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Mapping and Deep Analysis of Vehicle-to-Infrastructure Communication Systems: Coherent Taxonomy, Datasets, Evaluation and Performance Measurements, Motivations, Open Challenges, Recommendations, and Methodological Aspects

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ABSTRACT The vehicle-to-infrastructure (V2I) communication system allows the exchange of information between vehicles and road infrastructures. It aims to avoid or reduce vehicular accidents, increase mobility, and provide other road safety benefits. This paper aimed to review and analyze the literature on data exchanges in the V2I communication system. The factors considered to improve the understanding of various contextual aspects and the characteristics of the field were motivations, open challenges, and recommendations from other researchers. We systematically searched all articles on data exchanges in the V2I communication system from the three main databases, namely ScienceDirect, Web of Science, and IEEE Xplore, from 2008 to 2018. These indices were sufficiently extensive to encompass our field of literature. A total of 70 articles were selected based on our inclusion and exclusion criteria. Most studies (42/70) covered a developed V2I communication system, while numerous articles (22/70) focused on general research on the V2I communication system. The smallest portion of articles (6/70) comprised reviews and surveys. The V2I system plays a key role in vehicular ad hoc networks but is less implemented than vehicle-to-vehicle communication owing to its deployment costs and maintenance requirements. However, numerous studies have been conducted on the V2I communication system to promote its utility. Research areas on V2I communication classification vary but are all equally vital. We expect this systematic review to help emphasize current research opportunities and thus extend and create additional research fields.

INDEX TERMS Data exchange, road side unit, vehicular ad hoc network, vehicle to infrastructure.

ABBREVIATIONS

VANET	Vehicular ad hoc network
V2I	Vehicle to infrastructure
I2V	Infrastructure to vehicle
ITS	Intelligent transportation systems
SPaT	Signal phase and timing
DSRC	Dedicated short range communication
RSU	Road side unit

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I. INTRODUCTION

The vehicular ad hoc network (VANET), which comprises the main part of the intelligent transportation system (ITS), is an extension of the mobile ad hoc network in which the nodes are vehicles. The VANET uses three main types of communication, namely, vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-pedestrian (V2P) communications. One of the challenging tasks of the ITS is the delivery of traffic information to drivers to enable smooth and safe driving. V2V communication is commonly used to send data between vehicles; however, manual vehicles are not equipped with this capability. Therefore, V2I communication is needed to send information on vehicle status without the need to modify the indoor systems of manual vehicles [1]. The V2I communication system enables wireless exchanges of various safety and operational information between vehicles and infrastructures. Vehicles can receive real-time warnings regarding dangerous situations and send information to other vehicles by using road side units (RSUs) [2]. However, the high cost of implementing RSUs and the need for continuous maintenance of V2I systems make it less popular than the V2V in the field of ITS [3]. Numerous studies have been conducted to develop V2I communication systems to enhance their contribution to VANETs. This study aims to present the achievements of other researchers, summaries previous findings in response to the serious need to develop V2I communication systems, determine evaluation methods and criteria, propose a taxonomy of the existing literature and to distinguish the various aspects of this relevant research area.

The rest of this paper is organized as follows: Section 1 introduces the study, which is followed by the systematic review protocol description in Section 2. Section 3 presents the taxonomy, and Section 4 shows the statistical results of the reviewed articles. Section 5, discusses the datasets, evaluation techniques and performance measures, motivations, challenges, recommendations and methodological aspects extracted from the reviewed articles. Finally, the conclusions of this study are provided in Section 6.

II. SYSTEMATIC REVIEW PROTOCOL AND ANALYSIS

A. INFORMATION SOURCE

The most important keyword in this study was 'vehicle-to-infrastructure (V2I) communications.' This keyword excluded any non-V2I communications, such as those found on V2V or V2P communications. We limited our scope to English literature but considered all V2I communication systems in all scenarios. Three digital databases were explored to search for target articles: (1) IEEE Xplore is a scholarly research database that provides the most reliable and wide-ranging articles in the fields of computer science, electronic technologies and electrical engineering; (2) Web of Science (WoS) offers indexing of cross-disciplinary research in sciences, electronic technologies, social sciences, the arts and humanities; (3) ScienceDirect is a large database of scientific techniques and medical research. These three databases sufficiently covered the V2I and all communication types in this field and provided a broad view of existing literature in a wide but relevant range of disciplines.

B. SELECTION OF STUDY

Study selection involved a search for literature sources and three iterations of screening and filtering. All unrelated articles were removed in the first iteration of screening and filtering. Duplicates and irrelevant articles were removed in the second iteration by scanning the titles and abstracts. The full-text articles screened during the second iteration were then carefully reviewed in the last iteration. We applied the same eligibility criteria across all iterations.

C. SEARCH

The search was conducted in January 2018 by using the search boxes of ScienceDirect, IEEE Xplore and WoS. To identify the studies related to this area, the query comprised a mix of keywords, including 'vehicle-to-infrastructure', 'V2I', 'car to infrastructure' and 'C2I' in different variations and combined by the operator 'OR'. In addition, 'information exchange', 'exchanging information', 'data exchange', 'exchanging data', 'data integration' and 'information integration' in different variations were included and combined by the operator 'AND'. The query text is shown in Figure 1. The advanced search options in the search engines were used to exclude book chapters, short communications, correspondences and letters to gain access to up-to-date scientific works relevant to our survey on this emergent trend of V2I communications.

D. ELIGIBILITY CRITERIA

Every article that met the criteria listed in Figure 1 was included. We set an initial target for mapping the space of research on V2I communications into a general and a coarse-grained taxonomy of four categories. These categories were derived from a presurvey of the literature. After the initial removal of duplicates, articles that did not fulfill the eligibility criteria were excluded in the two iterations of screening and filtering. The exclusion criteria included the following: (1) the article was not in English; (2) the article focused on a specific aspect of smart cities and customer-to-customer communication, which represented car-to-car communication in other articles; (3) the subject was limited to V2P communication.

E. DATA COLLECTION PROCESS

We read and analyzed the final set of articles in Word format to simplify the steps. Moreover, the articles were classified in detail by using taxonomy, highlights and comments. The taxonomy suggested various classes and subclasses, including four main categories, namely, developments, frameworks/architecture, studies conducted on V2I and surveys/reviews. Texts were categorized depending on the authors' preferred style, and the collected data and relevant information were saved in Word files. All the articles

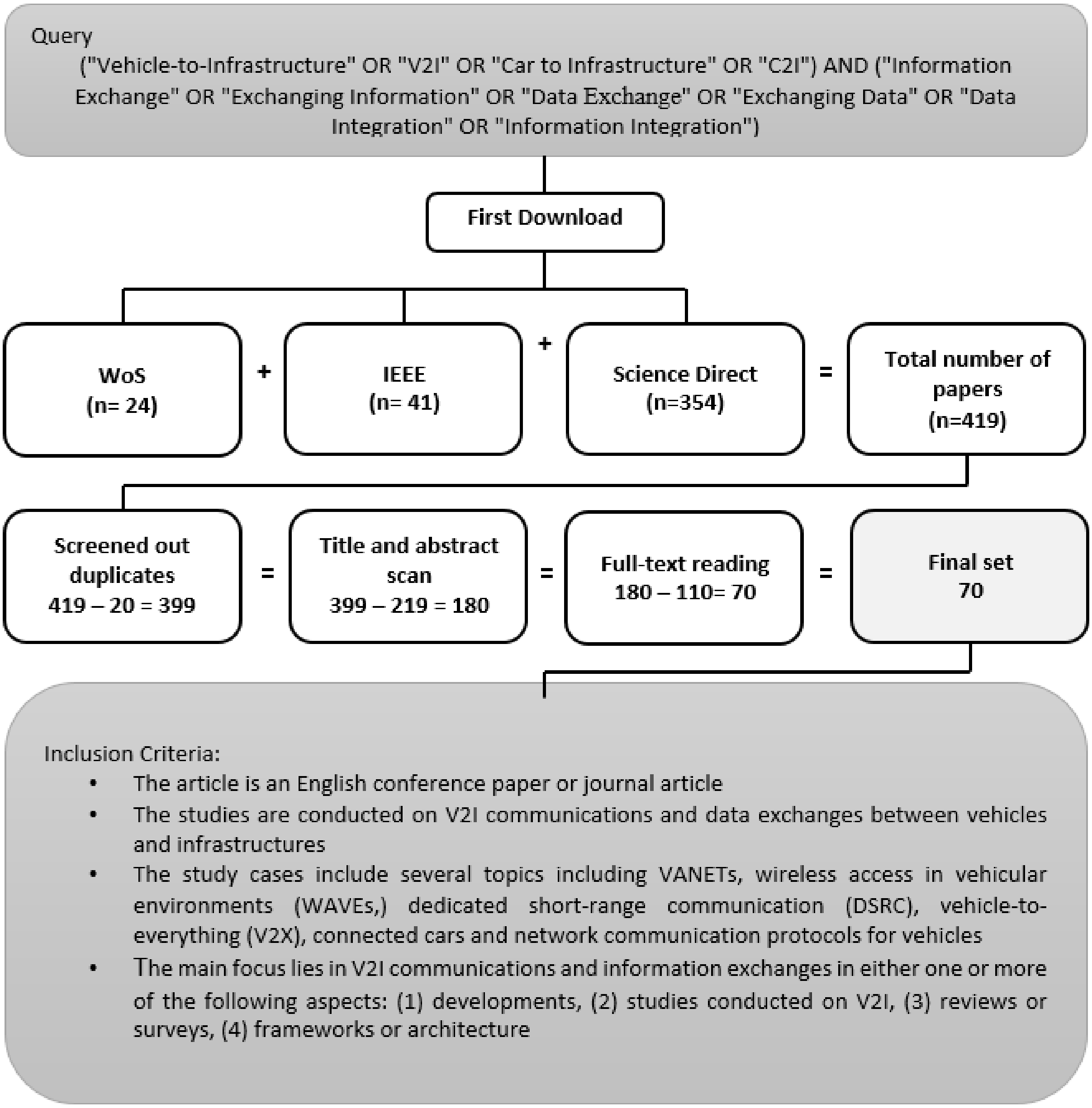

FIGURE 1. Flowchart of study selection including search query.

from various sources were analyzed in depth to provide readers with a comprehensive overview of the subject.

F. RESULT OF LITERATURE TAXONOMY

The initial query resulted in 419 articles: 24 from the WoS database, 354 from Science Direct and 41 from IEEE Xplore. The filtered articles published from 2008 to 2018 were adopted and grouped into three categories. A total of 20 out of 419 articles from the three databases were duplicates. After the titles and abstracts were scanned, 219 articles were further excluded, thereby resulting in 180 articles. The final full-text review excluded 110 articles. The final set included a total of 70 articles. The taxonomy presented in Figure 2 was used to review the main streams of research focusing on V2I communications.

This taxonomy showed the comprehensive development of various studies and applications. The classification suggested different classes and subclasses. The first class included studies with actual attempts to develop V2I communication systems by using either real time, simulation or both (42/70 papers). The second class included review and survey articles related to V2I communications (6/70 papers).

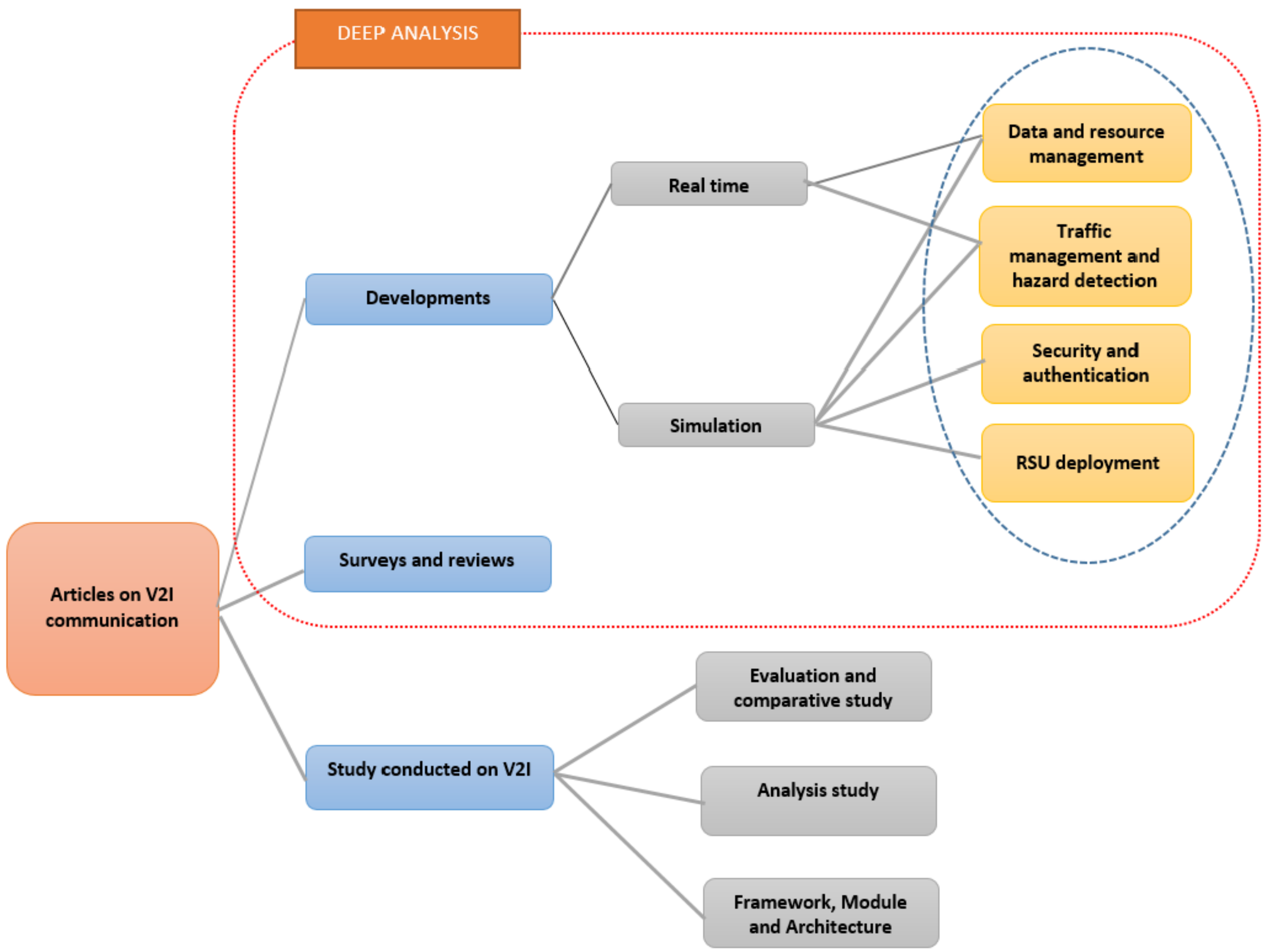

FIGURE 2. Taxonomy of research literature on V2I communications.

The final class included studies conducted on V2I communication systems (22/70 papers). The observed categories are listed in the following sections for statistical analysis.

G. DEVELOPMENTS

This section reviews the studies (42/70) that proposed a development system in which V2I communications were used as a mean contribution or a tool. These articles were classified into two groups according to the evaluation method used. The first group was real-time developments (11/42), which contained articles in which real-time field tests were used, and the second group was simulation developments (31/42), which contained articles in which some type of simulator was used to evaluate the work. These two groups were further classified into four subgroups according to the purpose of the study. In the real-time development group, the V2I communications were further classified into two subgroups, namely, data and resource management and traffic management and hazard detection. This section introduces these two classifications.

Firstly, a V2I-based architecture for communication between manually driven and autonomous vehicles (AVs) that provide continuous data traffic flow was proposed in [1]. In [4], a mechanism to deliver traffic information to drivers based on DSRC/WAVE was developed. Secondly, [5] proposed a traffic monitoring system based on cloud computing and mobile applications to reduce traffic congestions and road accidents. In addition, [6] proposed a V2X architecture for a smart traffic sign controller system that enhances traffic safety and efficiency applications. Furthermore, [7] proposed the design and implementation of a low-cost infrastructure network based on ZigBee technology to alert drivers of unexpected circumstances such as traffic accidents. Moreover, [2] developed and deployed a fog vision sensor to transmit a warning message to drivers on road weather conditions through a V2I system. In [8], a semantic Web of things framework was proposed to support collaborative sensing and cooperative environmental risk monitoring in hybrid sensor and vehicular networks. A generic method for detecting road events by using distributed data fusion and generating early warnings to drivers in the presence of inaccurate data sources was presented in [9]. Reference [10] introduced a context-aware driver assistance system that combined various advanced driver assistance functions into one system to improve driver behavior. Reference [11] proposed an integrated advanced driver assistance system for rural and intercity environments, and an approach to avoid rear-end collisions in congested traffic situations was developed in [12].

Simulation developments in V2I communications in the second group was further classified into four subgroups, two of which focused on similar topics as the real-time development, namely, data and resource management and traffic management. The other subgroups were on security and RUS deployment. This section introduces these four classifications.

Firstly, a handover algorithm based on V2I communications that reduces handover latency and packet loss was proposed in [13]. Reference [14] proposed an emergency broadcast scheme that utilizes RSUs with a reasonable delay and high delivery rate. Moreover, an enhanced cooperative load-balancing approach for efficient dissemination of data was proposed in [15]. Several protocols were proposed to overcome data delivery problems, such as the cross-layer protocol for V2I systems to deliver packets over minimum delay paths in [16] and the hybrid routing protocol for VANETs that was proposed in [17]. Reference [18] proposed a multiple priority-supported medium access control (MAC) protocol to optimize transmission probabilities of safety packets. Reference [19] developed an extension to the IEEE 802.11p protocol to support nonsafety applications whilst maintaining the delivery of safety services. A linear programming model to overcome message delivery problems and extend network lifetimes was proposed in [20]. Furthermore, [21] proposed a real-time traffic adaptive protocol based on data collection to minimize the network communication overhead. Algorithms for spectrum allocation and sensing to extend the spectrum allocated for the control channel in DSRCs was proposed in [22]. Reference [23] proposed a distributed sorting mechanism to improve RSU utility. In addition, an access request deadline-aware scheme that reduces blocking probability and response time was proposed in [24]. An intracluster-based V2I access protocol that provides resource management for real-time applications in the VANET was proposed in [25]. A primary–secondary user resource-management controller in cognitive radio vehicular networks under hard and soft collision constraints was designed in [26]. In [27], the performance of a distributed and adaptive resource management controller in cloud-assisted cognitive radio vehicular networks was designed and tested. A primary–secondary resource management controller on vehicular networks was introduced in [28], and a fuel efficient control strategy for a group of connected hybrid electric vehicles (HEVs) in urban road conditions was presented in [29]. Finally, an optimal speed control to maximize the fuel efficiency of heavy-duty vehicles was presented in [30] in which the existence of an ITS is assumed by using V2I communications to inform the platoon leader about future speed limitations.

Secondly, an autonomous vehicle path-planning (AVPP) algorithm to predict obstacle position and improve the autonomous vehicle safety was introduced in [31]. In [32], data integration was designed from a mobile measurement platform into the VANET application to send warning messages on road degradations to drivers. Furthermore, a new cooperative localization scheme that combines V2V and V2I measurements to overcome the problem of cooperative localization in tunnel environments was proposed in [33]. A novel technique on speed-based lane changing, collision avoidance and time of arrival based localization in VANETs was developed in [34]. Other works such as [35] focused on designing a trust model for vehicular networks by taking advantage of V2I communications to collect vehicle behavior information. A decentralized platooning control strategy was proposed in [36], and [37] proposed an enhanced cooperative driving system with the help of V2X communication to enhance the stability of local traffic flow. Thirdly, a flexible, secure and decentralized attribute-based key management framework, was proposed in [38] to establish trust between vehicles and to ensure security and authentication in VANETs. A computationally efficient privacy-preserving anonymous authentication scheme that uses anonymous certificates and signatures for VANETs was proposed in [39]. In addition, a general framework to measure traffic in three or more locations whilst preserving vehicle privacy was developed in [40]. Moreover, a secure and efficient message dissemination scheme with policy enforcement in the VANET was proposed in [41]. Fourthly, to enhance RSU deployment, a genetic and Dijkstra algorithm was proposed in [42] to minimize the number of RSUs based on deployment costs and delivery time requirements. By contrast, a new geometry-based sparse coverage (GeoCover) protocol for RSU deployment in vehicular networks was developed in [43].

H. SURVEYS AND REVIEWS

This category included the survey and review articles that summarized the current state of V2I communication system understanding. Only [44]–[48] and [49] (6/70) were included in this category. The main security and privacy issues in vehicular communication, including authentication in V2I, was covered in [44]. A survey on spectrum access technologies and the persisting challenges related to V2I communications was surveyed in [45]. A comprehensive overview of various radio channel access protocols and resource management approaches was provided in [46]. V2I communication characteristics in heterogeneous multitier network was surveyed in [47], whereas the utilization of cellular and DSRC networks to support V2I communications was discussed in [48]. Other works such as [49] focused on vehicular sensor networks and sensor information collection using two infrastructure-based VSN platform techniques (Senster and CarTel).

I. STUDIES CONDUCTED ON V2I COMMUNICATION

This category included numerous studies (22/70) related to V2I communication system. These articles were further classified into four groups. The first group (14/22) included evaluation and comparative studies. Works under this group evaluated and compared the performance of connectivity-aware routing and multipath transmission control protocols during multihop data exchanges between RSUs and vehicles [50]. The performance of the IEEE 802.11p for V2I communications was evaluated in [51], [52], whereas the adoption of the WAVE/IEEE 802.11p protocols to offload cellular networks was discussed in [53]. In [54], a highway-merging decision algorithm was developed to check if the IEEE 802.11p could support merging controls, and the use of a beaconing mechanism for V2I communication was presented in [55]. Other works presented field tests of Bluetooth and ZigBee technologies to evaluate the possibility of supporting extended V2I messaging facilities [3]. Several experiments were designed to demonstrate that Bluetooth could be used in R2V/V2I communications [56]. A set of tools that could be used to check the conformance of a cooperative–ITS (C-ITS) was presented in [57]. A simulation framework for testing and evaluating C-ITS applications was shown in [58]. Other works focused on V2X security [59]. The effect of mobility on the performance of V2X communication was analyzed in [60], whereas [61] demonstrated that 6 Mbps was not always the optimum beaconing data rate among vehicular networks. Finally, techniques for handling misbehaviors in VANETs were studied in [62].

The second group (5/21) consisted of analysis studies. An analysis of the possible implementation of driverless technologies for passenger cars and trucks as well as its degrees of automation was presented in [63]. The stability of the information consensus for a multiple, autonomous intersection was analyzed in [64]. Other works analyzed reliable data transfer for IP-based, DSRC communications networks implemented for logistics purposes [65]. A key indices analysis of IEEE 802.11p-based V2I systems in highway environments was presented in [66]. The performance of DSRCs were analyzed in [67] in the context of roadside-to-vehicle environments for different traffic loads.

The last group (3/22) included other studies related to V2I, such as frameworks, models and architecture. A framework that can act as a generalized firewall to protect operations from various cyber threats was proposed in [68]. A traffic model for self-driving and connected vehicles was designed in [69], whilst a new approach for the deployment of a communications architecture for ITS was proposed in [70].

III. DISTRIBUTION RESULTS

One of the contributions of this work was realizing the trends in the research literature by performing content analysis on several key journals in the field. Allthe articles (70) were included in the full list. Figure (3) shows the results of the review, which was divided into four main categories, namely, real-time developments, simulation developments, surveys and reviews. The final category comprised studies on V2I. Figure (3) shows the increasing interests in the simulation developments of V2I communication system.

The total number of selected published articles from the WoS database was 13, which consisted of 1 article for real-time developments, 4 for simulation developments, 1 for surveys and reviews and 7 for studies conducted on V2I. The total number of selected published articles from the IEEE database was 15, which consisted of 2 articles for real-time developments, 9 for simulation developments and 4 for V2I studies. The total number of selected published articles from the ScienceDirect database was 42, which consisted of 7 articles for real-time developments, 19 for simulation developments, 5 for surveys and reviews and 11 for V2I studies. The number of articles in the 4 categories according to the year of publication is shown in Figure (4). A total of 13, 12 and 16 articles were published in 2015, 2016 and 2017, respectively. By contrast, no articles were published in 2008. A total of 2 articles were published in 2009, and 3 articles were published in 2010 and 2011. Moreover, 7 and 5 articles were published in 2012 and 2013, respectively. Among the selected articles, 5 were published in 2014, and 4 were published in 2018.

IV. DISCUSSION

This review presented the most relevant studies on the V2I communication system. The objective of this work was to highlight the research trends in this research area. A taxonomy of the related literature was proposed, which can provide several benefits. Firstly, it organized various publications. A new researcher in this area may be overwhelmed by the large number of papers on the subject and the absence of any kind of structure and thus may fail to obtain an overview in this area. Secondly, various articles addressed the topic from an introductory perspective, whereas others examined existing data-exchanging applications in V2I systems. A taxonomy of the related literature can help sort these different works and activities into a clear and comprehensible layout. Finally, the structure introduced by the taxonomy provides researchers with important insights into the subject in several ways.

Firstly, it outlined the potential research directions in the field. For example, the taxonomy of V2I communication systems in the current work demonstrated that researchers are inclined to propose frameworks to develop V2I traffic management systems, thereby providing a possible path in this area. Secondly, the taxonomy could reveal gaps in the research. Mapping the literature on V2I applications into distinct categories highlighted weak and strong features in terms of research coverage. For example, the taxonomy in this work showed how groups of individual applications received significant attention in terms of reviews and evaluations at the expense of integrated solutions and frameworks as well as development efforts. The taxonomy also highlighted the lack of studies on RSU deployment efforts. Similar to taxonomies in other fields, the proposed taxonomy employed a common

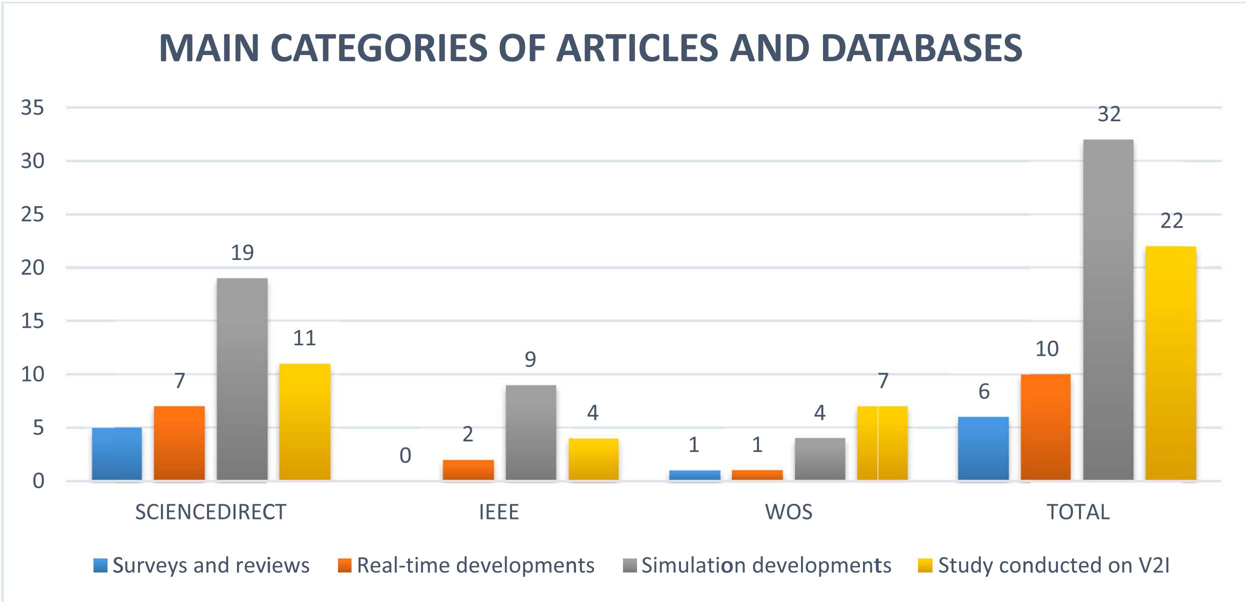

FIGURE 3. Number of included articles based on main categories and database source.

TABLE 1. Settings of search query.

Digital Library	WoS	IEEE	Science Direct
Years	Last 10 years	Last 10 years	Last 10years
Language	English	English	English
Run on	Full Text	Metadata	Full Text
Date of running search string	2018	2018	2018

language for researchers to communicate and discuss emerging works, such as development papers, comparative studies and reviews. The survey conducted revealed seven aspects of the literature content: the description of datasets used in the articles, the evaluation techniques adopted, the criteria used for the performance evaluation of the methods, the motivations behind the development of the V2I system, challenges to the successful utilization of these technologies, recommendations to alleviate these difficulties and the methodological aspects.

A. DATASETS

In our survey, we depended on the number of types of data sources for V2I communication systems in real-time developments such as devices that provided data between vehicles and infrastructure information. The details of V2I communication data sources in our survey are summarized in Table 2.

As shown in Table 2, the researchers generated their own datasets through experiments. Table 2 presents a detailed description of research experiments designed towards developing a hardware-based V2I communication system that consists of numerous factors. Most of the studies used a positioning system (GPS) and a wireless card, such as a Wi-Fi, Bluetooth or ZigBee card, in their research. Table 3 shows that only a few studies used a real device to generate their dataset. Other works obtained their data from the literature and public datasets.

B. EVALUATION TECHNIQUES

This section describes the evaluation process conducted on the use of V2I networking. This phase of the survey consisted of three main evaluation techniques for data collection across different vehicular communication systems, namely, actual experiments, simulations and comparisons. Table 3 illustrates the evaluation techniques used in the included articles.

Table 3 shows that most of the studies used simulations to evaluate their works, followed by comparisons.

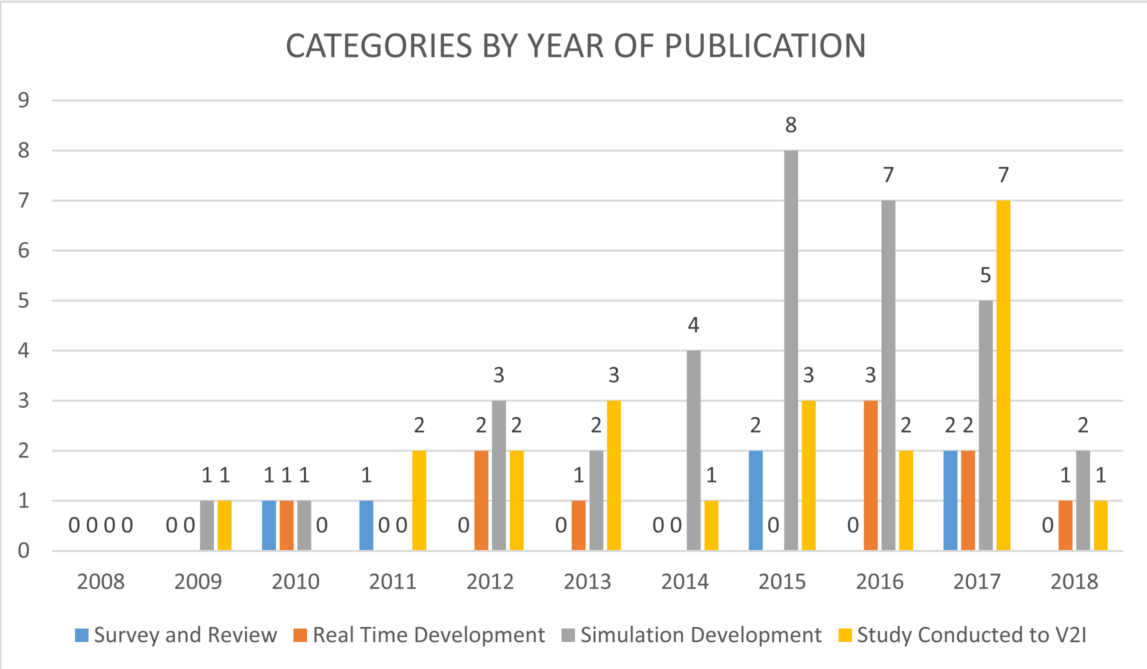

FIGURE 4. Number of articles in each category by publication yea.

However, a small proportion of the research depended on actual experiment evaluation techniques. A few of the studies used all three evaluation techniques.

C. PERFORMANCE MEASUREMENTS

The performance of thestudies involved in our survey were evaluated by using different measures related to time, data rate and resource management as well as other measurement criteria, including fairness index, service rate, blocking probability, reliable link range, authentication, pignistic probabilities, localization, emergency message generation, effectiveness, efficiency, accuracy, impact of measurement errors for traffic flow, impact of V2I deployment for traffic flow, deviation, probability of successful CWS detection, collision rate, deadline miss ratio (DMR), success rate of request–transfer ratio and percentage conflict request count per broadcast. All of these parameters are discussed in this section. Table 4 illustrates the measurement criteria used in the reviewed papers.

Table 2 presents various studies on V2I communication systems as well as a comprehensive survey on different criteria for evaluation. The most-used criteria to evaluate V2I system performance were delay, cost, packet loss, throughput, efficiency, packet delivery, goodput, time response, authentication, localization and deviation in 33%, 24%, 17%, 17%, 14%, 12%, 12%, 7%, 7%, 7% and 7% of the studies, respectively. Other criteria such as fairness index, service rate, emergency message generation, effectiveness and collision rate were used sparingly (only 5%). The rest of the criteria were used only once (2%). As clearly shown in Table 2, no study used all the measurement criteria. The variance in the use of these measurement criteria indicated the challenge in adopting specific types for the evaluation of V2I communication systems.

D. SURVEY ANALYSIS

This section summarizes of different types of review and survey articles related to V2I communication systems. Table 5 shows that most of the articles were concerned with the VANET and only partly covered V2I systems. In addition, only one article [47] focused on V2I systems as the main topic, and no survey or review article discussed all types of measurement criteria. To the best of our knowledge, the present survey offered an overall view and provided directions for future research and development. It created a new classification system for recent works based on data analysis provided by different studies. Moreover, the present survey relied on numerous factors such as coherent taxonomy, data sources, performance measurements, evaluation techniques to explore new trend challenges, motivations related to V2I systems, recommendations and methodological aspects to provide a comprehensive analysis for this research area.

E. MOTIVATIONS

The use of V2I communications in VANETs has numerous benefits. This section lists a few of the advantages reported in the literature, which were grouped into categories based similar benefits. The corresponding references were cited for further discussion, as shown in Figure 5.

TABLE 2. Dataset used in reviewed articles.

Real time data															
Ref	Type of data							Source							
	Vehicle speed	Vehicle position	Communication state	SPaT information	RSU position	Distance to the object	Road/weather conditions	GPS	temperature sensor	Laser scanner	Ultrasonic sensor	wireless card	camera	On-board unit (OBU)	On-board diagnostics (OBD)
[1]	*	*	*					*				*			
[4]	*	*		*	*			*				*	*	*	
[8]	*	*					*	*	*			*			*
[6]				*	*			*				*		*	
[7]	*	*						*				*		*	
[10]	*					*					*	*			
[2]	*	*				*	*	*	*	*		*	*	*	
[9]	*				*		*	*	*			*		*	
[5]	*	*						*				*	*	*	
[56]	*	*						*				*		*	
[11]	*	*				*		*		*		*	*		
[12]	*	*						*				*	*		
[34]	*	*						*				*	*	*	
[32]						*		*		*					

1) ENHANCING TRAFFIC MANAGEMENT AND ROAD SAFETY

V2I communication systems enhance traffic monitoring and management during congestions to reduce traffic light accidents as well as to improve road safety. A few of the main benefits of V2I communications include reducing injury-causing traffic accidents [10]–[12], developing practical solutions to reduce traffic congestion [52], [69], improving traffic management performance [68] and delivering adequate traffic information to drivers to ensure smooth and safe driving [4]. Other benefits related to traffic management include creating an intersection environment for road users and operators to bridge the gap between traffic flow modeling and communication approaches [37], mitigating cyber-security risks in urban traffic management and facilitating

TABLE 3. Evaluation techniques used in articles reviewed.

Ref	Evaluation technique		
	Actual experiments	Simulations	Comparisons
[1, 4, 6–8, 10] [2, 5, 9, 11, 12, 56]	✓		
[1, 5, 7–9] [11–43, 54, 56]		✓	
[2, 8, 9, 18, 21, 32] [13, 15, 23] [14, 16, 17, 19, 28–30, 33, 39–41, 43, 56]			✓

efficient and cyber-secure traffic management in metropolitan areas [68].

2) BENEFITS RELATED TO PRIVACY AND SECURITY

The security system is one of the most important issues in V2I communication and is considered a critical point in the development of robust V2I systems. A secure message dissemination scheme in the VANET with policy enforcement was developed in [41] to enable the security data access control policy [38]. A scheme to provide a computationally efficient conditional privacy-preserving anonymous authentication was developed in [39], thereby preventing denial-of-service attacks; eliminating misbehaving nodes in a distributed, collaborative and instantaneous manner [62]; mitigating cybersecurity risks in urban traffic management and facilitating efficient and cyber-secure traffic management in metropolitan areas [68].

3) BENEFITS RELATED TO COMMUNICATION AND CONNECTION

V2I communication systems enable information exchanges between vehicles and infrastructure, improve mobility and reliability and enhance routing protocols by providing direction and route optimization through networks. V2I communications are used in maximal fuel saving to inform the platoon leader about future speed limitations [30] and to improve fuel efficiency in a group of HEVs through a hierarchical control architecture [29]. Moreover, V2I communication systems allow information exchanges between vehicles based on V2I [1], relay time warnings on incidences and dangerous situations [2] and propose emergency broadcast schemes that use RSUs and V2I communications with a reasonable delay and high delivery rate [14]. Moreover, they also improve vehicular safety message delivery through the implementation of a cognitive vehicular network [22] and enhance file transfer outcomes between RSUs and vehicles [50]. The timely message delivery problem in hybrid sensor vehicular networks (HSVNs) was addressed in [20] via a new bi-objective linear programming model. In addition, V2I communication also improves the efficiency of communication between vehicles and RSUs [23], [24] and provides different types of protocols for vehicular networks. A hybrid routing protocol for VANETs was designed by combining DSRC technology and LTE [17], and a cross-layer position-based delay-aware communication protocol called PROMPT was designed for delay-aware vehicular access networks [16]. A GeoCover protocol for RSU deployment over urban VANETs was designed to solve the coverage problem [43] by using WAVE to collect as much data as possible at RSUs, thus reducing the use of cellular communications denoted as V2I communications [53].

4) BENEFITS RELATED TO SERVICE AND APPLICATION

Different kinds of services and applications exist in vehicular networks, such as safety applications that improve the safety of passengers by notifying vehicles on dangerous situation in the neighborhood. Benefits include the design and implementation of low-cost infrastructure networks based on ZigBee technology to alert drivers of unexpected circumstance on the road [7] and the detection of road events by using distributed data fusion [9]. Other benefits of traffic applications include traffic management and road information alerting drivers on traffic situations. Drivers can use this information to avoid congestion and to find the best route to their destination with minimum delays. Two applications using the DSRC/WAVE were proposed to deliver two different kinds of traffic information to drivers, namely, traffic flow and traffic signals to ensure adequate information for driving [4]. An intelligent traffic monitoring system based on cloud computing and mobile apps was proposed in [5]. Services to vehicles that get

TABLE 4. Measurement criteria used in articles reviewed.

Ref	PERFORMANCE MEASUREMENTS																														
	TIME					DATA RATE															RESOURCE MANAGEMENT										
	Delay/latency	Time to collision	Time gap	Travel time	System response	Data/packet loss	Packet delivery performance	Packet usage	Untransmitted packet risk index	Fairness index	Service rate	Blocking probability	Reliable link range	Authentication	Pignistic probabilities	Localisation	Emergency messages generation	Effectiveness	Efficiency	Accuracy	Impact of measurement errors for traffic flow	Throughput	Goodput	Utilisation of available capacity	Cost	Impact of V2I deployment for traffic flow	Deviation	Probability of successful CWS detection	Collision rate	DMR	Success Rate of request transfer ratio	Percentage conflict request count per broadcast
[1]	*					*																										
[4]																																
[8]	*																								*							
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Total	14	1	1	1	3	7	5	1	1	2	2	1	1	3	1	3	2	2	6	1	1	7	5	1	10	1	3	1	2	1	1	1
%	33%	2%	2%	2%	7%	17%	12%	2%	2%	5%	5%	2%	2%	7%	2%	7%	5%	5%	14%	2%	2%	17%	12%	2%	24%	2%	7%	2%	5%	2%	2%	2%

TABLE 5. Survey analysis used in articles reviewed.

Ref	Covered topics	Concerned with V2I
[49]	Vehicular sensor network was surveyed and evaluated. Results showed that VSN architecture was classified into two main parts: V2V-based techniques and V2I-based techniques, depending on wireless access methods. Each technique was reviewed and evaluated.	Infrastructure-based VSN platforms: Methods for collecting and storing sensor information using two techniques of infrastructure-based VSN platforms (Senster and CarTel) were reviewed; the performance of Senster in terms of load balancing, routing cost, hands-off overhead and content-based routing locality was evaluated.
[48]	Heterogeneous vehicular networking (HetVNET) architecture, challenges and solutions were surveyed. ✓ User cases and quality of service (QoS) requirements for safety and nonsafety applications were summarised ✓ A framework of the HetVNET was proposed and discussed ✓ V2V and V2I communication systems were discussed for comparisons ✓ Multichannel access and network design issues in HetVNET were discussed ✓ Open issues for future research was introduced, such has intersystem handover, big data, cross layer design, cooperation and vehicular cloud network	V2I Communications: The utilisation of cellular and DSRC networks to support V2I communication was discussed; the main problem that must be addressed before these networks can be applied in V2I systems was reviewed. Results showed that LTE was more suitable than DSRC for V2I communications.
[46]	The support of infotainment and road safety service in VANET was studied from a communication perspective, and numerous research challenges and issues were discussed. A systematic overview of communication solutions was presented to support infotainment and road safety applications in VANETs from the perspectives of users and services.	Optimal RSU deployment and RSU-assisted node cooperation were used to enhance the performance of VANETs and supporting safety applications. Results showed that the proposed solutions for RSU deployment must be evaluated using field tests. Numerous considerations such as safety, vehicle mobility and density, roadways and heterogeneous traffic types are needed.
[44]	The main security and privacy issues were reviewed as well as the research on these issues. Several open problems in modern cars related to security and privacy were highlighted.	Authentication in V2I systems
[45]	Two MAC protocol standards for WAVE, namely, the IEEE 802.11p protocol and the IEEE 1609.4 protocol, were overviewed. This overview was	A selection of works addressing numerous problems related to MAC protocol-based V2I communication systems was surveyed. The open
	followed by a survey of a selection of works addressing numerous problems of these protocols. The major challenges in vehicular network communications were also discussed briefly.	research challenges related to V2I communication, such as accurate modelling and analysis of V2I communications, channel access prioritisation and channel availability in vehicular dynamic spectrum access-oriented environments, were discussed.
[47]	V2I communication characteristics in heterogeneous multitier networks were surveyed. ✓ An overview of V2I applications and a number of V2I projects ✓ V2I communications over heterogeneous multitier networks ✓ V2I research challenges and possible solutions ✓ A summary of numerous recommendations for V2I	✓ V2I communication standards were discussed ✓ V2I communication applications were presented and a few of the selected V2I projects were discussed ✓ Characteristics and requirements of V2I communications in heterogeneous multitier environments with diverse underlying network technologies were discussed ✓ V2I communication challenges in heterogeneous multitier networks were surveyed as well as different solutions

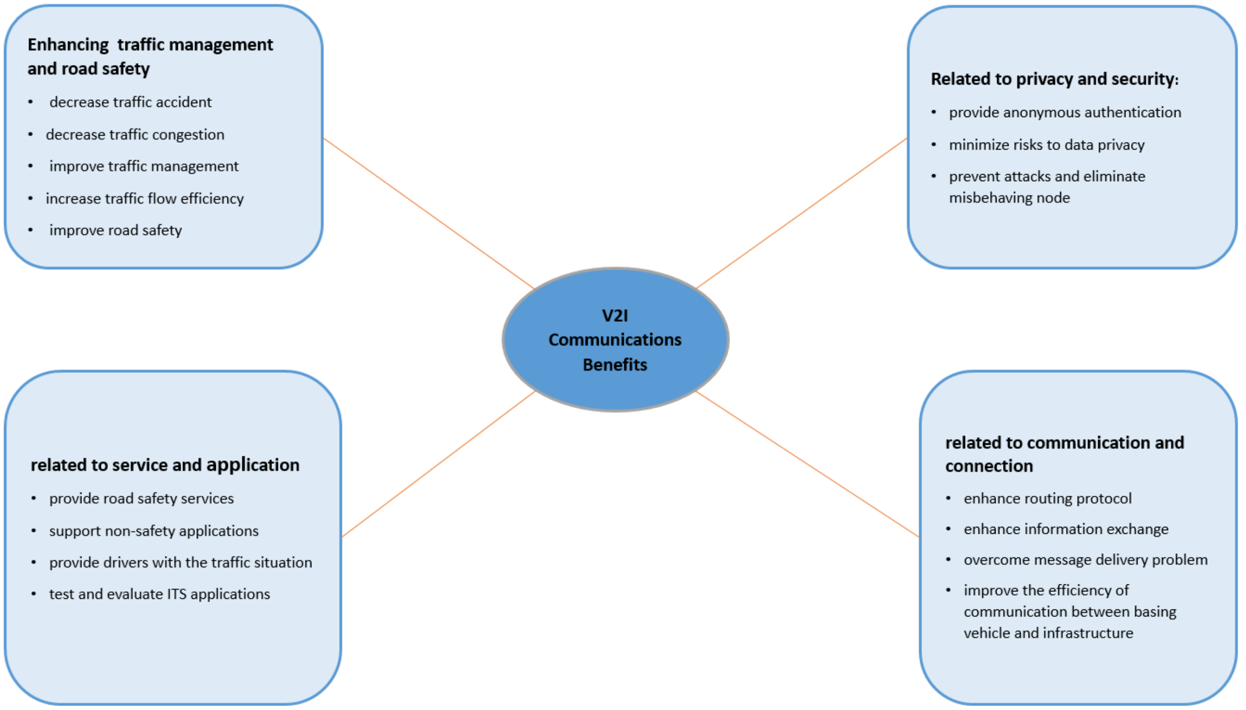

FIGURE 5. Categories of V2I communication system benefits.

stuck in tunnels with few available resources on data transfer through multihop in clustered vehicular cloud networks were suggested in [34]. Other benefits are related the support of nonsafety applications in vehicular networks. An extension to the IEEE 802.11p was proposed to support of nonsafety applications whilst preserving the delivery of safety services [19]. Cloud and Internet-assisted V2I communications for emerging nonsafety application was designed, and a fully distributed and scalable resource-management scheduler for vehicular real-time applications was tested in [25]. C-ITS applications were designed and tested in [58] by using a simulation framework consisting of driving, traffic and network simulators.

F. ISSUES AND CHALLENGES RELATED TO V2I COMMUNICATION SYSTEMS

Although V2I communication systems offer numerous benefits, such technologies are not perfect for communication network delivery. The surveyed works indicated that researchers were concerned with challenges associated with V2I applications as well as their communication systems. The main challenges in adopting V2I communication systems are listed below, along with citations for further discussion. The challenges were classified according to their nature, as shown in Figure 6.

1) CONCERNS ON TRAFFIC

Traffic information management, traffic data dissemination, and the use these data to improve traffic signal operations are the fundamental challenges to improving traffic safety and efficiency. Efficient traffic information dissemination for drivers to receive adequate information to ensure smooth and safe driving is a big challenge [4]. Efficient traffic control and management, optimal control of traffic flows and the dynamic control of traffic lights in isolated intersections are fundamental and urgent challenges in vehicular networks [6], [25]. One of the substantial challenges in traffic applications that should be addressed is data aggregation that deals with data collection from surrounding vehicles to obtain adequate traffic information [21]. Traffic safety and efficiency and cyber-secure threat management in metropolitan areas have become serious problems in smart cities [36], [68].

2) CONCERNS ON ROAD SAFETY

Numerous contributions have been made to ensure improvements in road safety. However, many challenges need to be addressed before road safety can be achieved. Data fusion of large amounts of data on intelligent transportation systems generally resolve to the problems of data source inaccuracy and unreliability [9]. Developing an open architecture to carry out an automatic driving system that can manage a set of car maneuvers similar to human drivers is necessary to improve road safety as well as to coordinate merging maneuvers for safe merging and to avoid rear-end collisions [1], [12], [54]. Other challenges related to road safety include drivers behaviors and poor infrastructure [10],

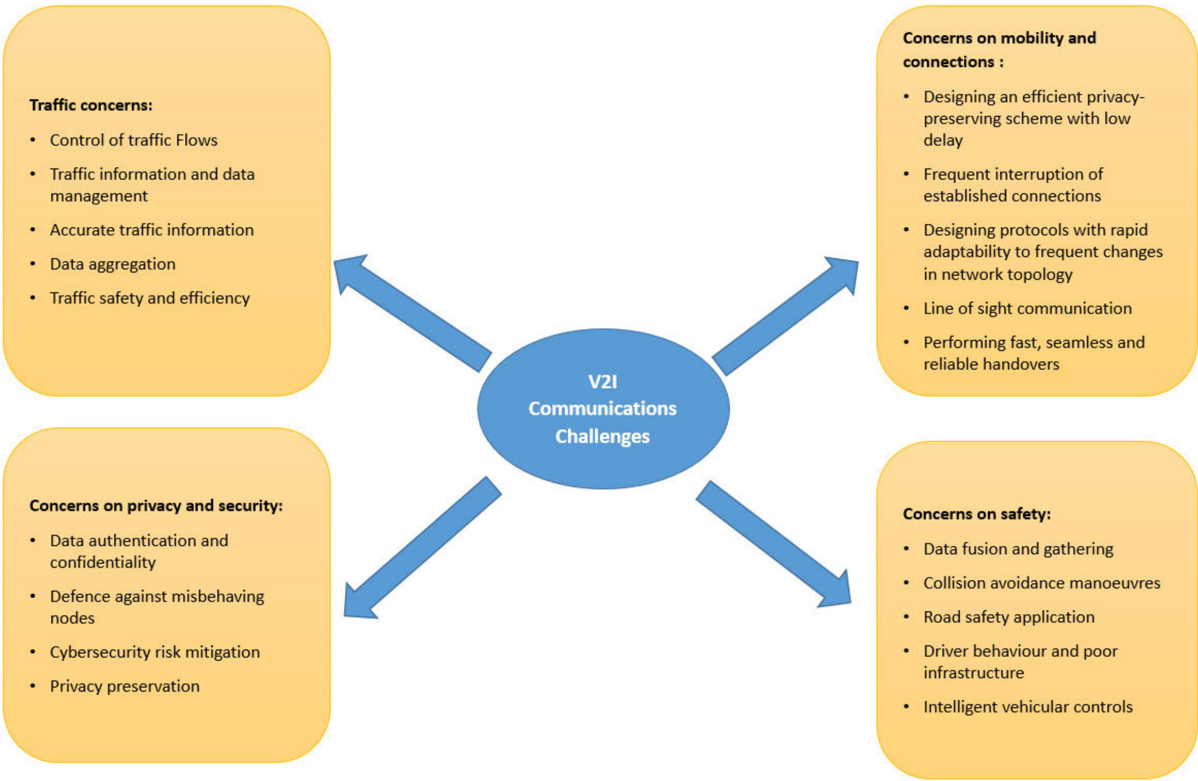

FIGURE 6. Categories of challenges related to V2I communication systems.

environmental monitoring [8], dynamic obstacles maneuvers [31] and the intelligent vehicular controls [11].

3) CONCERNS ON SECURITY AND PRIVACY

The VANET is subject to numerous security threats that can lead to service abuses. Authentication, misbehaving nodes, false information and secure data aggregation are the major concerns of vehicular networks. Security issues on privacy, authentication, data confidentiality and access control over transmitted messages in the VANET remain to be solved [41], [44]. Benefits offered by VANETs and ITS cannot be fully realized unless a mechanism to effectively defend against misbehaving nodes is developed to ensure reliable data delivery [62], establish trust between vehicles in a highly dynamic environment [38] and mitigate cybersecurity risks in urban traffic areas [68]. Another challenge is privacy preserving/anonymous authentication to achieve privacy protection in V2X systems [59]. A measurement scheme for privacy protection must be designed in which a vehicle will never transmit any unique identifiers or fixed numbers [40]. Moreover, an efficient privacy-preserving anonymous authentication scheme for VANETs with low certificate and signature verification delay is also needed [39].

4) CONCERNS ON MOBILITY AND CONNECTIONS

The high mobility of vehicles is another important characteristic of VANETs. The communication time between RSUs and vehicles is extremely low in VANETs owing to this characteristic. In a highly dynamic environment, establishing trust between vehicles is very difficult [38]. Therefore, an efficient privacy-preserving anonymous authentication scheme for VANETs with low certificate and signature verification delays should be designed [39]. The frequent interruption of established connections is another challenging task in the vehicular environment because V2I communication systems have a small coverage area. Moreover, passing vehicles are within the communications range of an RSU for a very brief time [51]. The topology of a VANET changes rapidly from time to time owing to the high mobility of vehicles, thereby causing frequent link disconnections [46]. Link failure also occur during handovers from 3G to Wi-Fi networks (RSU) in which the number of packets drop [50]. Another challenge related to mobility is network fragmentation in which network connections between several intermediate nodes are lost [14]. RSUs should be used to assist broadcasts to deal with fragmentation problems in VANETs. However, RSUs are generally expensive to install. Therefore, the utilization of RSUs in regions with poor resources have become a crucial subject [23]. Protocols designed for vehicular access networks should include quick adaptability to frequent changes in the network topology because vehicular mobility and delay awareness in data delivery are key challenges in vehicular communication [16]. Actual technologies include DSRC and IEEE 802.x standards which are used in short-range radio communications and automatic

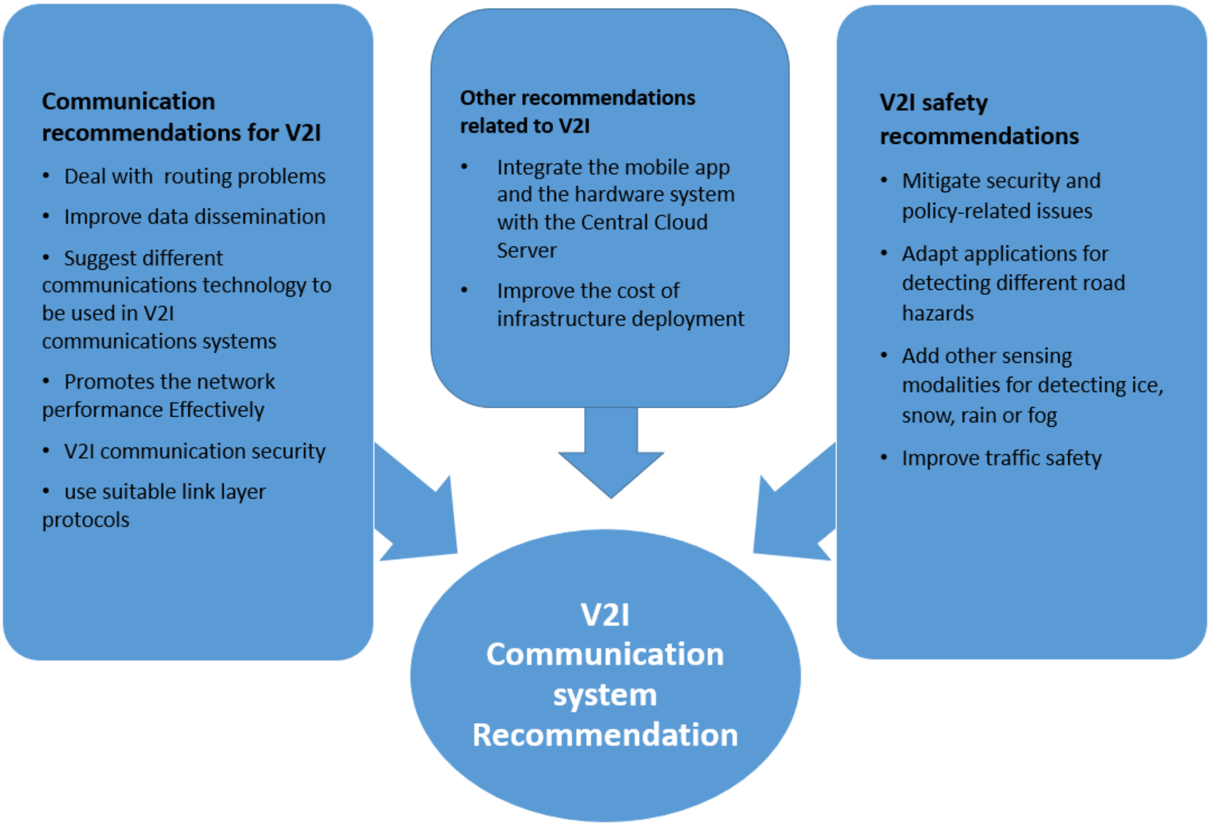

FIGURE 7. Categories of recommendations for V2I communication systems.

handshaking/authentication. However, these technologies oftentimes become crowded or saturated, thereby preventing effective data exchange [3], [56]. Channel congestion, broadcast storms and hidden nodes are among the problems of using DSRC for V2I communication. LTE systems can be widely used for V2I communications to ensure transmission efficiency; however, reducing the overhead is a challenging task [48]. Multichannel operations in vehicular environments is another remarkably challenging task [45]. Typical IEEE 802.11 radios can only tune into to a single channel at a time. Therefore, triggering vehicles' awareness of emerging safety alerts to take advantage of several nonsafety-related services is a major challenge [24]. Other issues of the distributed channel access scheme of the 802.11p are the absence of guaranteed bandwidth and access delays [19]. Issues also exist in the WAVE technology not being able to provide sufficient spectrum for the reliable exchange of safety information over congested urban scenarios [22]. The use of beaconing in a mobile context in which a passing vehicle is within the radio range of the TMU for a limited time as well as assorted mobility patterns of vehicles and routing messages to their final destination are other concerns related to mobility in vehicular communication [43],[51], [55]. Another challenge related to connection issues is GPS performance, which requires a clear line of sight for accurate service. However, this scenario presents a drawback when a vehicle is stuck in a long tunnel or in a place where GPS data is unavailable [5], [33], [34]. The optimal selection of underlying networks in the case of V2I communications in a heterogeneous multitier environment is always challenging. Performing fast, seamless and reliable handovers; maintaining effective QoS and applying traditional internet mobility management protocols for vehicular networks remain as some of the key challenges [47].

G. RECOMMENDATIONS

This section provides a summary of the most important recommendations in the literature to mitigate the challenges and issues facing the use of the V2I communication systems, as shown in Figure 7.

1) COMMUNICATION RECOMMENDATIONS FOR V2I SYSTEMS

This section presents important recommendations related to the communications aspect of the V2I communication system. Future research in this area included minimizing network discovery time; performing fast, seamless and reliable vertical handover; V2I communication security; V2I upper layer communication protocols; and data dissemination in V2I systems [47]. Recommendations included studying the effects of various channel types and packet sizes on the quality of transmission of the

V2X communication systems [60] and improving the communication overhead and the effect of unreliable communication channels [35]. Several features were added to the auxiliary network to expand the communications scheme to deal with real-time traffic planning and control. In addition, an extended analysis was made on the network's performance in critical scenarios, such as traffic jams, multiple node failures, and multiple traffic events [7]. A distributed sorting mechanism was used to promote RSU utility, reduce the cost of transmission and improve network performance effectively [23]. Further studies may focus on dealing with large-scale routing problems that consider large hybrid sensors and vehicular networks [20], integrate centralised router functionality into solutions of VANET networks based on cooperative systems (C-ITS) [17] and optimize the routing and dissemination end-to-end delay for delay-sensitive applications [42]. The bidirectional information exchange between vehicles and RSUs can further improve data dissemination using solutions such as cooperative awareness and decentralized environmental notification messages [6]. Trials will be carried out with different communication systems to select the best option with which to implement the V2I-based architecture for information exchanges among vehicles [1]. Further studies suggested the use of the Bluetooth as a suitable technology for high-speed vehicle communications by proposing an alternative and new use of the remote name request procedure described in the Bluetooth standard [56]. Other works suggested cellular communications because such technologies did not need any additional infrastructure. Hence, they were the preferred solutions for situations in which large latencies are acceptable [2]. The analysis in [51] indicated that the IEEE 802.11 standard, with its beaconing mechanism, is suitable for information exchanges in V2I communications. In the future, the authors will study the active scanning mode of IEEE 802.11 as an alternative to the beaconing mechanism. Other studies focused on providing an authentication facility to enable efficient group communication authentication with low computational costs [39] and addressing the problem of security during the IEEE 802.11p handover [13]. Future research directions extended the GeoCover protocol to connectivity and scheduling issues in VANETs. RSUs can be either active or reactive; hence, the redundancy of energy and coverage can be saved effectively [43]. The results on the optimal configuration of roadside beacons in V2I communications showed notable divergences among roadside configurations for different traffic loads and optimization criteria. Moreover, simulations have shown that a vast majority of errors come from simultaneous transmissions, thereby suggesting the use of suitable link layer protocols [67]. The results of the adoption of WAVE/IEEE 802.11p protocols for V2I systems showed that the deployment of a few RSUs and the use of low complexity routing protocols can lead to a significant reduction of cellular resource occupation, even approaching 100% with a high density of equipped vehicles [53].

2) SAFETY RECOMMENDATIONS FOR V2I SYSTEMS

Future research directions related to safety recommendation for V2I systems included the deployment of cybersecurity for managing traffic efficiency and safety in smart cities, which can significantly enhance travel efficiency and on-road safety and further mitigate cybersecurity risks in urban traffic management [68]. However, other security and policy-related issues will be further explored, including anonymity in VANETs, efficient authentication based on ASPE, collusion resistance under strong security requirements and misbehavior detection and revocation [38]. Further research directions included the adaptation of applications to detect different road hazards, specifically, traffic bottlenecks and heavy rains [9], that link drivers with their physical environment through a context-aware driver assistance system with different functions. Such functions can include a pedestrian detection and parking assistance system that can enhance driver decisions and improve road safety [10]. The new DSRC/WAVE technology was introduced, and one of the two applications, which is called the dilemma zone avoidance, was developed. Future studies should develop the other application and integrate the two to form a useful application [4]. Regional traffic management authorities can achieve near real-time detection of potential incidents by combining loop detectors and traffic cameras, which is ideal for detecting situations such as icy roads or stray animals [35]. Other studies intended to apply machine learning techniques to develop the best strategy for self-driving vehicles as well as traffic light controllers to improve traffic safety and efficiency in atypical situations [69]. The implementation of an AVPP algorithm in the presence of dynamic obstacles improved the safety and throughput of AVs as well as the implementation of the AVPP in an autonomous electric vehicle; thus, optimization-driven, decision-making and receding horizon controls will be considered in the future for investigation [31].

3) OTHER RECOMMENDATIONS FOR V2I SYSTEMS

This section presents other important recommendations related to V2I communication systems, such as improving the cost of infrastructure deployment [35], integrating mobile applications and the hardware systems with a central cloud server and implementing security algorithms (cryptography) into it to improve the system's efficiency and reliability [34]. The simulation evaluation of merging controls for V2V and V2I structures in highway environments indicated that the V2I structure was preferred over the V2V to support cooperative adaptive cruise control owing to its ability to reliably provide information at constant time intervals [54].

H. METHODOLOGICAL ASPECTS

Methodology is the systematic and theoretical analysis of the methods applied to a field of study. Methodological aspects comprised the types of devices and sensors, locations of experiments, numbers of vehicles and infrastructures during

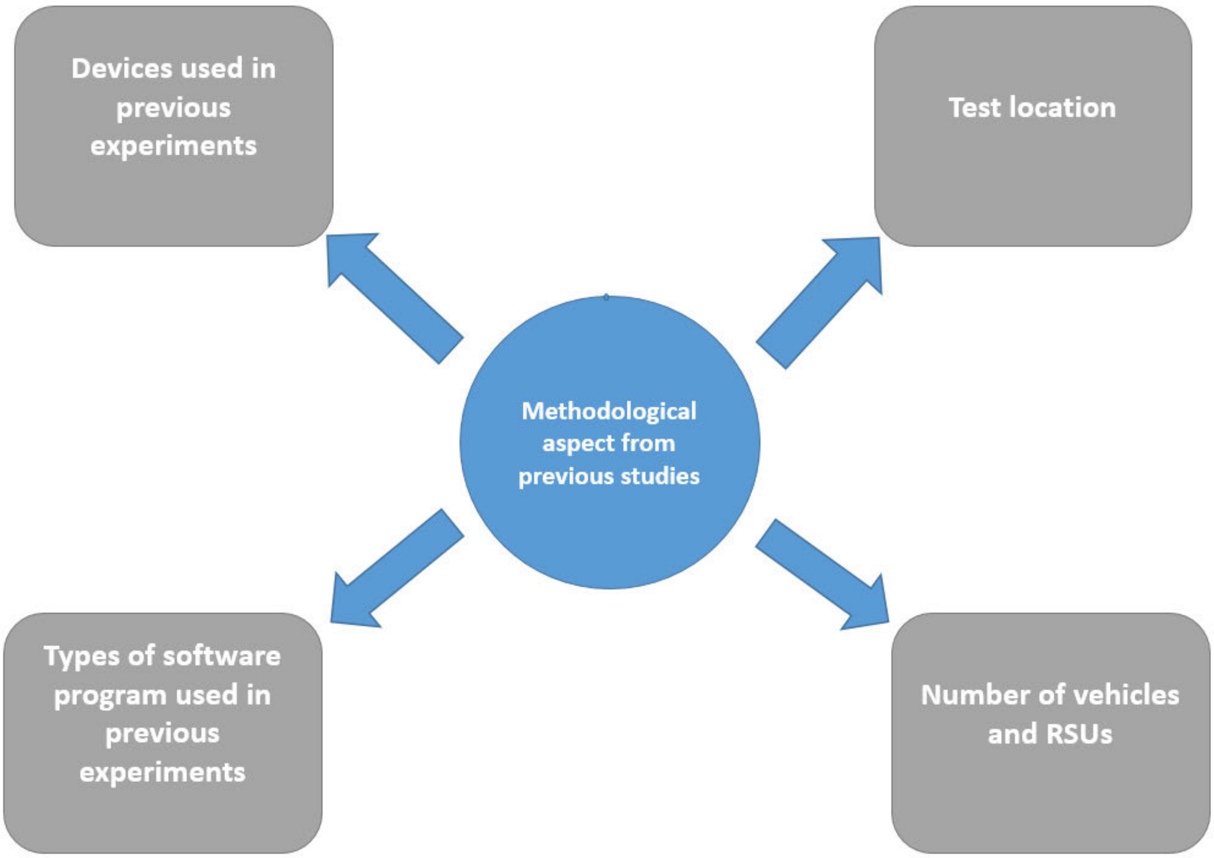

FIGURE 8. Methodological aspects from previous studies.

tests and the types of simulations used in the literature, as shown in Figure 8.

1) DEVICES AND SENSORS IN PREVIOUS EXPERIMENTS

This section presents a brief description of the devices used in previous actual experiments for V2I communication systems. Video transmission systems consisting of a surveillance camera were installed on the roadside [4], [5], [34]. Vehicles were equipped with OBUs to measure V2V connectivity [4]–[6], [34], and a car's absolute position was obtained through GPS [1], [4], [5], [12], [34] to detect the position and movement of other vehicles. RSUs and vehicles use different types of protocols to exchange information, such as the IEEE 802.11p DSRC, which was used in [4]. Tests were performed through a Wi-Fi system [1], ZigBee [7], [12], Bluetooth [10] and Raspberry Pi board [6], [8]. Different types of sensors were used in previous experiments to provide V2V and V2I communication systems. Touch, light, ultrasonic [10], Xbee (with Xbee modem) [9], air temperature and fog sensors were used to provide environment monitoring and to warn drivers about adverse road weather conditions [2].

2) TEST LOCATIONS

This section presents a brief description on the test locations of actual experiments conducted in previous studies to investigate V2I communications. A dilemma zone avoidance system was deployed in an actual trial in Michigan, USA. An RSU was installed at two intersections, including the northbound Telegraph route at Long Lake and the following intersection of Telegraph and Hickory Grove [4]. The Autopia group had a private driving circuit that consisted of a set of roads that emulated urban conditions. The driving circuit included roundabouts, crossroads, bends and straight stretches. This area had a longitude of over one kilometer [1], [7]. A fog vision sensor was developed and deployed to warn drivers of adverse road weather conditions, and the approach was demonstrated in Finland in actual scenarios [2].

3) NUMBER OF VEHICLES AND RSUs

This section presents a brief description of the number of vehicles and RSUs included in tests conducted in previous actual experiments on V2I communication systems. A one-way straight road with only one RSU was designed in [23], whereas one real RSU and two simulated RSUs were used in [8]. A prototype was designed in [5] and placed in one RSU and two vehicles for speed detection, lane change assistance and vehicle detection. Other experiments were conducted by fixing the number of the vehicles to only two. A trial was carried out with two vehicles and two different local control station LCSs installed in the circuit [1]. Other works considered three groups of scenarios with three cars and three RSUs with their sensors [9].

4) TYPES OF SOFTWARE PROGRAMMES USED IN PREVIOUS EXPERIMENTS

This section presents a brief description on the types of software used in previous experiments on V2I systems. The first group comprised eight studies that used Network Simulator software [16], [18], [23], [50], [51], [55], [61], [66]. The second group, which included seven studies, used a combination of two programs, namely, NS and SUMO simulation software [5], [13], [17], [19], [21], [34], [43]. The third group was composed of four studies that used MATLAB [29], [32], [33], [36]. The last group included 10 studies that used various types of software such as SUMO, which is a road traffic simulator [30], [42], Markovian random walk, with random positioning for simulating VC mobility [25], [26], OMNeT++ [67], Open Street Map [9], a hybrid-network simulator called GrooveNet [35], Manhattan [15], NetLogo [54] and PLEXE [37].

V. CONCLUSION

The V2I communication system is a fundamental technology for different vehicular applications. Research efforts in this area are still ongoing, and understanding and clarifying this research direction is crucial. This work aimed to contribute to such understanding by surveying and classifying relevant research efforts. The research efforts in this field were classified into three classes, namely, proposals for system developments, surveys and reviews and studies conducted on the V2I communication system. Highly valuable information was obtained through the concentrated reading and analysis of the reviewed articles related to V2I communication, such as motivations, challenges and issues, and recommendations related to V2I systems as well as performance measurements, data sources and methodological aspects.

REFERENCES

[1] V. Milanés, J. Godoy, J. Pérez, B. Vinagre, C. González, E. Onieva, and J. Alonso, "V2I-based architecture for information exchange among vehicles," *IFAC Proc. Volumes*, vol. 43, no. 16, pp. 85–90, 2010.

[2] J. Scholliers, M. Jutila, M. Valta, K. Kauvo, A. Virtanen, and P. Pyykönen, "Co-operative traffic solutions for hybrid communication environments," *Transp. Res. Procedia*, vol. 14, pp. 4542–4551, Jan. 2016.

[3] V. Iordache, R. A. Gheorghiu, M. Minea, and A. C. Cormos, "Field testing of Bluetooth and ZigBee technologies for vehicle-to-infrastructure applications," in *Proc. 13th Int. Conf. Adv. Technol., Syst. Services Telecommun. (TELSIKS)*, Oct. 2017, pp. 248–251.

[4] H. Su, C.-H. Cho, Y.-H. Chu, and W.-Y. Chang, "A traffic information dissemination mechanism based on DSRC/WAVE and its applications," in *Proc. 12th Int. Conf. Telecommun.*, Nov. 2012, pp. 629–632.

[5] Y. Agarwal, K. Jain, and O. Karabasoglu, "Smart vehicle monitoring and assistance using cloud computing in vehicular ad hoc networks," *Int. J. Transp. Sci. Technol.*, vol. 7, no. 1, pp. 60–73, 2018.

[6] N. Varga, L. Bokor, A. Takács, J. Kovács, and L. Virág, "An architecture proposal for V2X communication-centric traffic light controller systems," in *Proc. 15th Int. Conf. Telecommun. (ITST)*, May 2017, pp. 1–7.

[7] J. Godoy, V. Milanés, J. Pérez, J. Villagrá, and E. Onieva, "An auxiliary V2I network for road transport and dynamic environments," *Transp. Res. C, Emerg. Technol.*, vol. 37, pp. 145–156, Dec. 2013.

[8] M. Ruta, F. Scioscia, A. Pinto, F. Gramegna, S. Ieva, G. Loseto, and E. Di Sciascio, "A CoAP-based framework for collaborative sensing in the semantic Web of things," *Procedia Comput. Sci.*, vol. 109, pp. 1047–1052, Jan. 2017.

[9] J. Radak, B. Ducourthial, V. Cherfaoui, and S. Bonnet, "Detecting road events using distributed data fusion: Experimental evaluation for the icy roads case," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 1, pp. 184–194, Jan. 2016.

[10] W. Alghamdi, E. Shakshuki, and T. R. Sheltami, "Context-aware driver assistance system," *Procedia Comput. Sci.*, vol. 10, pp. 785–794, Jan. 2012.

[11] F. Jiménez, J. E. Naranjo, J. J. Anaya, F. García, A. Ponz, and J. M. Armingol, "Advanced driver assistance system for road environments to improve safety and efficiency," *Transp. Res. Procedia*, vol. 14, pp. 2245–2254, Jan. 2016.

[12] V. Milanés, J. Pérez, J. Godoy, and E. Onieva, "A fuzzy aid rear-end collision warning/avoidance system," *Expert Syst. Appl.*, vol. 39, no. 10, pp. 9097–9107, 2012.

[13] R. Zagrouba, T. Hayouni, and F. Kamoun, "Handover optimization within vehicular networks," in *Proc. World Congr. Comput. Appl. Inf. Syst.*, Jan. 2014, pp. 1–5.

[14] X. Fan, B. Yang, R. Yamamoto, and Y. Tanaka, "Road side unit assisted stochastic multi-hop broadcast scheme for instant emergency message propagation," in *Proc. 17th Int. Conf. Adv. Commun. Technol. (ICACT)*, Jul. 2015, pp. 450–457.

[15] G. G. M. N. Ali, P. H. J. Chong, S. K. Samantha, and E. Chan, "Efficient data dissemination in cooperative multi-RSU vehicular ad hoc networks (VANETs)," *J. Syst. Softw.*, vol. 117, pp. 508–527, Jul. 2016.

[16] B. Jarupan and E. Ekici, "PROMPT: A cross-layer position-based communication protocol for delay-aware vehicular access networks," *Ad Hoc Netw.*, vol. 8, no. 5, pp. 489–505, 2010.

[17] M. Srotyr, T. Zelinka, and Z. Lokaj, "Hybrid communication solution for C-ITS and its evaluation," in *Proc. Smart City Symp. Prague (SCSP)*, May 2017, pp. 1–7.

[18] C. Shao, S. Leng, Y. Zhang, and H. Fu, "A multi-priority supported medium access control in vehicular ad hoc networks," *Comput. Commun.*, vol. 39, pp. 11–21, Feb. 2014.

[19] M. Amadeo, C. Campolo, and A. Molinaro, "Enhancing IEEE 802.11p/WAVE to provide infotainment applications in VANETs," *Ad Hoc Netw.*, vol. 10, no. 2, pp. 253–269, 2012.

[20] S. Malika and B.-M. Louiza, "Efficient message delivery in hybrid sensor and vehicular networks based on mathematical linear programming," *Comput. Elect. Eng.*, vol. 64, pp. 496–505, Nov. 2017.

[21] Z. He and D. Zhang, "Cost-efficient traffic-aware data collection protocol in VANET," *Ad Hoc Netw.*, vol. 55, pp. 28–39, Feb. 2017.

[22] A. J. Ghandour, K. Fawaz, H. Artail, M. Di Felice, and L. Bononi, "Improving vehicular safety message delivery through the implementation of a cognitive vehicular network," *Ad Hoc Netw.*, vol. 11, no. 8, pp. 2408–2422, 2013.

[23] T.-Y. Wu, S. Guizani, W.-T. Lee, and K.-H. Liao, "Improving RSU service time by distributed sorting mechanism," *Ad Hoc Netw.*, vol. 10, no. 2, pp. 212–221, 2012.

[24] M. Khabbaz, C. Assi, M. Hasna, A. Ghrayeb, and W. Fawaz, "Modelling, analysis and performance improvement of an SRU's access request queue in multi-channel V2I communications," *Pervasive Mobile Comput.*, vol. 21, pp. 92–102, Aug. 2015.

[25] N. Cordeschi, D. Amendola, and E. Baccarelli, "Resource-management for vehicular real-time application under hard reliability constraints," in *Proc. IEEE/ACM 18th Int. Symp. Distrib. Simulation Real Time Appl.*, Oct. 2014, pp. 219–226.

[26] N. Cordeschi, D. Amendola, and E. Baccarelli, "Fairness-constrained optimized time-window controllers for secondary-users with primary-user reliability guarantees," *Comput. Commun.*, vol. 116, pp. 63–76, Jan. 2018.

[27] N. Cordeschi, D. Amendola, M. Shojafar, and E. Baccarelli, "Distributed and adaptive resource management in cloud-assisted cognitive radio vehicular networks with hard reliability guarantees," *Veh. Commun.*, vol. 2, no. 1, pp. 1–12, 2015.

[28] N. Cordeschi, D. Amendola, and E. Baccarelli, "Hard and soft optimal resource allocation for primary and secondary users in infrastructure vehicular networks," in *Proc. 12th Annu. IEEE Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2015, pp. 708–713.

[29] B. HomChaudhuri, R. Lin, and P. Pisu, "Hierarchical control strategies for energy management of connected hybrid electric vehicles in urban roads," *Transp. Res. C, Emerg. Technol.*, vol. 62, pp. 70–86, Jan. 2016.

[30] I. Johansson, J. Jin, X. Ma, and H. Pettersson, "Look-ahead speed planning for heavy-duty vehicle platoons using traffic information," *Transp. Res. Procedia*, vol. 22, pp. 561–569, Jan. 2017.

[31] D. G. Perumal, B. Subathra, G. Saravanakumar, and S. Srinivasan, "Extended Kalman filter based path-planning algorithm for autonomous vehicles with I2V communication," *IFAC-PapersOnLine*, vol. 49, no. 1, pp. 652–657, 2016.

[32] J. Ďurech, M. Hruboš, M. Franeková, and A. Janota, "Implementation of data from the mobile measurement platform to VANET application," in *Proc. ELEKTRO*, May 2014, pp. 430–434.

[33] G.-M. Hoang, B. Denis, J. Härri, and D. T. M. Slock, "Robust data fusion for cooperative vehicular localization in tunnels," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Jun. 2017, pp. 1372–1377.

[34] Y. Agarwal, K. Jain, S. Kumar, and G. N. Bhardwaj, "TLST: Time of arrival based localization and smart tunnel concept in VANETs," in *Proc. 3rd Int. Conf. Signal Process. Integr. Netw.*, Feb. 2016, pp. 763–768.

[35] C. Liao, J. Chang, I. Lee, and K. K. Venkatasubramanian, "A trust model for vehicular network-based incident reports," in *Proc. IEEE 5th Int. Symp. Wireless Veh. Commun. (WiVeC)*, Jun. 2013, pp. 1–5.

[36] A. Saxena, H. Li, D. Goswami, and C. B. Math, "Design and analysis of control strategies for vehicle platooning," in *Proc. 19th Int. Conf. Intell. Transp. Syst.*, Nov. 2016, pp. 1805–1812.

[37] D. Jia and D. Ngoduy, "Enhanced cooperative car-following traffic model with the combination of V2V and V2I communication," *Transp. Res. B, Methodol.*, vol. 90, pp. 172–191, Aug. 2016.

[38] D. Huang and M. Verma, "ASPE: Attribute-based secure policy enforcement in vehicular ad hoc networks," *Ad Hoc Netw.*, vol. 7, no. 8, pp. 1526–1535, Nov. 2009.

[39] P. Vijayakumar, V. Chang, L. J. Deborah, B. Balusamy, and P. G. Shynu, "Computationally efficient privacy preserving anonymous mutual and batch authentication schemes for vehicular ad hoc networks," *Future Generat. Comput. Syst.*, vol. 78, pp. 943–955, Jan. 2016.

[40] Y. Zhou, S. Chen, Y. Zhou, M. Chen, and Q. Xiao, "Privacy-preserving multi-point traffic volume measurement through vehicle-to-infrastructure communications," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5619–5630, Dec. 2015.

[41] X. Liu, Y. Xia, W. Chen, Y. Xiang, M. M. Hassan, and A. Alelaiwi, "SEMD: Secure and efficient message dissemination with policy enforcement in VANET," *J. Comput. Syst. Sci.*, vol. 82, no. 8, pp. 1316–1328, Dec. 2016.

[42] S. Mehar, S. M. Senouci, A. Kies, and M. M. Zoulikha, "An optimized roadside units (RSU) placement for delay-sensitive applications in vehicular networks," in *Proc. 12th Annu. IEEE Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2015, pp. 121–127.

[43] H. Cheng, X. Fei, A. Boukerche, and M. Almulla, "*GeoCover*: An efficient sparse coverage protocol for RSU deployment over urban VANETs," *Ad Hoc Netw.*, vol. 24, pp. 85–102, Jan. 2015.

[44] C. Bernardini, M. R. Asghar, and B. Crispo, "Security and privacy in vehicular communications: Challenges and opportunities," *Veh. Commun.*, vol. 10, pp. 13–28, Oct. 2017.

[45] R. F. Atallah, M. J. Khabbaz, and C. M. Assi, "Vehicular networking: A survey on spectrum access technologies and persisting challenges," *Veh. Commun.*, vol. 2, no. 3, pp. 125–149, Jul. 2015.

[46] H. T. Cheng, H. Shan, and W. Zhuang, "Infotainment and road safety service support in vehicular networking: From a communication perspective," *Mech. Syst. Signal Process.*, vol. 25, no. 6, pp. 2020–2038, Aug. 2011.

[47] E. Ndashimye, S. K. Ray, N. I. Sarkar, and J. A. Gutiérrez, "Vehicle-to-infrastructure communication over multi-tier heterogeneous networks: A survey," *Comput. Netw.*, vol. 112, pp. 144–166, Jan. 2017.

[48] K. Zheng, Q. Zheng, P. Chatzimisios, W. Xiang, and Y. Zhou, "Heterogeneous vehicular networking: A survey on architecture, challenges, and solutions," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2377–2396, 4th Quart., 2015.

[49] U. Lee and M. Gerla, "A survey of urban vehicular sensing platforms," *Comput. Netw.*, vol. 54, no. 4, pp. 527–544, Mar. 2010.

[50] S. K. Gupta and S. Khara, "Technique to improve the file transfer outcomes between road side unit and vehicles in vehicular ad-hoc networks," in *Proc. Int. Conf. Comput., Commun. Automat.*, May 2015, pp. 360–366.

[51] S. A. Sha-Mohammad, H. M. Abdel-Wahab, and D. C. Popescu, "A study of IEEE 802.11 standard for use in vehicle to infrastructure communication," in *Proc. IEEE Globecom Workshops (Globecom)*, Dec. 2013, pp. 1303–1307.

[52] A. Sassi, Y. Elhillali, and F. Charfi, "Evaluating experimental measurements of the IEEE 802.11p communication using ARADA LocoMate OBU device compared to the theoretical simulation results," *Wireless Pers. Commun.*, vol. 97, no. 3, pp. 3861–3874, Dec. 2017.

[53] A. Bazzi, B. M. Masini, A. Zanella, and G. Pasolini, "IEEE 802.11p for cellular offloading in vehicular sensor networks," *Comput. Commun.*, vol. 60, pp. 97–108, Apr. 2015.

[54] O. Shagdar and P. Muhlethaler, "Study on merging control supported by IEEE 802.11p systems for highway environments," in *Proc. IFIP Wireless Days*, Nov. 2013, pp. 1–4.

[55] A. Daniel, D. C. Popescu, and S. Olariu, "A study of beaconing mechanism for vehicle-to-infrastructure communications," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2012, pp. 7146–7150.

[56] D. Perez-Diaz de Cerio and J. L. Valenzuela, "Provisioning vehicular services and communications based on a Bluetooth sensor network deployment," *Sensors*, vol. 15, no. 6, pp. 12765–12781, Jun. 2015.

[57] H. Fouchal, E. Bourdy, G. Wilhelm, and M. Ayaida, "A validation tool for cooperative intelligent transport systems," *J. Comput. Sci.*, vol. 22, pp. 283–288, Sep. 2017.

[58] M. Aramrattana, T. Larsson, J. Jansson, and A. Nåbo, "A simulation framework for cooperative intelligent transport systems testing and evaluation," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 61, pp. 268–280, Feb. 2019.

[59] Y. Yang, Z. Wei, Y. Zhang, H. Lu, K.-K. R. Choo, and H. Cai, "V2X security: A case study of anonymous authentication," *Pervasive Mobile Comput.*, vol. 41, pp. 259–269, Oct. 2017.

[60] A. Sassi, F. Charfi, L. Kamoun, Y. Elhillali, and A. Rivenq, "The impact of mobility on the performance of V2X communication," in *Proc. 4th Int. Conf. Logistics*, 2011, pp. 434–438.

[61] M. Sepulcre, J. Gozalvez, and B. Coll-Perales, "Why 6 Mbps is not (always) the optimum data rate for beaconing in vehicular networks," *IEEE Trans. Mobile Comput.*, vol. 16, no. 12, pp. 3568–3579, Apr. 2017.

[62] J. Sun and Y. Fang, "Defense against misbehavior in anonymous vehicular ad hoc networks," *Ad Hoc Netw.*, vol. 7, no. 8, pp. 1515–1525, Nov. 2009.

[63] L. Shi and P. Prevedouros, "Autonomous and connected cars: HCM estimates for freeways with various market penetration rates," *Transp. Res. Procedia*, vol. 15, pp. 389–402, Jun. 2016.

[64] C. Wuthishuwong and A. Traechtler, "Stability of the consensus in the network of multiple autonomous intesections management," in *Proc. 20th Int. Conf. Autom. Comput.*, Sep. 2014, pp. 295–300.

[65] A. E. C. Mondragon, E. S. C. Mondragon, C. E. C. Mondragon, and F. Mung'au, "Estimating the performance of intelligent transport systems wireless services for multimodal logistics applications," *Expert Syst. Appl.*, vol. 39, no. 4, pp. 3939–3949, 2012.

[66] S. Chen, W. Nai, D. Dong, W. Zheng, and W. Jing, "Key indices analysis of IEEE 802.11p based vehicle to infrastructure system in highway environment," *Procedia-Social Behav. Sci.*, vol. 96, pp. 188–195, Nov. 2013.

[67] J. Vales-Alonso, F. Vicente-Carrasco, and J. J. Alcaraz, "Optimal configuration of roadside beacons in V2I communications," *Comput. Netw.*, vol. 55, no. 14, pp. 3142–3153, 2011.

[68] Z. Li and M. Shahidehpour, "Deployment of cybersecurity for managing traffic efficiency and safety in smart cities," *Electr. J.*, vol. 30, no. 4, pp. 52–61, 2017.

[69] P. Gora and I. Rüb, "Traffic models for self-driving connected cars," *Transp. Res. Procedia*, vol. 14, pp. 2207–2216, Jan. 2016.

[70] S. Sousa, A. Santos, A. Costa, B. Dias, B. Ribeiro, F. Gonçalves, J. Macedo, M. J. Nicolau, and Ó. Gama, "A new approach on communications architectures for intelligent transportation systems," *Procedia Comput. Sci.*, vol. 110, pp. 320–327, Jan. 2017.

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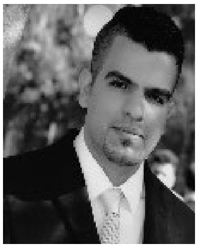

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