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Review

The State of the Art of Cooperative and Connected Autonomous Vehicles from the Future Mobility Management Perspective: A Systematic Review

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Abstract: Cooperative and connected autonomous vehicles (CCAVs) are considered to be a promising solution for addressing congestion and other operational deficiencies, as part of a holistic future mobility management framework. As a result, a significant number of studies have recently been published on this topic. From the perspective of future mobility management, this review paper discusses three themes, which are traffic management, network performance, and mobility management, including congestion, and incident detection using the PRISMA methodology. Three databases were considered for this study, and peer-reviewed primary studies were selected that were published within the last 10 years in the English language, focusing on CCAV in the context of the future transportation and mobility management perspective. For synthesis and interpretation, like-for-like comparisons were made among studies; it was found that extensive research-supported information is required to ensure a smooth transition from conventional vehicles to the CCAVs regime, to achieve the projected traffic and environmental benefits. Research investigations are ongoing to optimize these benefits and associated goals via the setting of different models and simulations. The tools and technologies for the testing and simulation of CCAV were found to have limited capacity. Following the review of the current state-of-the-art, recommendations for future research have been discussed. The most notable is the need for large-scale simulations to understand the impact of CCAVs beyond corridor-based and small-scale networks, the need for understanding the interactions between the drivers of CCAVs and traffic management centers, and the need to assess the technological transition, as far as infrastructure systems are concerned, that is necessary for the progressive penetration of CCAVs into traffic streams.

Keywords: traffic management; connected; autonomous; modeling; V2V; V2I

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1. Introduction

Urban mobility has reached a critical saturation point in terms of infrastructure use, as many metropolitan areas around the world are experiencing high levels of congestion on a daily basis. Cooperative and connected autonomous vehicles (CCAVs) are considered to be a promising solution for addressing congestion and other operational deficiencies, as part of a holistic future mobility management framework. Policies, strategies, and the technical requirements of CCAVs have been theoretically studied for quite some time; however, practical applications of the integration of CCAVs in current mobility systems have only become the focus of research very recently [1,2]. With the growing literature all over the world, a synthesis of the available information is, thus, required to provide insights into how traffic management systems and strategies and their implementation will be realized in future regimes of CCAVs. Such an effort was made by Elliott et al. [3], who covered five aspects of the operation of CCAVs in their review. These are the inter-connected and autonomous vehicles' (CAVs) communications, security, intersection control, collision-free navigation, and pedestrian detection and protection; therefore, they focus more on operational characteristics at the vehicle level. This paper extends the current reviews using information on future mobility planning, management, and the assessment of future mobility options. Thus, three key themes were selected for this review that were identified as key areas for future mobility management under the project [4]. These are traffic management, network performance (including modeling practices for CCAVs), and congestion and incident detection. In this way, the current paper systematically reviews the literature covering key issues of the transition from the current conventional transportation system toward CCAVs. This review presents the progress of the CCAVs to date and the future direction of the potential paths for effective management of future mobility in the era of CCAVs.

This paper is organized into four sections, covering the relevant information from recent CCAV-related research studies. Section 2 reports the method applied in the paper for reviewing recent advances in the field of CCAVs. Section 3 reviews studies covering three themes: (a) traffic management in the field of cooperative, connected and automated mobility; (b) network performance in the presence of CAVs; and (c) mobility management, including congestion and incident detection. Section 4 concludes the paper by summarizing the key knowledge gaps and future research directions regarding future mobility in the era of CCAVs. The highlights of this paper are below:

1. The traffic and environmental benefits of CCAVs are well understood, but quantification may be inappropriate and inconsistent at this stage because of the lack of appropriate modeling and simulation tools and of field trials.
2. Setting goals for mobility management analysis will dictate how the system will be optimized, but this is likely to undermine the results because of a lack of perception of the future transportation infrastructure.
3. Research efforts are slowly revealing the pathway to the CCAVs regime, e.g., the use of intersection control, but requires consistent and steady efforts and this paper contributes to this by providing future research direction.

2. Methods

The latest guidelines on the preferred reporting items for systematic reviews and meta-analysis (PRISMA) method [5] were followed in this study (see Appendix A). The research studies were identified from three registers; these are ScienceDirect (SD), the Institute of Electrical and Electronics Engineers (IEEE) website, and Taylor & Francis Online Journals. This review compiles information from recent studies covering CCAVs, connected vehicles (CV), connected autonomous vehicles (CAV), connected and automated hybrid electric vehicles (CAHEV), autonomous vehicles (AV), vehicle to vehicle (V2V), and vehicle to infrastructure (V2I) communication, and vehicular ad hoc network systems (VANETS). During the initial screening phase, papers focusing on health, flow improvement, efficiency improvement, cybersecurity assessment, and other topics not pertinent to the current paper's objectives were excluded. From the selected research papers, data on authors, years, study type, study location, modeling type, modeling tool, modeling strategy, and modeling process were collected.

The overall approach for the selection of studies is illustrated in the PRISMA diagram shown in Figure 1. The selected papers were published in the last ten years, in countries around the world. Initially, 1940 studies were identified from the three databases, which were all peer-reviewed articles. By means of exclusion of those papers not linked with the topic of the current study after reviewing the abstract, 275 studies were selected and retrieved. A further 177 studies were excluded after examining the detailed methodology and paper content. In the end, 75 studies were selected and 70 of them were synthesized for this research. The final 70 studies were grouped into three main themes for review and these groups can be seen in Table 1. The searches were conducted by all three authors during the period of October 2021 to February 2022.

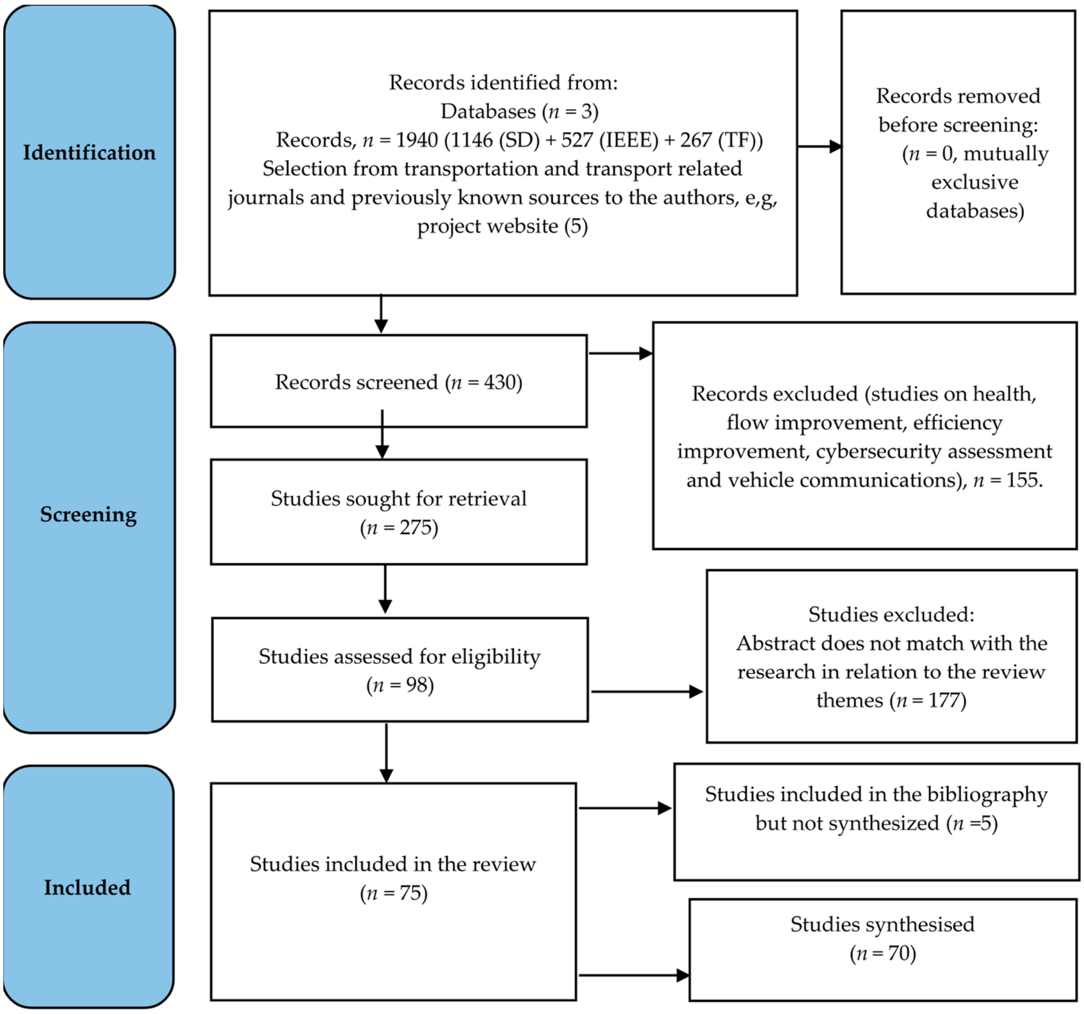

Figure 1. Flowchart of the systematic review using the PRISMA guidelines.

Table 1. Systematic classification of studies considered under each of the themes.

Topic	General Discussion	Theme 1: Traffic Management in the Regime of CCAV	Theme 2: Network Performance in the Presence of CAVs	Theme 3: Congestion, Incident Detection and Mobility Management
Number of Studies/Research papers	5	18	43 (8 of them repeated *)	26 (9 of them are repeated *)
List of papers	[1–3,5,6].	[7–24].	[1,9,10,15–18,21] *; [25–58].	[13,17,20,44] *; [28,36,39,41,43] **; [59–75].

Note: * discussed under theme 1 & ** discussed under theme 2.

The data synthesis method includes quantitative analysis covering the comparisons, integration and categorization of information, based on the three themes. The extracted information (i.e., study type and year) was gathered and processed in an Excel spreadsheet. The synthesis of the information was conducted using Thomas and Harden's [6] descriptive thematic analysis. Quantitative information on the size of the network and study description was also included in the discussion. However, the results of the studies were not compared against each other as the results are heterogeneous, even though they discuss the same type of road (e.g., freeways), because the modeling and analysis were very different in nature. Most importantly, the synthesis of the results from the studies was not included because the objective of this review paper is to identify the progress of knowledge on the three themes of future mobility and to highlight the gaps in knowledge addressing future mobility management.

3. Results

Three themes are presented in Table 1; the number of research papers and research studies that were included in the synthesis of information is also presented in the table.

3.1. Traffic Management in the Regime of CCAV

Traffic management in this section was discussed in terms of scenarios incorporating networks for both mixed traffic situations and for CCAVs only. Similar to management strategies for conventional traffic, traffic management under the regime of CCAVs aims to achieve numerous goals, such as the optimum use of energy, reliable journeys, and the reduction of accidents, economic loss, environmental pollution, and congestion. Achieving goals also varies, according to operational strategy. Gomides et al. [13] provided a systematic overview of the literature on traffic management solutions, covering V2V and V2I systems, and proposed a system to decrease the average travel time of vehicles, with a low impact on the traveled distance. Different levels of controllers for achieving different goals while managing traffic flow are also found in the literature. For instance, Tettamanti et al. [19] proposed a two-level control strategy to solve an optimization problem for network-wide traffic where, at local intersections, the controller ensures the safe crossing of vehicles and aims to reduce traffic emission in the junction area, while local controllers optimize network performance by minimizing queues in all road links. CCAVs are prioritized in these studies, and prediction models are often utilized in terms of facilitating future traffic management [8,20,21].

The following studies in this paragraph have employed many methods and models; however, the underlying basic components of achieving the above goals are improving vehicle communication in a flow of information that comes both from vehicles in the vicinity and from the traffic management center. Du et al. [11] reported that connected vehicles can improve mixed-traffic passing rates (comprising both CVs and conventional vehicles) at traffic signals, by reducing lost time from the yellow-light dilemma of the drivers and by improving the communication between vehicles. Chang et al. [9] claimed that in a 100% connected vehicle regime for autonomous vehicles, conventional traffic control systems, including traffic signals, markings, and signs, will be obsolete. For mixed traffic situations, however, signals will still be needed. Zhao and Zhang [24] provided a modeling framework that uses location-based traffic control devices and road geometry constraints. Concepts that are similar to these can be deployed in the transition period from conventional to a CCAV traffic management regime. Qian et al. [16] proposed traffic scheduling and control by adjusting the stable traffic state, using a hierarchical traffic management scheme. The process optimizes the departure times, travel routes, and signal timings using the National Electrical Manufacturing Association's phasing structure at the central controller, along with the longitudinal trajectories of CAVs using distributed roadside processors.

A number of studies investigated the management of the operation of connected vehicles by addressing their safe, efficient, and stable movement using trajectories [15] and preventing shockwave formation and propagation in the network under different assumptions [13,18,19]. Various studies focused on how such an operation can be managed; there is a lack of cross-comparison of the different operational studies to identify the most suitable methods. Li et al. [14] proposed a feedback-based platoon control protocol for CAVs with respect to the position and velocity dependencies and concluded that the convergence time of the control protocol is associated with the initial states of the scenarios. Conversely, Bian et al. [7] studied the benefits of V2V communications in reducing the time headway of platoons. In addition, Yang et al. [23] proposed a platoon formation approach for managing CAVs, using dynamic programming and car-following driving concepts, combined with feed-forward–feedback control. Chen et al. [10], on the other hand, proposed that AVs will show 'foresight' and will be able to determine the speeds and positions of the vehicles in front of them using sensors or through mutual information exchange. Ghiasi et al. [12] proposed an algorithm-based control of CAVs, so that CAVs in mixed traffic, in a hypothetical network, can gradually merge into the traffic stream at a reasonable speed by getting information from backward deceleration waves. Wang and Lin [22] proposed a bi-level eco-driving control strategy, based on a driving scenario classifier. The classifier determines the vehicle mode using real-time road information and a cost function that can be adjusted, according to the variables of safe driving, energy management, and exhaust emissions reduction. Although the above-cited studies, based on modeling and the analytical assumptions, reported various levels of positive results regarding the goals mentioned above, it has been stated that in the real world, the spatial position of the connected vehicle group/the platoon will also impact performance [17].

3.2. Network Performance in the Presence of CAVs

The simulation of CCAV has typically been undertaken by making a range of simple approximations and changes to pre-existing behavior, such as closer following distances, faster reaction times, and 'error-free' driving paradigms for the different types of networks (Table 2). Table 2 also provides a list of studies that investigate the performance of transport networks, using various types of models involving the behavior of autonomous and connected vehicles. These studies have examined the available technology, ranging from simple adaptive cruise control (ACC), which is now making its market breakthrough, through cooperative vehicles, wherein information is transmitted between vehicles, enabling 'smart' decision-making, all the way to fully automated vehicles and even CAVs, where extensive platoons may be formed. Interest in the simulation of CCAV systems is now undergoing a surge, following high-profile field tests and deployments [1].

Table 2. Studies on network performance in the presence of CCAV.

Study	Area of Interest	Study Focus	Traffic Type	Modeling Strategy
Wu et al. [41]	Intersection	Influence of CAVs platooning on intersection capacity	Mixed	Application of queueing theory, and Markov chain theory
Stern et al. [33]	Intersection control	Shared-phase dedicated-lane-based intersection optimization	Mixed	Algorithm and numerical models
Ma et al. [25]	Intersections	Trajectory planning for CAVs	Mixed	Algorithms
Sala and Soriguera [37]	Motorway/Expressway/Highway	Estimate of average CAVs platoon length	Mixed	Statistical analysis and iterative process
Chen et al. [28]	Motorway/Expressway/Highway	Assessing the stability conditions of mixed platoon system	Mixed	Mathematical modeling
Woo and Skabardonis [39]	Motorway/Expressway/Highway	CAVs impacts on forming platoons and traffic flow	CAVs	Microscopic traffic mode
Yao et al. [42]	Motorway/Expressway/Highway	Influence of CAVs on fuel consumption and emissions of mixed traffic flow	Mixed	Intelligent driving model (IDM); adaptive cruise control (ACC); cooperative adaptive cruise control (CACC)

Table 2. *Cont.*

Study	Area of Interest	Study Focus	Traffic Type	Modeling Strategy
Yao et al. [42]	Motorway/Expressway/Highway	Stability and safety evaluation of mixed traffic flow with CAVs	Mixed	IDM; ACC and CACC
Chen et al. [29]	Motorway/Expressway/Highway	Reconstruction of vehicle trajectories, based on motion detection	CAVs	IDM and simulations
Deveci et al. [21]	Motorway/Expressway/Highway	Prioritization of autonomous vehicles in real-time traffic management	CAVs	Fuzzy multi-criteria decision-based solution
Rubin et al. [36]	Motorway/Expressway/highway: Entry/exit ramps on multi-lane multi-segment highway	Structural formations of platoons and their mobility processes	Vehicles with V2V technology	M/M/1 queuing model and others
Nagalur et al. [38]	Motorway/Expressway/Highway: Lane bottlenecks	Lane assignment strategies: traffic flow at 'diverge and weave' bottlenecks	Mixed	Numerical simulations
Li et al. [46]	Motorway/Expressway/Highway: Merging section of an urban expressway	CAVs' and conventional vehicles' collaboration behaviors on the ramp area	Mixed	VISSIM simulation software
Wu et al. [40]	Motorway/Expressway/Highway: AV expressways and non-autonomous streets	Road users' route choices in a mixed network consisting of both an AV and non-AV facility	Mixed	Mathematical modeling approach
Dayi et al. [30]	Motorway/Expressway/Highway: Bottleneck section of expressways	Prediction of vehicle trajectory	Mixed	Numerical simulation
Amini et al. [26]	Motorway/Expressway/Highway: Freeway weaving segments	Optimizing CAVs trajectories at freeway	CAVs	Algorithm and mathematical modeling approaches
Jing et al. [31]	Motorway/Expressway/Highway: On-ramp and off-ramp	Trajectory planning for collision avoidance	CAVs	The collision prediction algorithm is validated through simulation
Makridisa et al. [69]	Motorway/Expressway/Highway:	Evaluate the behavior of CAVs under realistic traffic conditions	CAVs	VISSIM
Martin-Gasulla and Elefteriadou [35]	Single-lane roundabouts	Optimal coordination of CAVs to negotiate a roundabout, as well as maximizing performance	CAVs	Algorithm-based
Bhargava et al. [27]	Tunnel (Dartford–Thurrock Crossing tunnel, Kent, UK.)	Traffic queues and travel times analysis	Autonomous freight vehicles vs. conventional vehicles	VISSIM simulation software

Table 2. *Cont.*

Study	Area of Interest	Study Focus	Traffic Type	Modeling Strategy
Li et al. [45]	Tunnel entrance	Improving driving behavior with safe decisions	CAVs and conventional vehicle environment	Research builds an experimental test platform, using driving simulation technology
Ye and Yamamoto, [43]	Dedicated lanes for CAVs on traffic flow throughput	Performance of the traffic flow of CAVs and mixed traffic in dedicated lanes	Mixed	Cellular automation model
Stanek et al. [53]	Intersections and network	CAVs penetration	0 to 100% CAVs Penetration	VISSIM

- Location/area of the study:

Table 2 in this section was incorporated to make a like-for-like comparison of the different areas of the network. In other sections, the basis, i.e., the network, is diversified and a descriptive comparison seemed appropriate to convey the messages. System-wide dynamics have also been evaluated; Li et al. [46] investigated connected vehicles at an on-ramp when joining a motorway, whereas Patel et al. [52] investigated AV behavior on arterial and freeway networks, and Zhou et al. [57] conducted research into a T-junction's efficiency improvement. The table also shows that much attention has been paid by the researchers to those areas where only vehicle movements are expected (e.g., motorways); the complexity addressed in the research studies was to improve traffic parameters and optimize the merging and diverging activities. A rather more urban and complex road network was not of interest to the research studies, which may link to many other issues, such as object detection and complex interactions with the Internet of Things (IoTs).

- Simulations and field trials

For the simulation of purely autonomous vehicles, most studies have examined the impact of ACC, as it is these controllers that are at the heart of the longitudinal distance-keeping function of an AV, and the reported effects are quite variable. One reason for these seemingly contradictory findings may be the underlying assumptions used. This has been amply illustrated by James et al. [58] who also examined how these results varied through the use of four different controller models that were gleaned from field trials. While the controllers themselves were found to vary minimally, the use of different parameter settings within these functional forms was found to cause the simulated capacity to vary (by +/−4% at low penetrations, up to almost twice that at 100%), which, in the marginal situations found at lower penetrations, may mean the difference between capacity gain or capacity loss.

While interesting, it is notable that in all these studies, if they are using microscopic modeling, they have focused on comparatively small/toy networks. There are, however, some notable examples. Firstly, Stanek et al. [53] reported consistently positive benefits in two case studies in California, the first a 20-mile section of the I80, with 32 junctions (showing a 30% reduction in network delay, with 24% by 50% penetration, and a 6% increase in network speed), and the second, a 10-mile section of the Route 55 freeway corridor, with 6 interchanges at arterials, 2 interchanges at other freeways, and 14 ramps terminal intersections (showing a 33% reduction in network delay, 28% by 30% penetration, and a 23% increase in network speed). Secondly, Makridis et al. [50] found similar findings to James et al. [58], while examining a network of primarily motorway-class roads surrounding the city of Antwerp in the Netherlands (119 km, 117 junctions), finding the average speed on the network decreasing along with increases in density, especially at high penetrations. Stern et al. [33] conducted a field experiment with one CAV on a single-lane circular track with a radius of 41.4 m, in the presence of 21 additional passenger cars, and found that total fuel consumption was reduced.

A number of interpretations can be made from the above reviews. The studies were often based on hypothetical networks, wherein the researchers of those studies applied algorithm-based analysis or the application of mathematical models. This recent wave of interest has been able to make use of far more complex and powerful analytical tools, due to advances made in computing in recent decades. Furthermore, commercially available technology now allows researchers to base their models on far more certain ground. However, there are a limited number of simulation-based modeling studies observed in the literature, and the spatial coverage of these models is limited. The modeling studies, in general, focused on converting both existing models and modeling platforms to become adoptive of CAVs, while other cases utilized algorithms to represent CAVs. Both approaches have limitations and, thus, the studies are micro-simulations, except in a couple of instances; however, most importantly, none of the studies focused on complex urban road transport systems incorporating several types of road users.

- Model use

Table 2 shows the range of commercial software and research laboratory-developed models that were applied in different research papers, with modifications to accommodate the CAVs. Mena-Oreja et al. [51] simulated a 10-km ring road (with two lanes and ten sources of traffic or destinations on their route) with a traffic density of 36 veh/km, to evaluate AV penetration in mixed traffic using the SUMO modeling platform; they found that the desired gaps, safe gaps, and the maximum platoon length have an impact on platoon condition. Alam and McNabola [47] applied VISSIM and showed that eco-driving vehicles with V2V and V2I connectivity that were moving in platoons could improve traffic performance under heavy traffic loads. Similarly, Lou and Hong [44] applied VISSIM with improvements, using Visual Basic-based coding. Calvert et al. [32] applied an improved IDM and noted that at least 70% of automated vehicles could improve traffic flow. Many studies [9,17,18,42] applied IDM with other models, such as the ACC and CACC, or applied improvements to the modeling process with error estimation or from the behavior of the vehicles. Chang et al. [9] also applied both IDM and a laboratory-calibrated cooperative adaptive cruise-control model to capture the car-following behavior of connected vehicles, while Chen et al. [10] applied a cellular automation model on a circular road scenario, to evaluate an analytical model obtained from the mean-field theory in physics.

While many investigations have focused on the impact of longitudinal control/ communications, equally important paradigms governing lateral (lane-changing) and strategic (routing) behaviors have also been examined. For example, Lu et al. [15] addressed system-optimal and user-equilibrium (UE) traffic assignments, while investigating a trajectory-based traffic management problem to find the optimal trajectories for multiple AVs. Elsewhere, Bahrami and Roorda [48] addressed UE traffic assignment, where the link capacity is a function of the AV proportion of traffic, and modeled a small hypothetical network using the general algebraic modeling system. This investigation also covered a relatively large network, consisting of 416 nodes, 914 links, and 1406 OD pairs. Tani, Sumalee, and Uchida [55] experimented with an assignment model and showed in a test network that if the penetration ratio of CAVs increases, the lane flow will increase as the mean lane capacity increases (the lane capacity variance will decrease), as well as the mean and the variance of lane travel-time decrease. Wang et al. [56] investigated a dynamic cooperative lane-changing model for CAVs, with the possible accelerations of a preceding vehicle. Sun et al. [54] proposed a centralized two-stage optimization-based cooperative lane-change model, while Comert and Begashaw [49] proposed an improved process for estimating queue lengths in the presence of connected vehicles.

3.3. Mobility Management, including Congestion and Incident Detection

CCAVs comply with future mobility management; however, setting goals for mobility management is important, whether it is for travel time reduction, congestion reduction, avoidance, or traffic-flow improvement. CCAVs use data from observations in order to detect congestions; by definition, congestion is the function of a reduction in vehicle speeds, against the speeds set according to road classes, travel time, or a delay exceeding that usually incurred under light or free-flowing travel conditions [64]. Early works on congestion detection focused on floating car data [74]) or on data from V2V communications [59,63] and V2I [73], to detect differences in speed. To manage traffic systems in zones in a metropolitan area, where data are not available during operation, the concept of the deployment of mobile agents to collect and share traffic flow parameters to reduce the frequency of occurrence of traffic congestion and to ensure smooth traffic flow is common [20].

The extracted traffic data were used in various forms of algorithms to detect congestion. The researchers focused on using either reactive, proactive, or hybrid algorithms [71] for sensing potential congestion. Apart from congestion detection using the speed difference mentioned above, the algorithm uses various logics to determine abnormalities in traffic flow, such as a difference in the average traffic density parameters within a certain range in different locations, caused by unforeseen extreme events [44].

CCAVs can also use strategies to avoid congestion by using different routes with the help of the traffic management center, and can also reduce congestion by offering different mobility services. Such routing strategies can be performed through real-time information from V2V and V2I technologies [68] and can exchange information with a transport management center that may have a real-time multi-modal routing engine. A traffic management system may adjust the vehicle routes while vehicles are en-route to facilitate this. The concept is equally important in CCAVs as in other transport-related schemes [61]. To implement such a concept, a hierarchical routing system may be required. In a demonstration of such a system, Akabane et al. [59] designed and implemented a three-layer architecture, namely, environment-sensing and vehicle ranking, knowledge generation and distribution, and knowledge consumption, to detect disruptive events and generate alternative routes for vehicles.

For future mobility services, the traffic management center must have the capability to merge the recommendations of a group of travelers moving in the same direction and also to split the shared mobility number [65] according to requests made by the individual travelers and must be able to distribute the demand for available travel options, such as CAVs. Thus, CAVs can be included in the domain of mobility as a service (MaaS) [62,66] as per the definition of shared mobility [72]. On-demand services can also be offered by CAVs, as demonstrated for the city of Athens by Mourtakos et al. [69].

In traffic flow improvement, CCAV studies include stability when on platoon [28,36,39,41,67], flow improvement in different transport compositions [17,43], and speed adjustment and harmonization [70,75]. Kerner [67] analyzed the effect of autonomous driving vehicles on traffic breakdown in a mixed traffic flow and evaluated the stability of platoons of AVs. Using a simulation platform, Outay [70] evaluated the principles of a proposed safety-driving system for V2V and V2I in hazardous zones, such as in low-visibility areas, and recommended the proper speeds. Similarly, based on tests performed in a driving simulator, Zhao et al. [75] studied drivers' speed adjustments after receiving warnings with respect to different levels of visibility (i.e., no fog, slight fog, and heavy fog) and impact zones (i.e., clear zone, transition zone, and fog zone) in a connected vehicle environment.

These studies are generic in nature and are not specific to defined real-world context; thus, flow improvement to ensure efficient future mobility should be a key area for empirical research. Besides this, the goals discussed above will dictate how the traffic system will be optimized; thus, setting goals is important. The above studies cover different aspects of the goals and the conceptual demonstration, but there is as yet no research on system optimization, considering these goals.

4. Discussion and Future Direction

The reported findings demonstrate the positive results at the traffic-flow level, offering both improved traffic conditions and environmental benefits in introducing CAVs in hybrid traffic scenarios. It is expected that such hybrid states of traffic will be prevalent for many years to come and until a fully automated transport system has been realized. At the current stage of development, key research questions are linked to scenario analyses and the impact assessment of operation, policies, and measures. For this process, simulations regarding CCAVs are based on the application of mathematical models and algorithm-based analysis, considering hypothetical networks. In addition, the simulation-based studies in the literature have limited spatial coverage. With these issues in mind, the authors understand that potential upcoming research will be focused on the following areas.

- A need for extending the current practices by the utilization of large-scale simulation models in assessing traffic management strategies, with a special emphasis on the planning of large events. Attention will be given to the modeling of sustainable and innovative multimodal services, along with how the mass use of such services can benefit the transport supply holistically. Furthermore, the development of models capable of CCAVs will contribute to traffic simulation exploitation by quantifying the impact of traffic control measures, such as lane closures, tolls, recommended speeds, and other cooperative intelligent transport system devices that will be needed in future connected and automated transport systems.
- Existing studies have demonstrated the successful utilization of data from CCAV applications in detecting events and conditions that require special attention, as far as traffic management is concerned. However, the potential of CAVs as controllers of traffic has not as yet been assessed. Thus, investigations are required as to how autonomous vehicles will be controlled centrally vs. locally, how they can be used as assistive technologies for traffic management, and how AVs will control the speed of a platoon of vehicles to harmonize traffic flow on a link or to reduce queuing at intersections.
- Furthermore, this paper has not been accompanied by a consideration of how different traffic management strategies can improve the state of the network if this is required. In addition, the potential traffic and environmental benefits of CCAVs, in relation to mobility management concepts such as MaaS, are yet to be explored.

As the majority of the examined studies were based on models and simulated environments, there is a need to understand better the conventional and automated vehicle interactions seen in real networks. This finding links to the exploration of how parameterization that is generated from field trials will be embedded into future simulation models, to quantify the potential impacts of the proposed concepts in large-scale networks.

For the smooth penetration of CAVs in the real networks, a focus on infrastructure to optimize resources and the alteration of the system will also be emphasized. However, how cities and towns will manage the transition to a regime involving CCAV is unclear. Thus, further research will also be required in the following areas:

- Issues regarding the design and testing of different cases wherein mixed traffic scenarios at various networks need to be specified. Such case studies may explore drivers' reactions in the presence of CAVs, the seamless and cooperative interaction of human-driven and autonomous connected vehicles, the different network configurations, and the infrastructure's technological readiness levels.
- The research studies on CAVs are still predominately based on the perspective of the current transportation system, which will be partially or even completely changed in the future, e.g., the CAVs' temporary waiting area may be different from the conventional taxi stand and may be inaccessible for passengers. Understanding the design needs, integration, and implementation research should be a focus of research. In addition, whether CCAVs will be deployed at specific roadways, such as on a smart motorway or in the overall network, is still unclear, and the benefits and potential risks of such a system are also unknown.
- There is a serious need for assessing how obsolete infrastructure will be phased out, and its economic impact on a larger scale needs to be better understood.

In short, this review paper has reported future research areas, such as the design and testing of different traffic scenarios in different locations, with issues related to drivers' reactions in the presence of CAVs, model use, incident management, the seamless and cooperative interaction of human-driven and autonomous connected vehicles, and the different network configurations and technological readiness levels in terms of infrastructure. The level of uncertainty of the results of the studies reviewed is high, as none of the studies was conducted in the real world or in a practical setting. This also means that the uncertainty in terms of assumptions and parameters that is applied in models and analysis may have a higher degree of influence on the outcome. It is worth noting that a significant level of variability was observed, even in simple intersection analyses, as the modeling approaches, strategies, parameters, and modeling tools applied varied across different studies. This review study focused on the literature gaps rather than the study of a meta-analysis of the quantitative data; the synthesis of information in this review paper is less vulnerable to the risk of bias. Thus, the highlights and findings of this paper have less chance of inaccurate recommendations and misleading interpretations. On some occasions, it may appear that a meta-analysis can be performed in some specific sections of a network, e.g., intersection; however, the variability in modeling practices indicates that there is no meaningful use of the meta-analysis. It is believed that more studies on the performance improvement of CCAVs on a network portion will allow such meta-analysis in the future.

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Conflicts of Interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Appendix A

Table A1. PRISMA 2020 Checklist.

Section and Topic	Item #	Item Description	Location Where Item Is Reported
TITLE			
Title	1	Identify the report as a systematic review.	1
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	4
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	4

Table A1. *Cont.*

Section and Topic	Item #	Item Description	Location Where Item Is Reported
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	4 and 5
Information sources	6	Specify all databases, registers, websites, organizations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	5
Search strategy	7	Present the full search strategies for all databases, registers, and websites, including any filters and limits used.	4
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	4 and 5 Figure 1
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	5
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g., for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	5 and 6
	10b	List and define all other variables for which data were sought (e.g., participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	5
Study risk of bias assessment	11	Specify the methods used to assess the risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Not Applicable
Effect measures	12	Specify for each outcome the effect measure(s) (e.g., risk ratio, mean difference) used in the synthesis or presentation of results.	Not Applicable
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g., tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	5
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as the handling of missing summary statistics, or data conversions.	5
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	5
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	5
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g., subgroup analysis, meta-regression).	6
	13f	Describe any sensitivity analyses conducted to assess the robustness of the synthesized results.	Not Applicable

Table A1. *Cont.*

Section and Topic	Item #	Item Description	Location Where Item Is Reported
Reporting bias assessment	14	Describe any methods used to assess the risk of bias due to missing results in a synthesis (arising from reporting biases).	Not Applicable
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	6
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Figure 1
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	177 studies, not listed
Study characteristics	17	Cite each included study and present its characteristics.	6–12
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Not Applicable
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) effect estimates and their precision (e.g., confidence/credibility interval), ideally using structured tables or plots.	6–12 Table 1
Results of syntheses	20a	For each synthesis, briefly summarize the characteristics and risk of bias among contributing studies.	Not Applicable
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g., confidence/credibility interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	12 and 13
	23b	Discuss any limitations of the evidence included in the review.	13
	23c	Discuss any limitations of the review processes used.	13
	23d	Discuss implications of the results for practice, policy, and future research.	13
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	Not Applicable
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	Not Applicable
	24c	Describe and explain any amendments to the information provided at registration or in the protocol.	Not Applicable
Support	25	Describe the sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	14
Competing interests	26	Declare any competing interests of the review authors.	14

Table A1. *Cont.*

Section and Topic	Item #	Item Description	Location Where Item Is Reported
Availability of data, code, and other materials	27	Report which of the following are publicly available and where they can be found template data collection forms; data extracted from included studies; data used for all analyses; analytical code; any other materials used in the review.	14

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