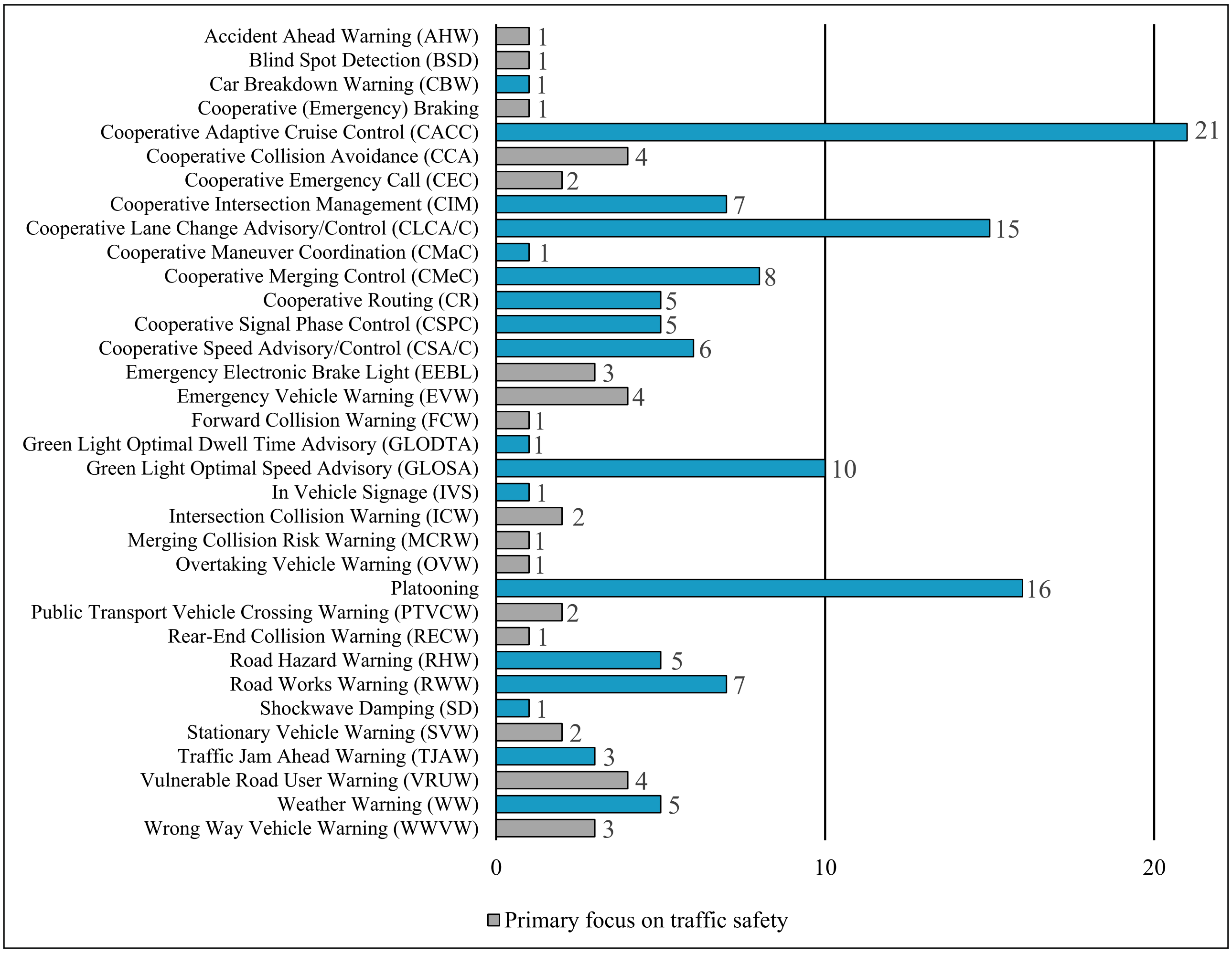

Fig. 3 C-ITS service test frequency

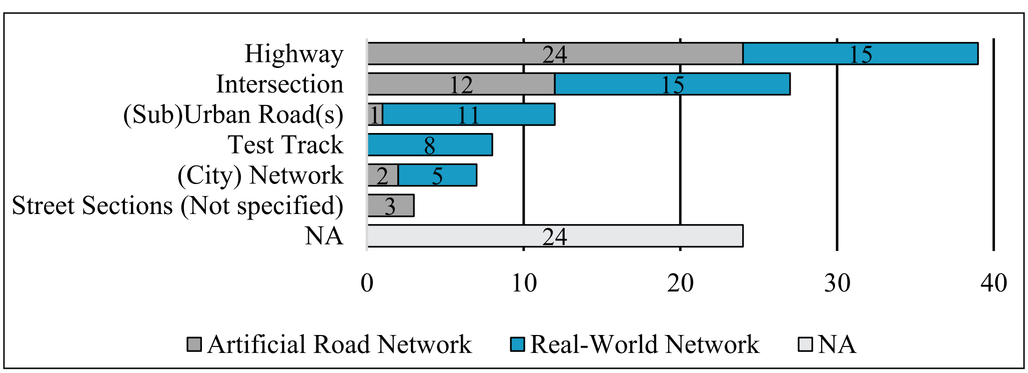

Fig. 4 Road type used for impact assessment study

the investigations on these road types were all conducted using Field Operational Tests (FOTs).

In general, C-ITS IA studies are mainly carried out on small sections of road networks (e.g., highways and intersections). Larger networks are hardly ever considered, which would, however, be relevant especially regarding interactions between different road sections (see Sect. 5).

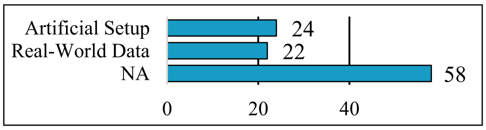

Fig. 5 Traffic data source

4.1.3 Traffic demand

The study conditions can also be differentiated based on the traffic demand.

Figure 5 shows that the number of studies using artificial demand and real measurements is quite similar. It is notable that in more than half of the studies no information was given on what demand was used or how it came about.

In studies with artificial traffic demands, there are different approaches as to which traffic indicators are used and how they are obtained. Several scenarios with different traffic flows or traffic volumes are used, whereby these in turn can be firmly defined or generated randomly [34–38]. A temporal and spatial variation of the traffic indicators is also a common approach, e.g., by trapezoidal progressions of traffic flow profiles or by defining different traffic flows on the main carriageway of highways or their on-ramps [20, 39, 40].

Similarly, studies based on real traffic demand data can be differentiated according to how the data is obtained. For example, indicators such as traffic volume, traffic flow or traffic compositions are collected by different sensor systems from highway operators, navigation service providers or federal statistical offices [41–43]. Furthermore, especially with FOTs, the data originates from vehicle sensor measurements [44–46].

4.2 Impact assessment methods

This section describes how the current literature has proceeded methodologically and which tools have been used to measure the impact of C-ITS services. In total, eight methods have been identified in the literature (see Fig. 6).

Simulations are the most frequently used method, followed by FOTs. The evolution of the number of publications related to simulations and FOTs over time is depicted in the Annex (see Sect. 7.2). Other methodological approaches are used less often. Literature reviews, questionnaires and interviews are generally used in combination with other methods (see Sect. 4.2.3).

It is worth mentioning that only driving simulations as well as microscopic and sub-microscopic level simulations were used for simulation-based IA. Traffic simulations at higher levels of abstraction, such as mesoscopic and macroscopic simulations, have not been used.

4.2.1 Simulation

Driving simulators and traffic simulations usually use different study designs. Driving simulators use a human-in-the-loop approach to test the human response or the acceptance of a C-ITS service. In contrast, traffic simulations assess general effects on traffic, analysing the impact of C-ITS using a software tool with a specific traffic simulation model.

The four simulation studies that applied a driving simulator study used a highway as the test route, with only one having a road topology based on a real network. None of the studies provide information regarding the traffic demand.

Chang et al. [47] for example used a driving simulator to assess the effectiveness of Weather Warnings (WW), assessing the impact on both road safety and traffic efficiency. Using a real vehicle converted for driving simulation purposes and 35 test subjects, changes in driving

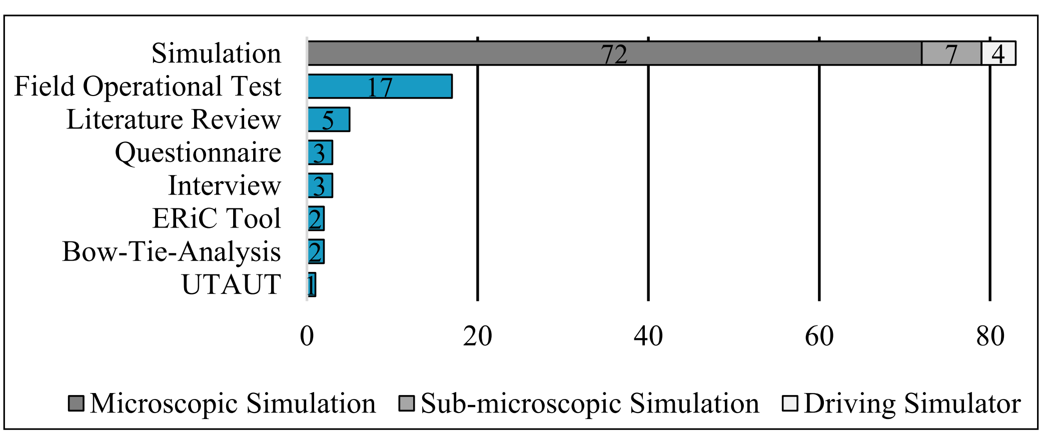

Fig. 6 Impact assessment methods

Step 1: Proposal and description of C-ITS service.

- Provision of a (mathematical) description of the functioning of the C-ITS service assessed in the respective paper.

Step 2: Definition and description of the study design.

- Definition of impact categories to be considered in connection with the C-ITS service (see Section 4.3).
- Definition of KPIs to be used to quantify the impact on each category (see Section 4.3).
- Definition of the communication standard used to exchange the C-ITS messages between the entities in the traffic area (e.g., ITS-G5, C-V2X).
- Selection of the type of simulation with which the impacts are to be assessed (see Section 4.2.1).
- Selection of the software tool.
- Selection of the simulation model (see Figure 9).
- Definition of the spatial conditions (see Section 4.1.2).
- Collection or creation of the underlying transport demand information (see Section 4.1.3).
- Definition of simulation scenarios based on various characteristics:
  - Variation of C-ITS usage (with and without use of C-ITS service, variation of equipment rates).
  - Variation of traffic parameters (traffic flow, density, vehicle type distribution etc.).
  - Variation of the functional parameters (e.g., different distances to the vehicle in front in the case of CACC, change of sensitivity in the case of warning applications leading to earlier/later warnings, etc.).

Step 3: Conduction of simulation studies.

- Conduction of the simulations based on defined study design.
- Calculation of the selected KPIs.

Step 4: Conduction of simulation studies.

- Analysis of the effects of the different simulation scenarios based on the defined study design and derivation of findings.
- Conduction of further analyses, such as statistical analyses to test the significance level of the results.
- Indication of the limitations of the respective simulation studies.
- Provision of further development and test opportunities of C-ITS services.

Fig. 7 Workflow steps of traffic simulation studies

behaviour with and without fog warning were investigated. The behaviour of non-human-driven vehicles was modelled using the Intelligent Driver Model (IDM) [48].

Another study using a driving simulator was conducted by Lee et al. [49], who investigated the lane change behaviour of manually driven vehicles under Platooning conditions and tested the effects of hybrid vehicle type structures in terms of cooperative and non-cooperative vehicles on road safety. 30 participants took part in the study, which was conducted on an artificially constructed highway section.

Payre and Diels [50] used traffic simulations to assess Emergency Electronic Brake Light services (EEBL), Emergency Vehicle Warnings (EVW), Road Work Warnings (RWW) and Traffic Jam Ahead Warnings (TJAW) in terms of user acceptance with 36 participants. Therefore, a 3-mile two-lane highway section was simulated, with the scenarios having been displayed on a 220° screen in front of the vehicle.

Zheng et al. [51] assessed the user acceptance of lane change requests with 30 participants. Using a gaming steering wheel and pedals, scenarios with different types of lane change requests were displayed on an 85-inch screen and the compliance rate with the recommendations was assessed.

Compared to the driving simulations, the traffic simulations were not conducted exclusively on highway sections but use all types of road topologies (see Fig. 4). The traffic simulation studies also show different approaches regarding the study design. Figure 7 therefore summarises how previous research has proceeded in these traffic simulation studies on an abstract level.

As described in this process, an essential point when conducting simulation studies is the selection of a suitable tool. Therefore, Fig. 8 provides a summary of the software applications used in the simulation studies.

The simulation tools are often used in combination. This is the case, for example, with the sub-microscopic traffic simulations. Coppola et al. [52], Ma et al. [53], Liu et al. [54], Thormann et al. [55], Gratzer et al. [56], and Okada et al. [57] use MATLAB [58] as well as Simulink [59], with Coppola et al. [52] and Ma et al. [53] additionally using SUMO [60] as a traffic simulator. Furthermore, some of the listed tools are couplings of individual tools. For example, VEINS [61] and PLEXE [62] are frameworks that combine the traffic simulator

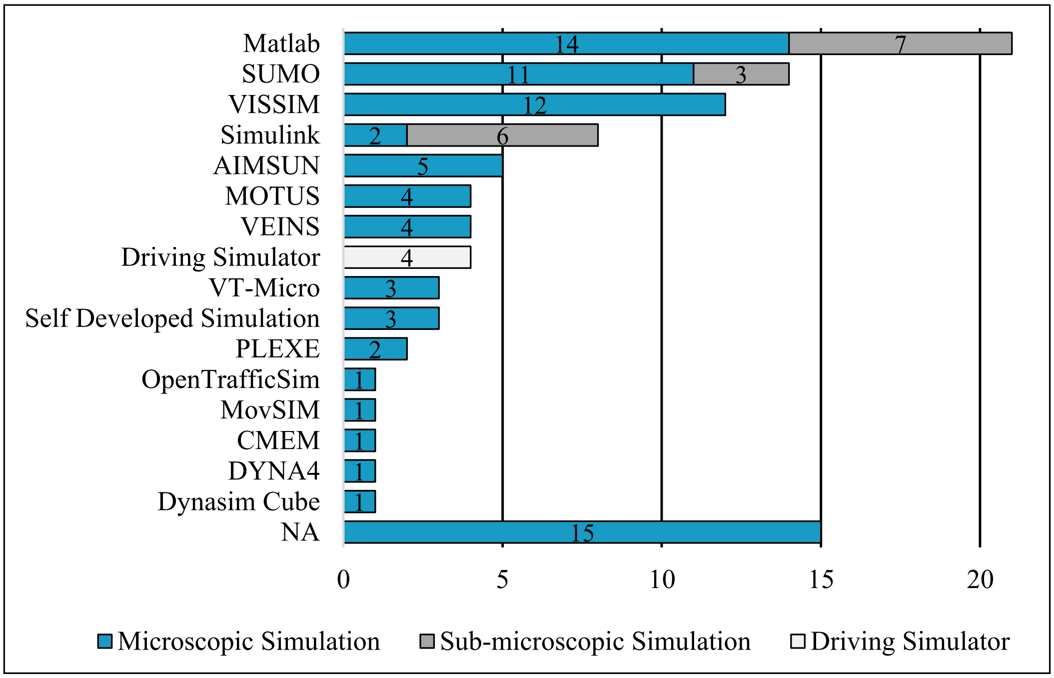

Fig. 8 Simulation software

SUMO with the network simulator OMNeT++ [63] to simulate C-ITS services.

In addition to the tool choice, a distinction can also be made by the simulation model used. Depending on the model, the behaviour, and interactions of the individual agents in the simulation may differ, and they may accordingly react differently to the C-ITS services. Simulation tools use certain models as a standard variant, for example, SUMO uses the Krauss model [64] by default, while VISSIM [65] uses the Wiedemann model [66]. However, simulation tools offer the option to select other models or to implement a self-developed model.

The simulations models used (see Fig. 9) present microscopic simulation models that include car-following models and cellular automata. These are designed to capture the interactions between individual vehicles or drivers and their surrounding environment and aim to represent traffic as a collective phenomenon, by simulating the behavior and motion of each entity and their response to the surrounding conditions. Submicroscopic simulations further use mathematical models that describe vehicle subsystems (i.e. powertrain dynamics, tire models) and forces acting on vehicles as a function of input to the vehicle system such as steering angles, accelerator and brake inputs and road profiles [48]. For example, Coppola et al. [52] extend the Krauss model by additionally using the power-based models developed by Rakha et al. [67] and Fiori et al. [68] to compute instantaneous fuel consumption. Liu et al. [54] developed a sub-microscopic model using engine, generator and battery models. Okada et al. [57] used engine and generator models to calculate and assess fuel consumption.

In general, self-developed simulation models were most frequently used for the C-ITS service tests since the function of the C-ITS service to be assessed is often directly encoded in the functioning of the developed model. In contrast, most studies use existing traffic modelling approaches to assess the impacts of C-ITS. Besides self-developed models, the most commonly used is the IDM [48]. The Krauss model and the Wiedemann model are also frequently applied. This is plausible because these two models are the default models of the SUMO and VISSIM tools, respectively. Additionally, there are other models such as the Gipps model [69], which is a preceding variant and basis for the Krauss model, the Cooperative Adaptive Cruise Control (CACC) Model of the PATH FOT [70], the Newell model [71] and further models that are only used sporadically. The NaSch model [72] is the only one using a cellular automaton instead of a car-following model. The Optimal Velocity Model [73], the Modified Comfortable Driving Model [74], the Full Velocity Difference Model [75] the Rajamani CACC Model [76], the Ploeg CACC Model [77] as well as the Bilateral Multi-Anticipation Model [78] were used once each.

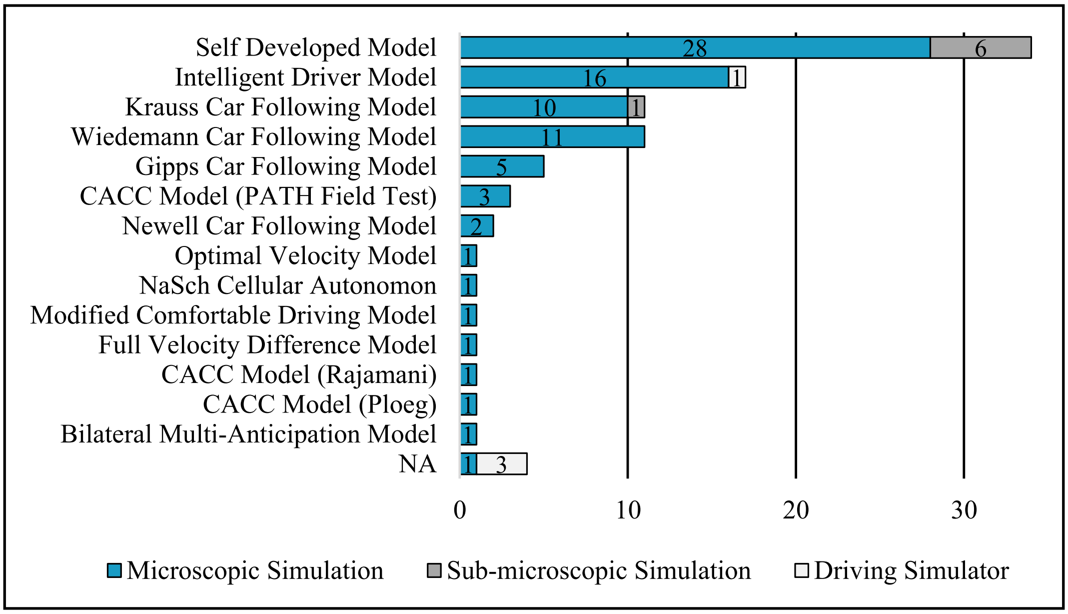

Fig. 9 Simulation models

For driving simulators, mostly no information was given about the underlying simulation model. There was only one mention that the IDM was being used for traffic simulation.

4.2.2 Field operational test (FOT)

In contrast to simulations, FOTs exclusively use real networks, as C-ITS services are physically assessed using the road types described in Table 1.

Using test tracks, Raboy et al. [79], Tahir et al. [80], and Xu et al. [81] conducted FOTs to assess C-ITS services in terms of their functionality. Raboy et al. [79] conducted a FOT for cooperative lane changes using longitudinal speed control. The authors test the functionality of the service by investigating speed oscillations and vehicle positioning accuracy at the Federal Law Enforcement Training Centre in Maryland. Tahir et al. [80] analyse the functionality of V2X technologies providing weather information (WW) by examining the average packet size, packet reception rate, latency, and packet loss rate. The FOT was conducted on the SoD5G test track in Finland. Xu et al. [81] perform a comparison between Dedicated Short-Range Communication (DSRC) and 4G LTE based on the Cooperative Collision Avoidance (CCA) service and compare the message delay and the packet loss rate of both communication technologies. In addition to the functional investigations, Zhao et al. [82] use the 2.4 km long test track of Chang'an University to test Rear-End Collision Warnings (RECW) with regard to road safety. Besides message delay and warning accuracy, mean accelerations and speeds are examined to assess safety aspects. Another investigation regarding functionality and road safety was carried out by Gkemou et al. [83]. Here, Road Hazard Warnings (RHW), RWW, Vulnerable Road User Warnings (VRUW), WW and Wrong Way Vehicle Warnings (WWVW) were examined on the CIDAUT test track in Spain, on a test route in Thessaloniki, on the ATTIKI ODOS highway in Greece, as well as on the A22 highway in Italy. With 53 test drivers distributed over the individual test sites, the functionality of the services under consideration was assessed using indicators such as the number of false warnings, the message reception time, the warning reliability, and the vehicle positioning and speed accuracy. Additionally, the deceleration during the warning, the reaction time and the Time-to-Collision (TTC) were used to assess road safety. Hsu et al. [84] investigated the road safety of motorbike warning systems (VRUW) on a test track in Taiwan,

Table 1 Road network type – field operational test

Road Network Type	No. of Papers using FOTs
Test track	7
Intersection	7
(Sub)Urban road(s)	5
Highway	3
(City) Network	1

where an index is calculated using the average speed, acceleration noise and highspeed motorcycle ratio, and is used to estimate the level of road safety. Almannaa et al. [85] investigated CACC systems in traffic light-controlled intersections on a 500 m test track in Virginia. With a total of 32 drivers and 1,536 recorded trips, the impact on traffic efficiency and sustainability was quantified by relative fuel savings, average speeds and travel times, and space–time trajectories.

Additionally, several investigations were also conducted on suburban roads with intersections. For example, Figueiredo et al. [86] assess EVW on a suburban street in Aveiro (Portugal), where the functionality of the service was tested using message delay and message loss. Calvert and Arem [87] assessed CACC as well as Cooperative Signal Phase Control (CSPC) on the N205 in the Netherlands. The functionality of the services was assessed based on the number and ratio of disengagements, the time in which CACC was used actively, the time headway distribution as well as space–time trajectories. Furthermore, the impact on traffic efficiency was analysed based on average accelerations, travel times, the number of platoon split ups and traffic flow. Road safety was estimated based on the proportion of heavy braking manoeuvres and TTC. Public Transport Vehicle Collision Warnings (PTVCW) were tested by Lokaj et al. [88] in Ostrava, and the effects on road safety and user acceptance through acceleration and speed as well as Human-Machine-Interface (HMI) distraction were investigated. Edwards et al. [89] assess the impact of Green Light Optimal Speed Advisory (GLOSA) through a series of FOTs in Bordeaux (France), Helmond (Netherlands), Newcastle (UK), Verona (Italy), Copenhagen (Denmark) and Thessaloniki (Greece). With over 400 vehicles, CO_2 savings, number of stops and the average journey times were assessed.

FOTs in intersection areas were carried out by Stahlmann et al. [45] and Skoufas et al. [90]. Stahlmann et al. [45] analyse GLOSA at three different intersections in Gothenburg and assess the C-ITS service on a functional level using the information distance, latency as well as the message delivery ratio. Skoufas et al. [90] use a railway junction in Thessaloniki to assess traffic safety using PTVCW. They recorded the average accelerations, jerks, and speeds with and without C-ITS of a total of 168 taxi drivers over 28 days and used these values to assess the impact on road safety.

Ferreira et al. [46] test Accident Ahead Warnings (AHW), Cooperative Routing (CR), EVW, RHW, RWW, TJAW and WWVW on the A5 in Lisbon. Jang et al. [91] conducted a test study on a highway in Seoul and the influence of EVW, Forward Collision Warning (FCW), RWW, Stationary Vehicle Warnings (SVW) and WW on road safety is assessed. Data such as average speed, acceleration noise, distance headway, jerk, speeding rate, TTC and Time Exposed TTC (TET) are recorded or calculated from 700 vehicles and a crash potential index is derived from these indicators.

Chen et al. [92] assessed Platooning on a sector of the road network of Beijing in terms of functionality and impact on both traffic efficiency and road safety. With six drivers, data was collected on approximately 2700 km of driving distance, and the impact was assessed by investigating latency, packet loss rate, acceleration, speed, time headway distribution, reaction time and TTC.

4.2.3 Further methods for C-ITS impact assessment

In addition to FOTs and simulations there are other methods for IA used in the literature, however, their application frequency is significantly lower (see Fig. 6).

For example, Rämä and Innamaa [93] and Silla et al. [94] used the European Risk Calculation Tool (ERiC-Tool) to assess the impact of C-ITS services on traffic safety. ERiC is an application developed specifically for road safety assessment by the VTT Technical Research Centre of Finland. It uses accident data from the CARE database [95] and estimates changes in the number of road fatalities and injuries with the help of the safety mechanisms of the C-ITS service used [93].

Ehlers et al. [96, 97] use a Bow-Tie-Analysis (BTA) to assess traffic safety of Cooperative Emergency Calls (CEC) and RHW. BTA is a probabilistic approach to risk assessment that combines the two methods Fault Tree Analysis and Event Tree Analysis. It consists of several elements, namely

- modelling causalities that cause malfunctions of any kind,
- proactive countermeasures designed to prevent or mitigate these malfunctions in advance,
- a critical event that occurs based on the malfunctions following causalities and considering proactive countermeasures,
- reactive countermeasures to reduce the impact of critical events that have already occurred, and
- the consequences of the critical event.

The probabilities of the malfunction or causality are considered model inputs, and the consequences are considered outputs. C-ITS services occur as proactive and/or reactive countermeasures, which in combination with the malfunction probabilities allows the impact to be estimated. Ideally, probabilities of causalities and effects of countermeasures are known. However, as this is usually not the case, expert interviews

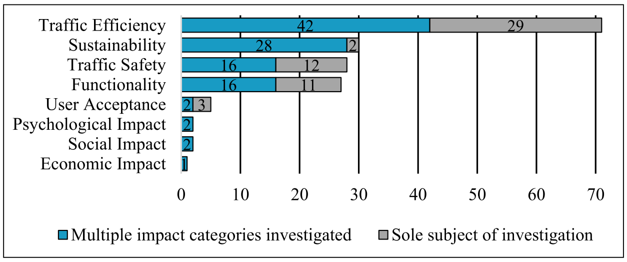

Fig. 10 Impact categories

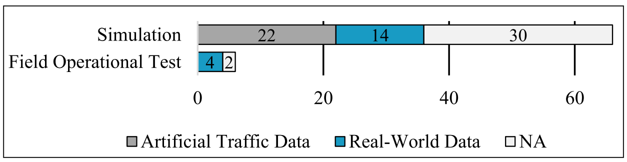

Fig. 11 Impact assessment methods – traffic efficiency

are used for estimating these probabilities. BTA is therefore frequently used in combination with other methods [96].

Another method used to assess the impact of C-ITS on user acceptance is the Unified Theory of Acceptance and Use of Technology (UTAUT). Zhang et al. [98] use UTAUT in their IA study and assess the technology acceptance of the C-ITS service VRUW. Again, additional methods are needed to collect the necessary data, for which Zhang et al. [98] used questionnaires.

Literature reviews have been used in two ways for C-ITS IA, firstly to summarise the results of other studies (see Bauder et al. [99]), and secondly as an input for other methods of IA. For example, Ehlers et al. [96, 97] used literature reviews for defining probabilities of BTA parameters. Rämä and Innamaa [93] and Silla et al. [94], on the other hand, use the method for the ERiC tool.

Similarly, questionnaires and interviews are used in combination with other methods. Lokaj et al. [88] use questionnaires with FOTs, Payre and Diels [50] with simulations and Zhang et al. [98] with UTAUT to ask drivers about their experiences with the tested services. Expert interviews are used by Ehlers et al. [96, 97] in conjunction with BTA to estimate causality probabilities, and by Silla et al. [94], in addition to the ERiC tool, to assess the impact of C-ITS on road safety.

4.3 Impact categories

The impacts of C-ITS are determined based on specific impact categories, which have been implicitly mentioned so far without being explicitly defined. Impact categories describe an umbrella term for the impacts that are candidates for assessment and are intended to reflect the essential features of the subject under investigation [16]. In the field of road transport, such features would include transport efficiency, sustainability, and road safety, but also user acceptance, social impacts, psychological impacts, and functionality assessment. Figure 10 provides a summary of the impact categories used in the 104 papers analysed.

In most of the cases, more than one impact category is investigated. For the category sustainability, it is noticeable that this is rarely the sole subject of IA studies. Studies that assess psychological, social, or economic impacts are examined exclusively in connection with other categories. Furthermore, the evolution of the number of

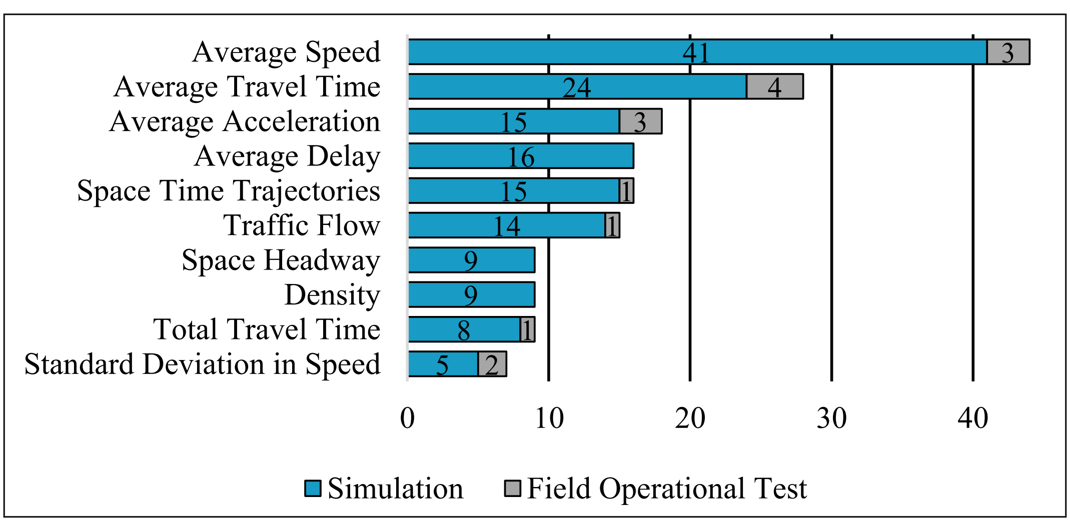

Fig. 12 Top 10 KPIs – traffic efficiency

publications related to the impact categories over time is depicted in the Annex (see Sect. 7.2).

4.3.1 Traffic efficiency

The impact category traffic efficiency subsumes all indicators describing the way in which different (groups of) entities move within a transportation system. (e.g., speed, acceleration, travel time, traffic flow). Methodologically, only simulations and FOTs were used to assess the impact of C-ITS on transport efficiency, with simulations being used in over 90% of the cases (see Fig. 11).

Most of the simulation studies that provide demand information use artificially generated data; in 14 cases real traffic data were used as input. In contrast, FOTs, when specified, only use real traffic demand.

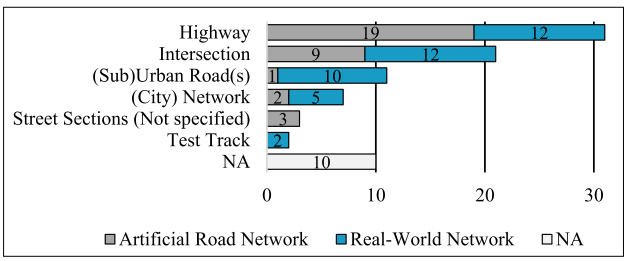

Fig. 13 Road types used for assessing traffic efficiency

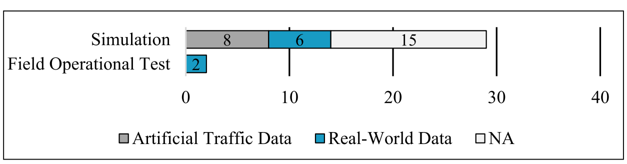

Fig. 14 Impact assessment methods – sustainability

Figure 12 shows the most commonly used Key Performance Indicators (KPIs) for assessing transport efficiency.

In general, many indicators are related to speeds, travel times and accelerations of vehicles. In addition, indicators of the fundamental diagram of traffic such as traffic flow and density as well as distances between vehicles and position developments of vehicles as a function of time (space–time trajectories) are used to assess traffic efficiency.

Looking at the road types (see Fig. 13), a similar distribution as in Fig. 4 can be seen. Only test tracks are used less frequently in comparison.

A breakdown according to network realism again shows that highways and intersections have a high proportion of artificial networks. The same applies to unspecified road types (see Sect. 4.1.2). In general, all road types were used at least once to assess the effects of C-ITS on traffic efficiency.

4.3.2 Sustainability

The impact category sustainability summarises all the effects of C-ITS on factors such as fuel consumption, energy consumption, and air pollution (e.g., emissions, particulate matter). Again, only simulations and FOTs were used to assess changes by applying C-ITS services (see Fig. 14).

Regarding the KPIs for the sustainability assessment of C-ITS (see Fig. 15), several variants of fuel consumption as well as emissions were used.

The KPIs are calculated based on different consumption models. For example, Qin et al. [37], Huang et al. [100], Shi et al. [101], and Liu et al. [102] use the VT-Micro model [103] and Coppola et al. [52], Kamalanathsharma and Rakha [104], Wu et al. [105], and Yu et al.

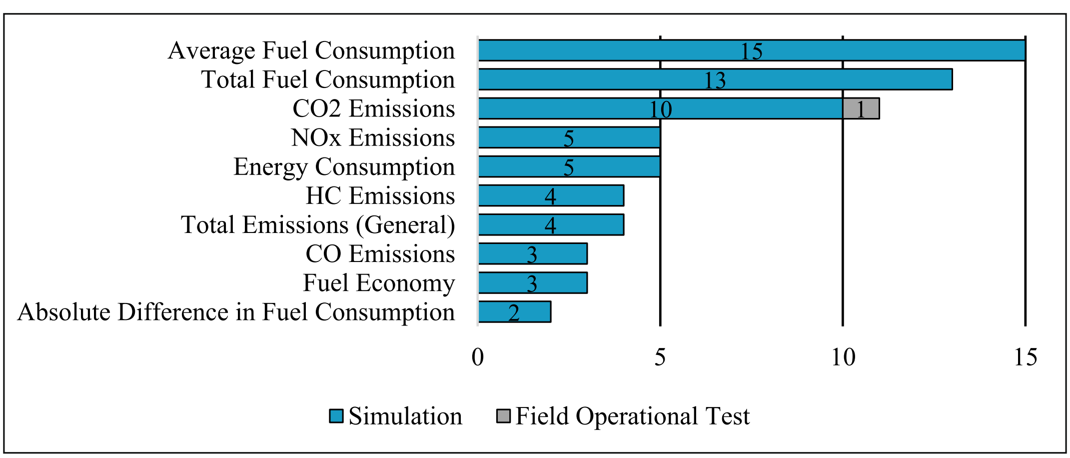

Fig. 15 Top 10 KPIs – sustainability

[106] use the VT-CPFM [67] model, both being developed by the Virginia Polytechnic Institute and State University to calculate emissions. The default emission model of simulation applications is also applied in some cases. For example, Studer et al. [107] use the emissions model implemented in VISSIM. Talavera et al. [36], Wang et al. [38], Pribyl et al. [43] and Soon et al. [108] use emission models implemented in SUMO, whereby Talavera et al. [36] and Wang et al. [38] use the Handbook Emission Factors for Road Transport (HBEFA) Model [109]. Pribyl et al. [43] and Soon et al. [108] do not provide more details on which of the models included in SUMO (HBEFA or PHEM) are applied. In addition an instantaneous emission model by Panis et al. [110] is used by Mintsis et al. [111]. Ding et al. [112] and Li et al. [113] use an instantaneous fuel consumption model by Kamal et al. [114] and Biggs and Akçelik [115], respectively, and Wang et al. [116] and Zhao et al. [117] apply the model developed by Akçelik [118] to assess the impact of C-ITS on fuel consumption. Liu et al. [119] use the Comprehensive Modal Emissions Model (CMEM) developed by Barth et al. [120]. Furthermore, Okada et al. [57] calculate the fuel consumption based on the applied engine and generator models, and Ma et al. [53] calculate the energy consumption based on the battery model used.

Considering the road types used for the sustainability studies, intersections and (sub)urban roads were most frequently used as test locations (see Fig. 16).

4.3.3 Traffic safety

The category traffic safety encompasses all indicators used to describe an accident situation (e.g., type of accidents, number of accidents/injuries) and indicators used to estimate the effects of C-ITS on accident probability. To assess the impact of C-ITS on road safety, several methods were used (see Fig. 17).

While simulations and FOTs were again used most frequently, additional approaches such as literature reviews, interviews, BTA, the ERiC Tool as well as questionnaires were applied. As described in Sect. 4.2.3, literature reviews, interviews as well as questionnaires are auxiliary methods that are used in combination with other methods. Both the ERiC tool as well as BTA are exclusively used to assess road safety.

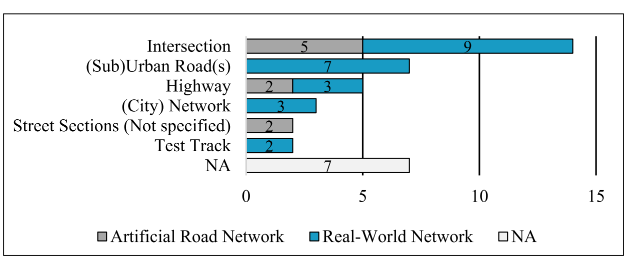

Fig. 16 Road types used for assessing sustainability

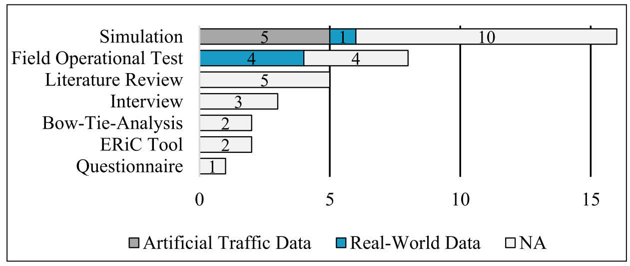

Fig. 17 Impact assessment methods – traffic safety

In the overall comparison, it is noticeable that simulations no longer occupy a dominant share. This is because assessing road safety with traffic simulations is challenging (see Sect. 5) and therefore alternatives such as FOTs, BTA or the ERiC tool are applied. Regarding the source of traffic demand, in most cases no information was provided.

The KPIs used to assess the impact of C-ITS services on road safety consist of variants of the Time-to-Collision (TTC) indicator such as the Time Exposed Time-to-Collision (TET) and the Time Integrated Time-to-Collision (TIT), acceleration and accident information, as well as average speed, reaction time and average braking distance (see Fig. 18).

The TTC variants are used particularly in simulation studies, the measurements of speed and reaction time are mainly used in FOTs, and acceleration noise exclusively in FOTs.

Looking at road types, highways are the most frequently used road type for road safety assessment of C-ITS, followed by intersections (see Fig. 19).

Due to the higher proportion of FOTs, test routes are in the third place in the road safety assessment of C-ITS impact. Especially noticeable is the high number of studies that do not provide information on the underlying road types.

4.3.4 Functionality

The functionality category comprises all indicators used to technically assess C-ITS services and their underlying technologies. The functionality assessments of the C-ITS services were conducted using only simulations and FOTs (see Fig. 20).

The number of studies without indicating traffic data sources is high. This is because the functionality assessment of C-ITS services can (often) be conducted without additional traffic, as interactions between road users do not necessarily have to be considered to assess service functionality. For example, for the analysis of

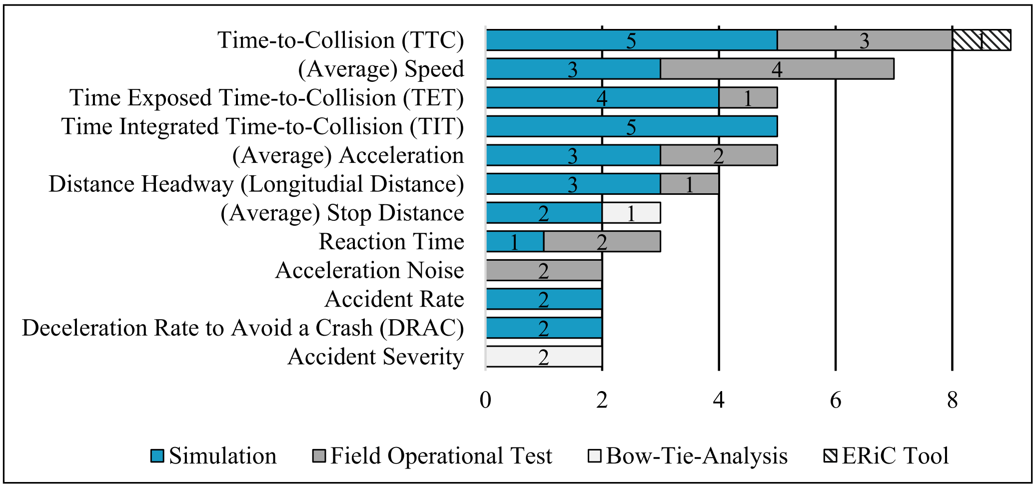

Fig. 18 Top 12 KPIs – traffic safety

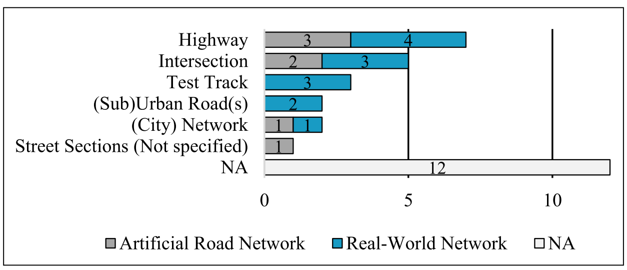

Fig. 19 Road types used for assessing traffic safety

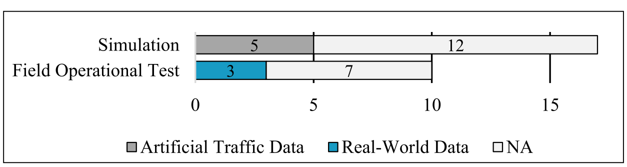

Fig. 20 Impact assessment methods – functionality assessment

data transmission (i.e., packet loss rate, message delay, latency), other vehicles do not have to be simulated or tested in FOTs.

In addition, vehicle status information, service accuracy indicators as well as indicators for assessing the computational efficiency of services which e.g., use optimization problems as a basis, are also considered (see Fig. 21).

Intersections are the most frequently used road type for the functionality assessment of C-ITS, using both real and artificial networks (see Fig. 22).

Test tracks rank high due to the more frequent use of FOTs for functionality assessment of C-ITS. In general, five out of eight test track studies include functionality assessments (compare Fig. 4).

4.3.5 User acceptance

In this paper, the category user acceptance includes all indicators that are used to measure user behaviour or willingness to use and adopt C-ITS services. Therefore, four different methods were used (see Fig. 23).

The three simulations can be subdivided in terms of their type into two driving simulator studies and one microscopic traffic simulation. Questionnaires, again, serve as an auxiliary method and can be allocated once each to UTAUT, FOTs and driving simulator studies.

Overall, the KPIs consist of indicators on the recommendations provided by the C-ITS service (e.g., Number of Agreed/Ignored/Declined Recommendations), specially defined indicators (e.g., HMI Distraction) as well as trip-specific indicators such as speed. In addition, UTAUT constructs, and Likert Scales are used (see Fig. 24).

User acceptance was assessed on highways, intersections and once on a (sub)urban road (see Fig. 25).

4.3.6 Further impact categories

In contrast to the aforementioned impact categories, social, psychological, and economic impacts of C-ITS are rarely investigated.

- Psychological impact in this context comprises all indicators that measure the effect that C-ITS can have on the mental and emotional states of road users, such as cognitive, emotional, and behavioural responses (e.g., alertness, reaction times, distraction).
- Social impact encompasses indicators referring to the effects of C-ITS on individuals and communities (e.g., public health, comfort, financial burden).

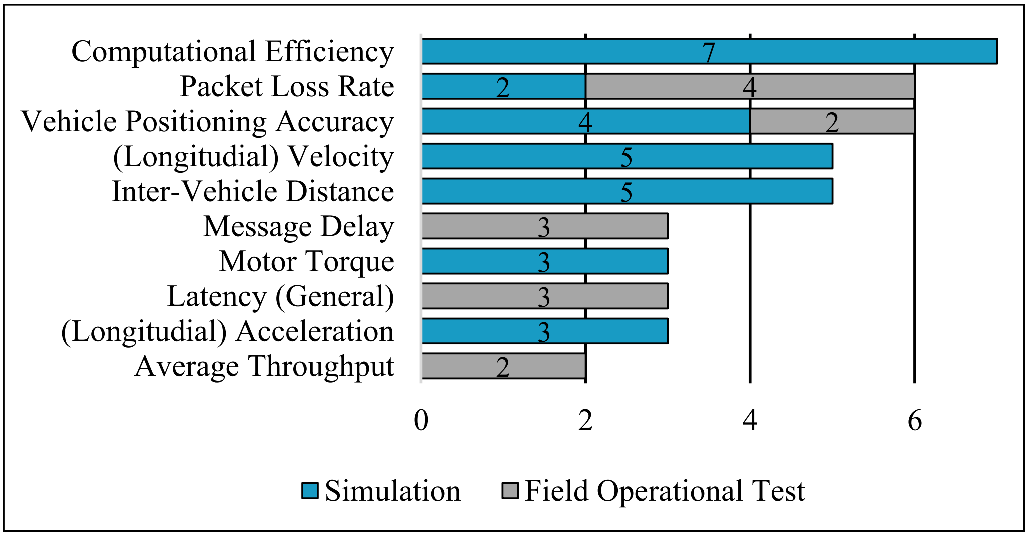

Fig. 21 Top 10 KPIs – functionality assessment

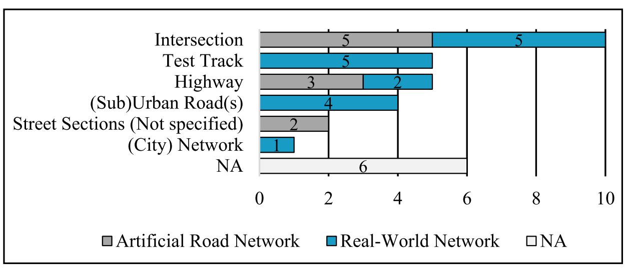

Fig. 22 Road types used for functionality assessment

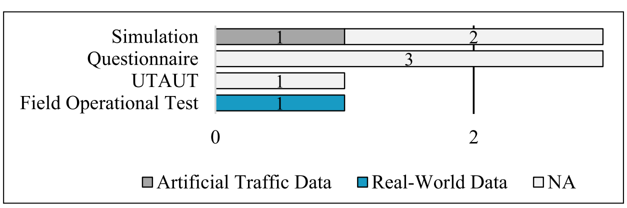

Fig. 23 Impact assessment methods – user acceptance

- The economic impact of C-ITS includes the effects of the respective services on costs for individuals or society (e.g., fuel costs, externalised costs of climate change)

In two studies, the effects of C-ITS on social impacts are simulated using indicators such as Passenger Comfort and Discomfort Indices. The psychological effects of C-ITS were assessed twice using FOTs. The effects of C-ITS on the attention of drivers or their reaction time were tested. The economic impact, on the other hand, was only assessed once in the selected papers. The indicators used were the costs for energy consumption, fuel, electricity, and the total costs.

5 Future research

C-ITS IA has been covered several times in the literature and is usually an essential part of a paper defining or testing new services. The number of tests as well as the diversity of study designs is high (see Sect. 4). Nevertheless, based on the studies conducted to date, potentials for future investigations can be identified. In the following subsections, the authors derive future research directions regarding C-ITS IA based on the literature review presented in this paper.

5.1 Interrelations of impact categories and rebound effects

The frequency distribution of the tested impact categories is heterogenous, with the impact of C-ITS services being most frequently assessed based on transport efficiency, sustainability, traffic safety, and functionality. Regarding the user acceptance of C-ITS and the impact on psychological, social, and economic aspects, hardly any studies have been conducted. Future research should therefore also take greater account of these impact categories.

Furthermore, one aspect that has not been considered in the selected literature is that the impact categories can be interrelated. A change in the impact of one category might result in a change of impacts in other categories. An exemplary representation of category interrelations is depicted in Fig. 26.

User acceptance is the basis for the impact of C-ITS services on other impact categories. With higher user

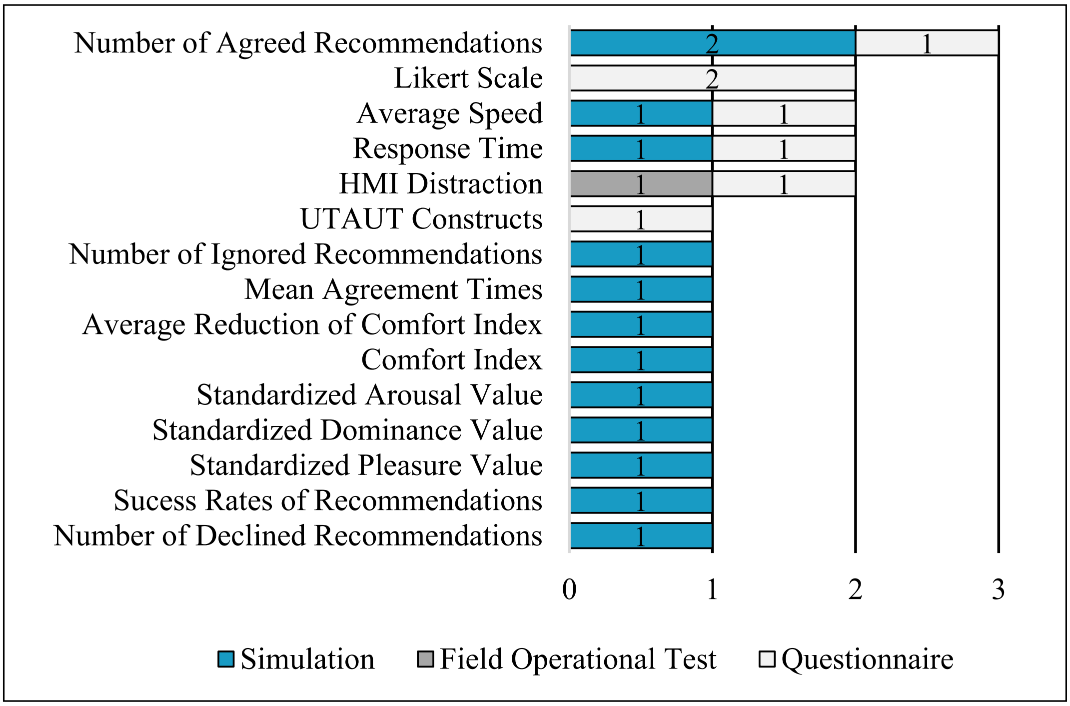

Fig. 24 KPIs – user acceptance

acceptance and consequently higher C-ITS usage, stronger (positive) effects of the respective service in terms of e.g., traffic efficiency, sustainability or traffic safety can be achieved, and vice versa. User acceptance, in turn, is driven by psychological factors such as feeling of safety, user stress or uncertainty, and requires correct functionality of C-ITS services.

Both social impact as well as economic impacts are not necessarily directly measurable, but a consequential effect of other impact categories, for example:

- Fewer braking and acceleration manoeuvres (traffic efficiency) lead to higher comfort (social impact), lower fuel costs (economic impact) and lower emissions (sustainability)
- Improved safety (traffic safety) leads to fewer fatalities (social impact) and less accident costs (economic impact)
- Less emissions (sustainability) lead to less air pollution (social impact) and less external costs of climate change (economic impact)
- Less costs (economic impact) lead to less financial burden (social impact)

Furthermore, regarding interdependencies of the C-ITS impact categories, long-term developments such as rebound effects are not analysed. For example, lasting changes in transport efficiency due to the application of C-ITS services can lead to changes in user behaviour, such as changes in commuting routes due to lower travel times. This, in turn, can lead to an increase in traffic volume, which cancels out the initial improvements achieved by C-ITS services. System dynamics approaches, such as causal loop diagrams (CLD), offer valuable tools considering this issue. By employing CLDs, researchers can map out the complex interdependencies between factors within the C-ITS context, allowing for a comprehensive understanding of how changes in one aspect of the system can propagate and influence other components. By capturing the dynamics of the system, such approaches facilitate a holistic assessment of C-ITS impacts, enabling policymakers and researchers to anticipate and address potential rebound effects through targeted interventions and policies.

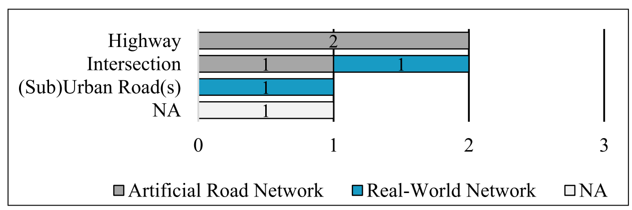

Fig. 25 Road types used for assessing user acceptance

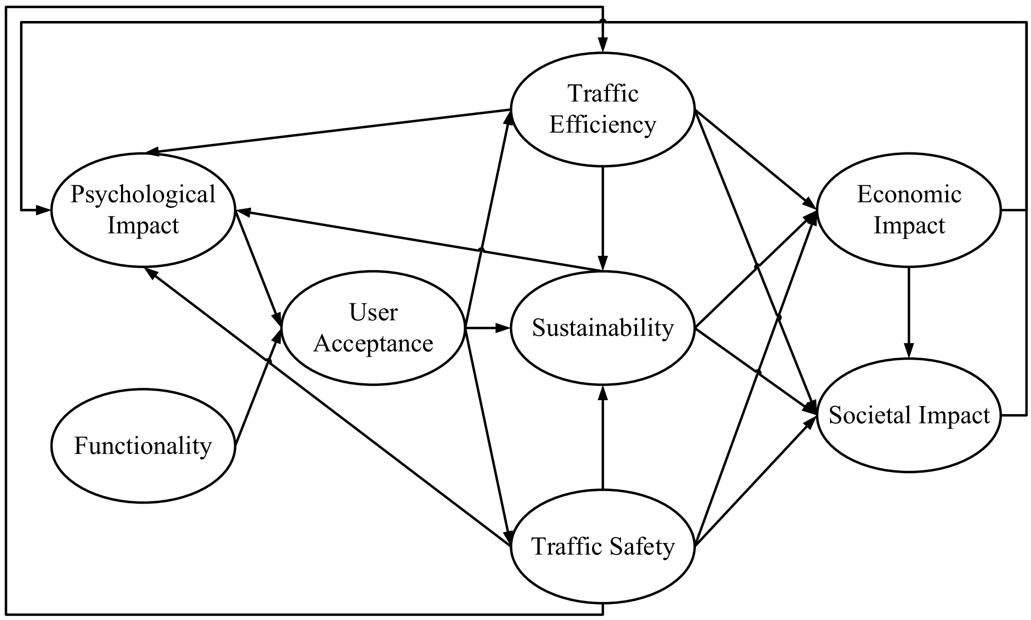

Fig. 26 Interrelations of impact categories

5.2 Assessment and publication of emerging C-ITS services

As described in Sect. 4.1.1 some services defined by different organisations dealing with C-ITS (C2C Communication Consortium, C-Roads, ETSI) have not yet been assessed in highly ranked journal publications. Table 2 provides a summary of the services for which IA studies are still pending.

Furthermore, C-ITS services specifically addressing traffic safety are assessed less frequently than services regarding the impact categories traffic efficiency and sustainability. One reason for the lower testing frequency of road safety services is attributed to the methodological difficulty of capturing impacts, especially in the context of simulation studies, as it is particularly difficult to define KPIs for measuring road safety impacts.

Firstly, accidents often depend on causes that are not included in simulation models and arise for reasons other than pure vehicle interaction in traffic (e.g., unfavourable driving conditions, distracted drivers, influence of psychosomatic conditions or medication, wildlife accidents). Secondly, the simulation models used are frequently designed as accident-free (e.g., Krauss Model). In this context, auxiliary KPIs are used to estimate the impact of C-ITS on road safety, such as the TTC, or the minimum braking rate required to avoid an accident (Deceleration Rate to Avoid Collision – DRAC) is calculated. Using this, a threshold can be used to classify various events as an accident or not. This is often the case in simulations, where unrealistically abrupt braking manoeuvres are required to comply with the collision-free condition of the simulation model. Using the example of the DRAC, the maximum deceleration rate that can realistically be assumed can therefore be set as the limit for the classification as accident or non-accident.

5.3 Assessment of C-ITS service bundles

Regarding the literature considered, it is noticeable that C-ITS services were typically only assessed separately. Although several studies examine more than one C-ITS service, impacts were only assessed independently, in isolation from the interrelations with other C-ITS services. Only Malone and Soekroella [121] and Ognissanto et al. [122] carry out impact analyses based on C-ITS service bundles using cost–benefit analyses. However, the bundles tested were implemented as a whole, again evaluating only the overall impact without considering interdependencies of the individual services.

A possibility for future research would be to investigate how different C-ITS services interact when implemented together. Future research activities could investigate whether and which services lead to increased or unchanged impacts or cancel out each other's positive effects. A closer examination of service bundles could thus reveal possible well-harmonizing service combinations.

Table 2 C-ITS services not yet be assessed in highly ranked journal papers

C-ITS Services not yet assessed:	Service Category [31, 32]
Cooperative glare reduction	Day 1
Dynamic access control of designated infrastructure	Day 1
Dynamic environmental zones	Day 1
Road operator vehicle warning	Day 1
Stop sign violation warning	Day 1
Traffic light prioritisation	Day 1
Unsecure blockage of road warning	Day 1
Vehicle access restrictions	Day 1
Winter maintenance warning	Day 1
Cooperative and automated parking	Day 3 +
GLOSA 2.0[a]	Day 3 +
Target driving area reservation	Day 3 +

[a] In addition to the basic GLOSA service, GLOSA 2.0 uses vehicle feedback information to control traffic light phases [32]

5.4 Spatial scope and generalisation of impact assessment studies

Future research areas can also be identified based on the spatial conditions underlying the IA studies. The current literature mostly conducts studies based on highway sections, intersections or (sub) urban roads. The road types used correspond to smaller sections of larger road networks, meaning that the impact of C-ITS is only assessed at points in road networks with few interactions with other street segments.

However, it would be relevant to investigate interactions between different road segments, as changes in traffic efficiency at one point in a road network can also result in (positive or negative) changes at other points in traffic. Future research should therefore expand the geographical scope of investigation and assess the impacts of C-ITS not only on specific road sections but based on larger road networks.

Furthermore, the IA of C-ITS raises the question of whether the results of the respective IA study can also be generalised. Since each selected test site for IA studies also shows individual framework conditions, it cannot be inferred that the results achieved in a single test can be obtained for all possible implementation sites. A key question for future research would therefore be: 'How can the results of a particular test be ensured to be generalisable?'.

When considering C-ITS based on large road networks, the question arises, especially for V2I-based C-ITS applications, where these technologies should best be placed and where they have the greatest benefit in terms of positive impacts on relevant impact categories. In the current literature, locations for C-ITS implementations are defined in advance, and IA studies are conducted based on these locations. However, an inverse approach would be feasible, namely the implementation of C-ITS services based on the characteristics of different locations by using a target-oriented approach, since C-ITS services might not result in the same impacts under all location-dependent conditions. Accordingly, future research should focus not only on assessing the effect of C-ITS at pre-selected locations, but specifically on identifying the conditions under which C-ITS services work well in terms of their impact.

5.5 Level of detail of simulation models

The consideration of larger networks for C-ITS IA studies is accompanied by an examination of the underlying simulation models. As shown in Fig. 6, except for driving simulators, only microscopic and sub-microscopic simulation models are used for traffic simulations. Especially in simulation studies using large traffic networks and with a high number of simulated entities, microscopic as well as sub-microscopic simulation models can have high runtimes due to their computational complexity. Therefore, in future research, simulation models that can simulate traffic flow at a higher level of abstraction, such as mesoscopic and macroscopic traffic simulation models, should be investigated for their applicability to C-ITS IA studies.

6 Conclusion

This paper investigates the current state of the art in C-ITS IA using a structured literature review approach and highlights several important findings. In addition to the general focus on the topic of C-ITS IA the 104 highly ranked journal publications analysed in this work were examined in terms of their IA methodology, the impact category considered, as well as for current research gaps and future research potential.

In general, there has been a steady increase in the number of papers published in this area, indicating both research interest and relevance. Numerous C-ITS services have already been tested in the past and some conclusions can be drawn from a comparison of these tested services. A comparison of the assessed C-ITS services of the published studies considered in this context with the services defined by ETSI, C-Roads and the C2C Consortium reveals some services that have not been covered by IA studies in highly ranked journals. In addition, some dependence of the testing frequency of C-ITS services on their primary objectives can be identified. Due to methodological challenges, services specifically designed for safety purposes are tested less frequently than those

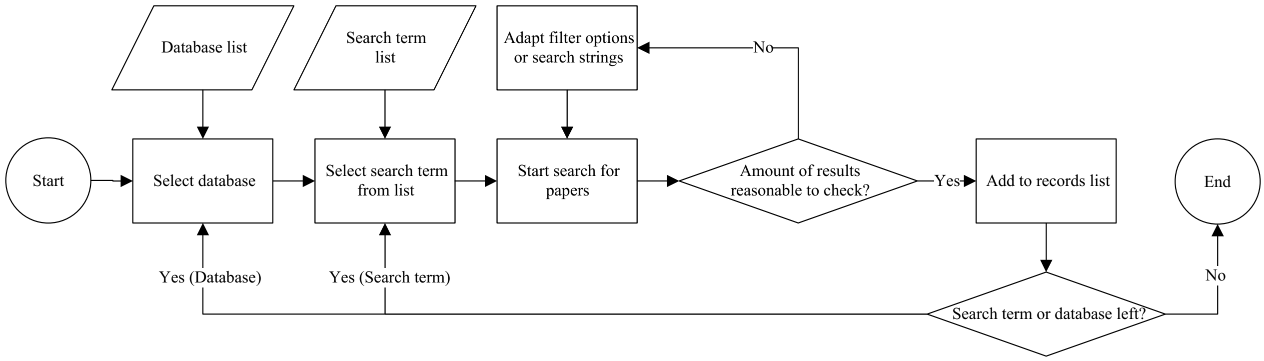

Fig. 27 Database search process

aimed at improving transport efficiency or sustainability. Opportunities for future research activities therefore lie in the investigation of services that have not yet been tested, as well as in research into methods for reliably assessing the impacts of C-ITS on road safety.

Furthermore, an important finding emerges from the analysis of current C-ITS IA studies, as impacts are only considered in a restricted way in each case, whether due to spatial conditions or in terms of consequential effects or rebound effects of the individual services. For example, an important yet unanswered question arising from the analysis of the current literature is whether the results of the studies, based on different settings (e.g., selected C-ITS service, local context, traffic volume, methodology etc.), are generalisable. Meaning investigating whether the impacts are valid and reliably transferable to general conditions or whether they are only obtained under the given settings. Furthermore, the current state of research does not consider the consequential effects of C-ITS, again in terms of the spatial scope, but also considering potential causal relations of different impact categories and performance indicators. For example, the impact of C-ITS on a particular section of a road network may also have an impact on other road sections which, although not directly in contact with the C-ITS service, are nevertheless indirectly affected by it. Furthermore, the sole consideration of a single variable or impact category is not sufficient for a holistic assessment. The different impact categories and their indicators can be linked, which leads to follow-up effects and possibly also to rebound effects. However, by focusing on a limited aspect of the traffic system, such consequences cannot be detected. A holistic assessment should therefore consider the impact of C-ITS on both the specific subsystem and the overall transport system. This requires a systematic analysis that considers the interactions between the different components of the transport system. Future research activities should therefore consider such interactions of the different impact categories and their characteristics to be able to capture the overall impacts of C-ITS on the 'system traffic'.

In summary, the contents of this paper provide a high-level overview of the current state of the art in the field of C-ITS IA and point out directions for future research. C-ITS stakeholders may benefit from the results in various ways. For example, road operators could be supported when deploying C-ITS services through increased awareness regarding relevant impact dimensions and

Table 3 Filter Criteria

Step	Variable	Description	Number of papers after filters were applied	Number of papers removed
1	Publication year	2016 to 2022	221	42
2	Publication type	Journal publications only	137	84
3	Journal ranking	Q2 or higher	113	24
4	C-ITS type (1)	"Not Specified" C-ITS types were filtered	111	2
5	C-ITS type (2)	Studies only testing C-ITS Message types have been removed	107	4
6	Impact assessment method	Only studies that clearly state the impact assessment methods used	104	3

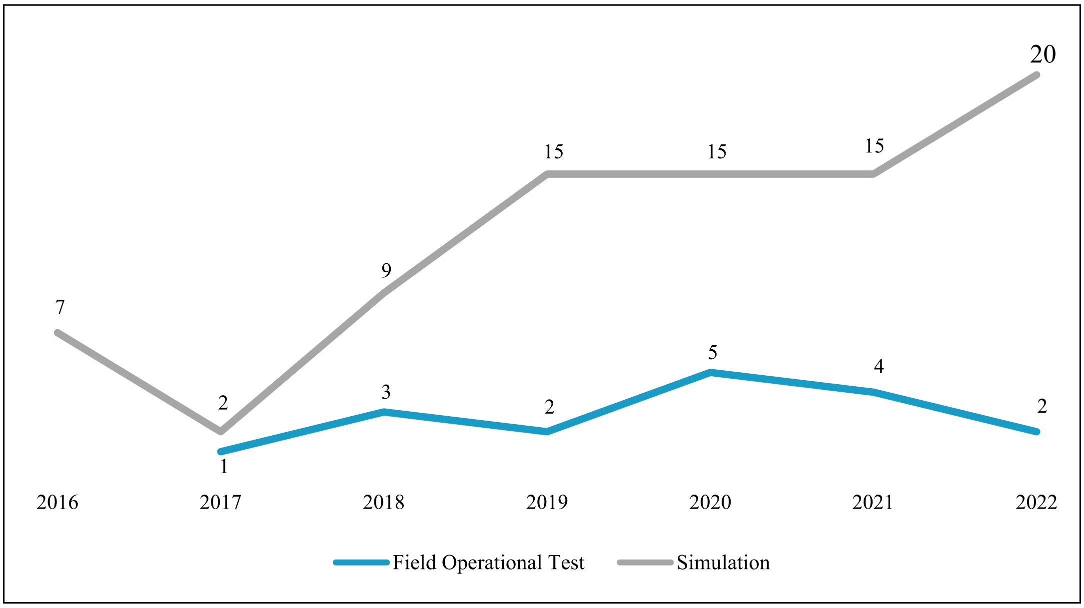

Fig. 28 Development simulation & FOTs-publication quantity

prevailing methods. Researchers and system developers could be supported through increased awareness when designing follow-up C-ITS impact studies and contextualizing their results within the existing state of the art. For example, they may use the literature classification as navigational aid to identify aspects that are not covered by the state of the art so far.

7 Annex

7.1 Methodology (extended)

The procedure in each of the four phases of the PRISMA approach is described in detail in the following sections.

7.1.1 Identification

In the identification phase, both the databases as well as search terms were determined. As this work is focused on C-ITS services, several combinations of the terms 'C-ITS' and 'Cooperative Intelligent Transport System'

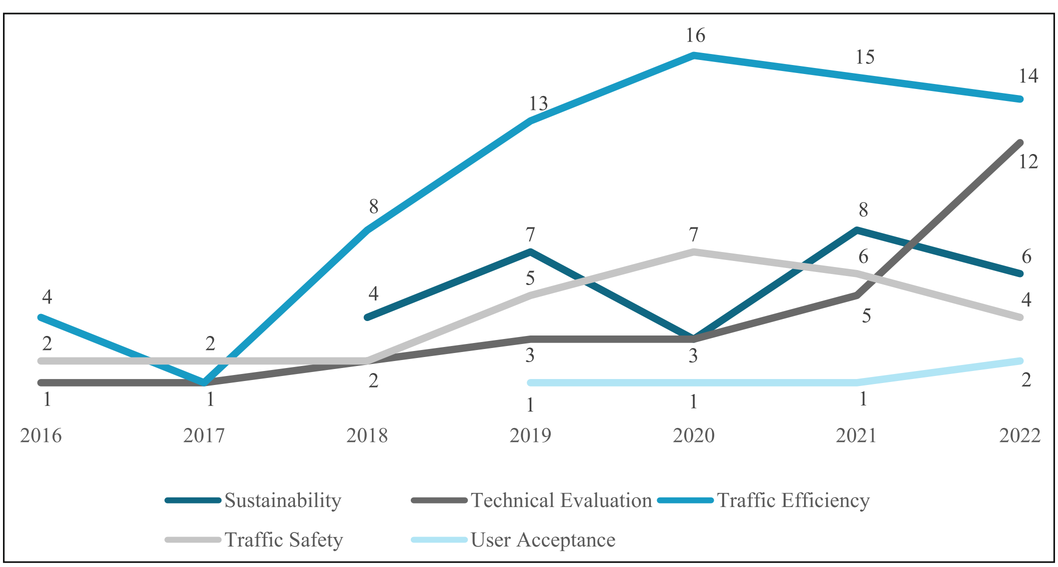

Fig. 29 Development impact categories-publication quantity

have been used as search terms and combined with other terms specifically related to impact assessment and its methodology. The following expressions were used:

- C-ITS
  - Field test
  - Impact
  - Impact assessment
  - Simulation
- Cooperative intelligent transport system
  - Field test
  - Impact
  - Simulation

After some initial database research, two additional search terms were added based on the experience gained. The services investigated in this work have different terminologies and are not always referred to as 'C-ITS' services. Therefore, the general term of these types of communication technologies 'V2X' was added to broaden the search space. The list has been expanded to include the two entries 'V2X field tests' and 'V2X simulation'.

The database and the list of search terms formed the starting point for the identification phase. The detailed process of the database search is shown in Fig. 27.

After completing the search for each database and search term, duplicate entries were removed. Due to the similarity of the search terms, the number of duplicates in the search process was high. Accordingly, 24,087 entries were removed, leaving 25,927 entries for screening at title level.

7.1.2 Screening

In the screening phase, the identified papers were screened at title level according to the preliminary list. The individual titles were checked whether they fit the thematic focus 'C-ITS' in terms of content. If this was not the case, the entries were removed from the list. A total of 23,504 entries were removed from the list in this way. The remaining 2,423 entries were screened at abstract level. Analogously, the abstracts were again used to check whether the papers fit the thematic focus 'C-ITS'. Papers identified as not fitting (1,707 entries) were again dropped, leaving 716 for a more detailed content analysis.

7.1.3 Eligibility

The remaining papers were subjected to a more detailed analysis in the eligibility phase. The content of the papers was checked to see whether they fit into the thematic focus of C-ITS. If this was not the case, the entries were removed from the list (453 entries). Moreover, the papers that were considered as suitable in terms of content (263 papers) were subjected to a classification according to several criteria (general information, criteria related to C-ITS impact assessment, study setup criteria) to be able to analyse the papers more precisely.

To make the number of papers to be analysed in this work manageable, filter criteria were defined in a further step. An overview of the criteria applied is illustrated in Table 3.

A comparison of the number of publications by year shows an increase in research interest from 2016 onwards. The preliminary list of papers was filtered accordingly. To identify potentially high-quality publications from the list, only publications from scientific journals ranking Q2 or higher were considered. Non-specified C-ITS services were excluded, as no concrete conclusion can be drawn about the service or its functionality. Furthermore, studies that only focus on C-ITS message types were removed, as they only describe the type of information exchanged via V2X communication, but not how this information is subsequently processed or how the information contained therein is used. Finally, publications that did not provide methodological approaches were also removed.

7.1.4 Included

After applying the PRISMA method and the filtering procedure as described in Table 3, 104 papers remained, which are analysed in more detail in the following sections. A list of the included papers along with their classification can be found in Tables 4 and 5.

7.2 Evolution of publication counts

Figure 28 presents a comparative analysis of the number of publications related to the impact assessment methods FOTs and simulations from 2016 to 2022. It provides an overview of the overall development of the frequency of highly-ranked publications for each method.

Starting with a single study in 2017, the number of FOTs has fluctuated for the past years, ranging from two to five studies annually. Notably, in 2019 and 2022 two FOT-studies were published, while 2020 exhibited the highest count at five. However, these fluctuations indicate no discernible trend for a consistent rise or decline in FOT usage over time.

In contrast, the number of simulation studies for C-ITS impact assessment shows an increasing trend. Starting with seven simulation studies in 2016, the number gradually increases to 20 simulations in 2022, with a onetime decrease in the frequency of simulation studies in 2017. This trend underlines the growing use and importance of simulation methods in research.

Table 4 Literature table—methods and impact categories

References	C-ITS service	Method						Impact categories							
		FOT	Simulation	Questionnaire	Interview	Literature review	Other	Traffic efficiency	Sustainability	Traffic safety	Functionality	Economic impact	Social impact	User acceptance	Psychological impact
[34]	CSPC		x					x							
[35]	CMeC		x					x			x				
[36]	CACC		x					x	x						
[37]	Platoon-ing		x					x		x			x	x	
[38]	CIM		x					x	x		x				
[40]	CMeC, Platoon-ing		x					x							
[41]	Platoon-ing, RWW		x					x							
[42]	CLCA/C, RWW		x					x							
[43]	CLCA/C, CR, GLOSA, Platoon-ing		x					x	x						
[44]	CACC	x	x					x		x					
[45]	GLOSA	x									x				
[46]	AHW, CR, EVW, RHW, RWW, TJAW, WWVW	x									x				
[47]	WW		x					x		x					
[49]	Platoon-ing		x							x					
[50]	EEBL, EVW, RWW, TJAW		x	x										x	
[51]	CLCA/C		x											x	
[52]	GLOSA		x					x	x		x				
[53]	CACC		x					x	x		x				
[54]	CSA/C		x					x			x	x			
[55]	Platoon-ing		x							x	x				
[56]	Platoon-ing		x							x	x				

Table 4 (continued)

References	C-ITS service	Method						Impact categories							
		FOT	Simulation	Questionnaire	Interview	Literature review	Other	Traffic efficiency	Sustainability	Traffic safety	Functionality	Economic impact	Social impact	User acceptance	Psychological impact
[57]	CSA/C		x						x		x				
[79]	CLCA/C	x									x				
[80]	WW	x									x				
[81]	CCA	x									x				
[82]	RECW	x								x	x				
[83]	RHW, RWW, VRUW, WW, WWVW	x								x	x				
[84]	VRUW	x								x					
[85]	CACC	x						x	x						
[86]	EVW	x									x				
[87]	CACC, CSPC	x						x			x				
[88]	PTVCW	x		x				x		x				x	
[89]	GLOSA	x	x					x	x						
[90]	PTVCW	x								x					
[91]	EVW, FCW, RWW, SVW, WW	x								x					
[92]	Platoon-ing	x						x		x	x				x
[93]	CBW, EEBL, IVS, RWW, TJAW, WW					x	x	x		x					x
[94]	BSD, Coop-erative (Emer-gency) Braking, VRUW				x	x	x			x					
[96]	CEC, RHW				x	x	x			x					
[97]	CEC, RHW				x	x	x			x					
[98]	VRUW			x			x							x	

Table 4 (continued)

References	C-ITS service	Method						Impact categories							
		FOT	Simulation	Questionnaire	Interview	Literature review	Other	Traffic efficiency	Sustainability	Traffic safety	Functionality	Economic impact	Social impact	User acceptance	Psychological impact
[99]	CLCA/C, EEBL, ICW, MCRW, OVW, SVW, WWVW					x				x					
[100]	CACC		x					x	x						
[101]	CACC		x					x	x						
[102]	GLOSA		x					x	x		x				
[104]	CACC, GLOSA		x						x						
[105]	GLOSA		x					x	x						
[106]	CSA/C		x					x	x	x					
[107]	GLOSA		x					x	x						
[108]	CR, CSPC		x					x	x						
[111]	CSA/C		x					x	x						
[112]	CMeC		x					x	x						
[113]	CSA/C, GLODTA		x					x	x						
[116]	CACC		x					x	x						
[117]	Platoon-ing		x					x	x						
[119]	CSPC		x					x	x						
[123]	CACC		x					x		x					
[124]	CACC		x					x							
[125]	CACC		x					x							
[126]	ICW		x							x					
[127]	CR		x					x	x		x				
[128]	CACC		x					x							
[129]	CACC		x					x							
[130]	CACC		x						x						
[131]	CACC		x					x							
[132]	CACC		x					x							
[133]	CIM		x					x	x	x					
[134]	CACC, Platoon-ing		x					x							

Table 4 (continued)

References	C-ITS service	Method						Impact categories							
		FOT	Simulation	Questionnaire	Interview	Literature review	Other	Traffic efficiency	Sustainability	Traffic safety	Functionality	Economic impact	Social impact	User acceptance	Psychological impact
[135]	CCA		x							x					
[136]	CCA		x							x					
[137]	CCA, CIM		x								x				
[138]	CIM		x					x							
[139]	CLCA/C		x					x							
[140]	CLCA/C		x					x							
[141]	CIM		x					x	x				x		
[142]	CACC		x					x							
[143]	CLCA/C		x					x	x						
[144]	CLCA/C		x					x							
[145]	CLCA/C		x					x							
[146]	CLCA/C		x					x							
[147]	CLCA/C		x					x		x					
[148]	CLCA/C, CMeC		x					x							
[149]	CLCA/C, CMeC		x					x							
[150]	CLCA/C, GLOSA		x					x							
[151]	CMaC		x					x							
[152]	CMeC		x					x		x					
[153]	CMeC		x					x			x				
[154]	CMeC		x					x		x					
[155]	CACC		x							x					
[156]	CR		x					x	x						
[157]	CSA/C		x					x							
[158]	CIM		x					x			x				
[159]	CSPC		x					x							
[160]	CACC		x					x							
[161]	GLOSA		x					x	x						
[162]	Platoon-ing		x								x				
[163]	Platoon-ing		x								x				
[164]	Platoon-ing		x								x				

Table 4 (continued)

References	C-ITS service	Method						Impact categories							
		FOT	Simulation	Questionnaire	Interview	Literature review	Other	Traffic efficiency	Sustainability	Traffic safety	Functionality	Economic impact	Social impact	User acceptance	Psychological impact
[165]	Platoon-ing		x					x							
[166]	Platoon-ing		x								x				
[167]	RHW		x					x	x						
[168]	SD		x					x							
[169]	CIM		x					x							
[170]	Platoon-ing		x					x							

Table 5 Literature table—road types, road data sources, temporal conditions and traffic demands

References	C-ITS service	Road type							Road data source			Temporal conditions			Traffic demand		
		Highway	(Sub) Urban road(s)	Intersection	(City) network	Test track	Street Sections (Not specified)	NA	Artificial road network	Real-world network	NA	Peak hours	Off-peak hours	NA	Real-world data	Artificial setup	NA
[34]	CSPC			x					x					x		x	
[35]	CMeC	x							x					x		x	
[36]	CACC	x							x					x		x	
[37]	Platooning							x			x			x		x	
[38]	CIM			x			x		x					x		x	
[40]	CMeC, Platooning	x							x					x		x	
[41]	Platoon-ing, RWW	x								x				x	x		
[42]	CLCA/C, RWW	x								x		x			x		
[43]	CLCA/C, CR, GLOSA, Platooning		x	x	x					x		x			x		
[44]	CACC		x	x						x		x	x				x
[45]	GLOSA			x						x				x	x		
[46]	AHW, CR, EVW, RHW, RWW, TJAW, WWVW	x								x				x			x
[47]	WW	x								x				x			x
[49]	Platooning	x							x					x			x
[50]	EEBL, EVW, RWW, TJAW	x							x					x			x
[51]	CLCA/C	x							x					x			x
[52]	GLOSA		x	x						x				x			x
[53]	CACC		x	x						x				x			x
[54]	CSA/C						x		x					x			x
[55]	Platooning							x			x			x			x
[56]	Platooning							x			x			x			x
[57]	CSA/C							x			x			x			x
[79]	CLCA/C					x				x				x			x

Table 5 (continued)

References	C-ITS service	Road type							Road data source			Temporal conditions			Traffic demand		
		Highway	(Sub) Urban road(s)	Intersection	(City) network	Test track	Street Sections (Not specified)	NA	Artificial road network	Real-world network	NA	Peak hours	Off-peak hours	NA	Real-world data	Artificial setup	NA
[80]	WW					x				x				x			x
[81]	CCA					x				x				x			x
[82]	RECW					x				x				x			x
[83]	RHW, RWW, VRUW, WW, WWVW	x				x				x				x	x		
[84]	VRUW					x				x				x			x
[85]	CACC					x				x				x	x		
[86]	EVW		x	x						x				x			x
[87]	CACC, CSPC		x	x						x				x	x		
[88]	PTVCW		x	x						x				x	x		
[89]	GLOSA		x	x						x		x	x		x		
[90]	PTVCW			x						x				x	x		
[91]	EVW, FCW, RWW, SVW, WW	x								x				x	x		
[92]	Platooning				x					x				x			x
[93]	CBW, EEBL, IVS, RWW, TJAW, WW							x			x			x	x		
[94]	BSD, Coopera-tive (Emer-gency) Braking, VRUW							x			x			x			x
[96]	CEC, RHW							x			x			x			x
[97]	CEC, RHW							x			x			x			x
[98]	VRUW			x					x					x			x

Table 5 (continued)

References	C-ITS service	Road type							Road data source			Temporal conditions			Traffic demand		
		Highway	(Sub) Urban road(s)	Intersection	(City) network	Test track	Street Sections (Not specified)	NA	Artificial road network	Real-world network	NA	Peak hours	Off-peak hours	NA	Real-world data	Artificial setup	NA
[99]	CLCA/C, EEBL, ICW, MCRW, OVW, SVW, WWVW							x			x			x			x
[100]	CACC							x			x			x			x
[101]	CACC	x								x		x					x
[102]	GLOSA			x					x					x			x
[104]	CACC, GLOSA							x			x			x			x
[105]	GLOSA					x				x				x		x	
[106]	CSA/C							x			x			x			x
[107]	GLOSA			x						x		x	x		x		
[108]	CR, CSPC				x					x				x		x	
[111]	CSA/C		x	x						x				x	x		
[112]	CMeC	x							x					x			x
[113]	CSA/C, GLODTA		x	x						x				x			x
[116]	CACC	x								x				x		x	
[117]	Platooning							x			x			x			x
[119]	CSPC			x						x		x	x		x		
[123]	CACC							x			x			x			x
[124]	CACC	x							x					x		x	
[125]	CACC	x							x					x		x	
[126]	ICW			x					x					x			x
[127]	CR			x					x					x		x	
[128]	CACC							x			x			x			x
[129]	CACC	x							x					x			x
[130]	CACC							x			x			x			x
[131]	CACC	x							x					x		x	
[132]	CACC	x								x				x			x
[133]	CIM			x			x		x					x		x	

Table 5 (continued)

References	C-ITS service	Road type							Road data source			Temporal conditions			Traffic demand		
		Highway	(Sub) Urban road(s)	Intersection	(City) network	Test track	Street Sections (Not specified)	NA	Artificial road network	Real-world network	NA	Peak hours	Off-peak hours	NA	Real-world data	Artificial setup	NA
[134]	CACC, Platooning	x								x				x	x		
[135]	CCA							x			x			x			x
[136]	CCA							x			x			x			x
[137]	CCA, CIM			x					x					x		x	
[138]	CIM			x					x					x		x	
[139]	CLCA/C	x								x		x			x		
[140]	CLCA/C	x							x					x	x		
[141]	CIM			x					x					x			x
[142]	CACC	x							x					x			x
[143]	CLCA/C							x			x			x			x
[144]	CLCA/C	x							x					x	x		
[145]	CLCA/C	x								x		x					x
[146]	CLCA/C	x							x					x		x	
[147]	CLCA/C	x							x					x		x	
[148]	CLCA/C, CMeC	x							x					x			x
[149]	CLCA/C, CMeC	x								x				x		x	
[150]	CLCA/C, GLOSA		x	x					x					x			x
[151]	CMaC	x							x					x			x
[152]	CMeC	x								x				x	x		
[153]	CMeC	x							x					x			x
[154]	CMeC				x				x					x		x	
[155]	CACC	x							x					x		x	
[156]	CR				x					x		x				x	
[157]	CSA/C	x							x					x		x	
[158]	CIM			x					x					x		x	x
[159]	CSPC				x					x		x			x		
[160]	CACC	x							x					x			x
[161]	GLOSA		x	x						x				x			x

Table 5 (continued)

References	C-ITS service	Road type							Road data source			Temporal conditions			Traffic demand		
		Highway	(Sub) Urban road(s)	Intersection	(City) network	Test track	Street Sections (Not specified)	NA	Artificial road network	Real-world network	NA	Peak hours	Off-peak hours	NA	Real-world data	Artificial setup	NA
[162]	Platooning							x			x			x			x
[163]	Platooning							x			x			x			x
[164]	Platooning							x			x			x			x
[165]	Platooning							x			x			x			x
[166]	Platooning	x							x					x			x
[167]	RHW	x								x				x	x		
[168]	SD	x							x					x			x
[169]	CIM				x				x					x			x
[170]	Platooning							x			x			x			x

Methods other than FOTs and simulations were only used sporadically. In the period 2016–2018, one study was published each year that used interviews or literature reviews as a methodology. In contrast, questionnaires were only used in one study in each of the years 2020 to 2022. A BTA was used as a methodology once in each of the years 2016 and 2018 and UTAUT only once in 2022.

In addition to the methods, the development of the analysed impact categories can also be analysed. Figure 29 depicts the quantity of publications across different impact categories from 2016 to 2022.

In 2016, there were two publications related to sustainability, while there was only one technical evaluation. There were also four studies analysing the impact of C-ITS on traffic efficiency, and two publications analysing issues related to traffic safety. There are variations and trends in the number of publications in these categories over the years.

For example, the number of studies on sustainability fluctuates between 2016 and 2021, ranging from three to eight publications per year and peaking at eight publications in 2021. The number of technical evaluations remained relatively low in the early years and started to increase significantly in 2021 and 2022. Traffic efficiency studies show an upward trend, with publications increasing from four in 2016 to 16 in 2020, before stabilising around 15 in the following years. Similarly, traffic safety shows a variable trend over time, with an increase in the number of studies until 2020, followed by a decrease until 2022. The number of user acceptance studies remains generally low and constant over time.

7.3 Literature Table

Tables 4 and 5 show a list of the journal papers analysed in this work with their classification.

Abbreviations

AHW	Accident ahead warning
BSD	Blind spot detection
BTA	Bow-tie-analysis
CACC	Cooperative adaptive cruise control
CAV	Connected and automated vehicles
CBW	Car breakdown warning
CCA	Cooperative collision avoidance
CCAM	Connected, cooperative and automated mobility
CEC	Cooperative emergency call
CIM	Cooperative intersection management
C-ITS	Cooperative intelligent transport system
CLCA/C	Cooperative lane change advisory/control
CMaC	Cooperative maneuver coordination
CMeC	Cooperative merging control
CR	Cooperative routing
CSA/C	Cooperative speed advisory/control
CSPC	Cooperative signal phase control
DRAC	Deceleration rate to avoid collision
EEBL	Emergency electronic brake light
ERiC	European risk calculation tool
EVW	Emergency vehicle warning
FCW	Forward collision warning
FOT	Field operational test
GLODTA	Green light optimal dwell time advisory
GLOSA	Green light optimal speed advisory
HBEFA	Handbook Emission Factors for Road Transport
HMI	Human-machine-interface
IA	Impact assessment
ICT	Information and communication technology
ICW	Intersection collision warning
IDM	Intelligent driver model
IVS	In-vehicle signage
MCRW	Merging collision risk warning
OVW	Overtaking vehicle warning
PHEM	Passenger Car and Heavy Duty Emission Model
PTVCW	Public transport vehicle crossing warning
RECW	Rear-end collision warning
RHW	Road hazard warning
RWW	Road works warning
SD	Shockwave damping
SVW	Stationary vehicle warning
TET	Time exposed time-to-collision
TIT	Time integrated time-to-collision
TJAW	Traffic jam ahead warning
TTC	Time-to-collision
UTAUT	Unified theory of acceptance and use of technology
V2X	Vehicle-to-everything communication
VANET	Vehicular ad-hoc network
VRU	Vulnerable road user
VRUW	Vulnerable road user warning
WW	Weather warning
WWVW	Wrong way vehicle warning

Author contributions

MW carried out the literature review for this paper and made a substantial contribution to the preparation of the manuscript. AS provided ongoing support throughout the research and writing process and made a substantial contribution to the content of the article. Similarly, MN made a substantial contribution to the manuscript through proofreading and feedback. All authors read and approved the final manuscript.

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Availability of data and materials

The dataset(s) supporting the conclusions of this article is(are) included within the article (and its additional file(s)).

Declarations

Competing interests

The authors declare that they have no competing interest.

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