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A Comprehensive Survey on Cooperative Intersection Management for Heterogeneous Connected Vehicles

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ABSTRACT Nowadays, with the advancement of technology, world is trending toward high mobility and dynamics. In this context, intersection management (IM) as one of the most crucial elements of the transportation sector demands high attention. Today, road entities including infrastructures, vulnerable road users (VRUs) such as motorcycles, moped, scooters, pedestrians, bicycles, and other types of vehicles such as trucks, buses, cars, emergency vehicles, and railway vehicles like trains or trams are able to communicate cooperatively using vehicle-to-everything (V2X) communications and provide traffic safety, efficiency, infotainment and ecological improvements. In this paper, we take into account different types of intersections in terms of signalized, semi-autonomous (hybrid) and autonomous intersections and conduct a comprehensive survey on various intersection management methods for heterogeneous connected vehicles (CVs). We consider heterogeneous classes of vehicles such as road and rail vehicles as well as VRUs including bicycles, scooters and motorcycles. All kinds of intersection goals, modeling, coordination architectures, scheduling policies are thoroughly discussed. Signalized and semi-autonomous intersections are assessed with respect to these parameters. We especially focus on autonomous intersection management (AIM) and categorize this section based on four major goals involving safety, efficiency, infotainment and environment. Each intersection goal provides an in-depth investigation on the corresponding literature from the aforementioned perspectives. Moreover, robustness and resiliency of IM are explored from diverse points of view encompassing sensors, information management and sharing, planning universal scheme, heterogeneous collaboration, vehicle classification, quality measurement, external factors, intersection types, localization faults, communication anomalies and channel optimization, synchronization, vehicle dynamics and model mismatch, model uncertainties, recovery, security and privacy.

INDEX TERMS Vehicular ad-hoc networks (VANETs), intersection management (IM), vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), trajectory planning (TP), spatio-temporal (ST), connected autonomous vehicles (CAVs), vulnerable road users (VRUs), connected vehicles (CVs), autonomous vehicle (AVs).

I. INTRODUCTION

Number of vehicles on the roads has grown dramatically in the recent years. In 2006, there were approximately 250 million commercial vehicles and 680 million passenger cars. In 2015, this number grew to 335 million commercial vehicles and almost 950 million passenger cars [1] causing traffic congestion. IM appears to be one of the most demanding issues within the transport and road sectors that has a great impact on traffic safety, efficiency, infotainment and environment. Safety is recognized as one of the most important issues in IM in such a way that around one third of accidents with injury are reported at the city intersections [2]. Besides, statistics in Europe and the United States show that over 40 percent of collisions take place at the intersections [3]. This makes safety as one of the hottest topics in the IM sector that requires great deal of attention. Traffic efficiency as the second major pillar of the intelligent transport systems (ITS) is intertwined with traffic safety and must be jointly considered in many traffic situations. For example,

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severe collisions with fatalities in low congested traffic are more probable due to head-on collisions or in presence of VRUs. On the other hand, in congested situations, the likelihood of less serious crashes is higher. Traffic delay is another management concern that intersections are dealing with and incurs huge congestion costs. Intersections largely contribute to travel delays and crash numbers in urban environments [4]. Besides, crashes and delays have a great impact on human time and energy wastage [3]. It has been demonstrated that human errors have a significant role in road accidents by 75 percent [5]. Vehicle's throughput, speed, travel time, fuel consumption and emissions are other important factors that are highly affected by an IM mechanism.

To control the intersection, the advent of traffic lights has remarkably helped to improve the traffic performance at intersections. Nonetheless, traffic lights seem to be not so effective for a high volume of traffic since they are not dynamically adaptable to the real time vehicular traffic [6]. Recently, autonomous vehicles (AVs) have emerged and they are rapidly under development due to the tremendous advancements in computer, communication and automotive technologies, whereby they can hugely amend this problem at the intersections. Together with vehicles autonomy, the genesis of vehicular communications has promised great potentials for promotion of the intersection performance. It is assumed that cooperative coordination of the vehicles and infrastructures using vehicular ad-hoc networks (VANETs) contributes to the optimized traffic in terms of safety, efficiency, infotainment and environmental sustainability. Furthermore, vehicles and roads are endowed with advanced sensors that yield abundant information of the surroundings. Such sensor-based information together with vehicle state information provide deeper, real-time and global perception of the environment beyond the visual field using VANETs. These smart IM approaches can significantly diminish travel time, fuel consumption and emissions of the vehicles. Besides, they can also increase the drivers' awareness and throughput compared to the traditional traffic lights. Considering level of autonomy of the road users as well as installed infrastructures, intersections can be categorized into three groups, i.e., signalized, autonomous and hybrid. Signalized intersections benefit from stop signs or traffic lights to control the vehicles crossing while they can negotiate with the traffic lights for an optimized passage order. In case of autonomous intersections, connected autonomous vehicles (CAVs) or CVs make their decision to traverse the intersection through V2V or V2I communications. Lastly, hybrid intersections accommodate human-operated vehicles and CVs.

Two major standards exist for V2X communications, ITS-G5 standardized in Europe [7] and dedicated short range communication (DSRC) [8] in US. V2X communications incorporate V2V and V2I as the principal variations. European and US standards convey some similarities. They both operate at 5.9 GHz band as the spectrum is sub-divided in a few 10 MHz channels. Security and privacy mechanisms are identical and they both operates outside the context of a BSS (basic service set) known as (OCB) mode of IEEE 802.11. In addition, 802.11p forms the physical and MAC layer of DSRC [9] and ITS-G5 [7]. On the other hand, standards of the protocols in the upper layers are distinct. Upper layers of DSRC are characterized by IEEE WAVE standards [10]. DSRC IEEE 1609 defines a broadcast protocol for routing namely Wave Short Message Protocol (WSMP) [7]. Besides, it uses Basic Safety Message (BSM) [11] and its format is defined by SAE J2735 [12] standards. In terms of ITS-G5, for instance, it uses Geonetworking for single and multi-hop ad-hoc communication. ITS-G5 mainly specifies two types of safety messages called cooperative awareness message (CAM) and decentralized environmental notification message (DENM). CAM is periodic while DENM is event-triggered message that notifies a hazardous situation [7]. Nonetheless, some CVs benefit from the cellular-V2X (C-V2X) that provides quality of service (QoS) and incorporates technologies such as 3rd generation partnership project (3GPP) [13] or long term evolution (LTE) [14]. V2V via cellular network is performed through a particular mode that supports direct communication like DSRC. DSRC and ITS-G5 are short-range communications which are fast, reliable in sparse area, with extensive hardware support that preserve user privacy. On the contrary, C-V2X operates more dependable in dense areas, supports long-range communication, and has hardware support constraints. Moreover, it supports point to point communication in addition to broadcasting. Besides, communication capacity in ITS-G5 and DSRC is limited due to the spectrum allocation and high demands resource optimization. In addition to the DSRC and C-V2X, some researchers have opted for other types of wireless communications such as Bluetooth or Wi-Fi for VANETs.

Development of an effective intersection management system requires consideration of all aspects. Researchers in [15]–[17] have proposed diverse approaches to coordinate the CVs at the intersections. Over the past few years, some surveys have addressed IM in different ways. Rios-Torres and Malikopoulos [18] focused on state of the art scheduling policy methods based on heuristics and optimization for intersection crossing and highway on ramps merging. They considered both centralized and distributed coordination techniques. Chen and Englund [19] surveyed cooperative IM mechanisms at the signalized and free signalized crossroads from three perspectives; virtual traffic lights, trajectory planning (TP) and spatio-temporal (ST) resource reservation. Namazi *et al.* [20] also conducted a literature review on the management of signalized and non-signalized intersections under vehicular environment in a systematic way. Moreover, Khayatian *et al.* [21] presented a survey on IM of CAVs from different aspects consisting of architecture, vehicle dynamics, wireless technologies, scheduling mechanisms, collision detection, human-operated vehicles, recovery, security, safety, robustness issues and simulation tools. Krishnan *et al.* [22] performed a partial non technical study on IM while Guo *et al.* [23] addressed solutions for traffic flow estimation and optimizing traffic signal timings based on CAVs at the urban signalized intersections. Furthermore, Zhong *et al.* [24] surveyed AIM with the focus on three hierarchical layers namely corridor coordination, IM and vehicle control. Other IM design concepts such as computation convolution, centralization, collision detection strategies, priority policies, and also roadmap from signalized IM to AIM were also discussed. In another work, Malik *et al.* [25] studied the recent articles in cooperative driving, related taxonomy, platooning and especially various issues that exist in the leader election of vehicles platooning. Here, authors briefly addressed intersection management solutions as one of the collaborative driving applications and presented the relevant approaches.

In this paper, we explore the state-of-the-art cooperative intersection management approaches for heterogeneous vehicles from different aspects in the last two decades. We analyzed more than 1,200 relevant publications including surveys, reviews and short articles involving heterogeneous CAVs or CVs roaming roads and rails at various kinds of intersections. Consequently, our research resulted in approximately 379 papers such that to the authors' knowledge, this study is the first that takes into account main aspects of intersection management for heterogeneous vehicles at the signalized, non-signalized and hybrid intersections. We specified a goal-based classification of the literature and presented a systematic evaluation of the approaches at the end. Additionally, numerous challenges for a robust and resilient IM are discussed to enlighten the future directions for further studies in this field.

This paper is organized as follows. Section II introduces the fundamentals of the intersection management in terms of a centralized and distributed architecture, different scheduling policies such as first come first serve (FCFS), optimization and heuristic-based algorithms, intersection modeling methods containing ST reservation and TP, and intersection goals namely; safety, efficiency, passenger infotainment and environment. Next, intersections are categorized into three groups namely; 1) signalized intersections 2) semi-autonomous intersections 3) autonomous intersections. Sections III, IV and V address these types of intersections consecutively where all the IM methods are introduced and compared. The following section deals with IM literature for VRUs. Several communication types based on centralized and distributed architectures are involved to interconnect VRUs. Section VII deals with diverse challenges that intersections encounters and greatly affect their performance. These concerns span a wide range of items comprising sensors, information management and sharing, planning universal scheme, heterogeneous collaboration, vehicle classification, quality measurement, external factors, intersection types, localization, faults, communication anomalies and channel optimization, synchronization, vehicle dynamics and model mismatch, model uncertainties, recovery, and security and privacy. Section VIII summarizes the discussion, visualizes the results and conducts a deeper analysis on IM solutions. Finally, the last section concludes the work.

II. INTERSECTION MANAGEMENT (IM) FUNDAMENTALS

A. ARCHITECTURE ALTERNATIVES

Traffic coordination methodologies of the intersection is mainly categorized into two groups of V2I and V2V. V2I is the centralized approach and takes advantage of infrastructure/intersection manager for traffic control while V2V is distributed and vehicles undertake coordination by exchanging information between each other and making decisions locally. Occasionally, in a hybrid methodology no infrastructure is involved though a vehicle temporarily takes charge of the intersection coordination.

1) DISTRIBUTED: VEHICLE-TO-VEHICLE COMMUNICATION (V2V)

This approach is more suitable for non congested intersections like those in rural areas. Comparatively, distributed approaches can provide more reliability and resiliency. They are more scalable due to their independence from the roadside unit (RSU) support. Besides, in the distributed control, computation is spread across the vehicles and TP and resource reservation are performed locally in the vehicles. This leads to more robustness where a vehicle failure does not inevitably result in system breakdown. On the downside, high communication bandwidth is required due to drastic communications among vehicles to make a common decision.

2) CENTRALIZED: VEHICLE-TO-INFRASTRUCTURE COMMUNICATION (V2I)

A centralized approach empowers more control and management over the vehicles as computations consisting TP and resource grant are conducted inside the RSU. Besides, they can also handle high computation loads and less network overhead is assumed for this solution as the infrastructure can maintain the traffic information. Therefore, vehicles need not periodically broadcast their status. As the pitfall, the deployment of RSUs is costly and these are not as reliable as in distributed control due to the single point of failure. Therefore, mechanisms are required to ensure system robustness. V2I approaches are classified into two groups. In the first method, the RSU assigns a cross-time to the vehicles to follow based on the received status information from them which results in higher throughput. Adversely, in the second one, the vehicle proposes a safe cross speed/time by sending a query to the RSU and receives either approval or rejection for this request. This method requires more processing time compared to the other approach due to its interface nature. Additionally, the packet size of the exchanged information has an impact on the network overhead.

B. SCHEDULING POLICY

Basically, in topology design of the intersection, a standard traffic coordination algorithms should be applicable to diverse kinds of intersections. Therefore, it should take into account some other factors such as lane numbers, width, and turn allowance or u-turn permissions. Several methods such as mathematical optimization, multi-agent systems (MAS), heuristic, linear and dynamic programming cooperate in the intersection management. Besides, apart from time and space, some other variables contribute to the intersection safety such as braking, speed, headway, acceleration/deceleration, throttling, maneuvering that are to be considered. Furthermore, sound algorithm design for an intersection management should make use of an adaptive and flexible vehicle model where variables are defined in execution time. Moreover, safety margin size and model inaccuracy are directly related. Vehicles enter the intersection and avoid collisions based on some coordination rules such as arrival time, scheduling policy and priorities that are defined in the algorithms. Besides, algorithms should be fast and reliable to cope with high traffic mobility. On the other hand, processing time to determine the collisions and schedule safe crossing at the intersection is of high importance particularly in case of an optimization-based approach. Bigger processing time leads to larger safety margin around vehicles which is not satisfactory. In addition, there is an uniform relationship between the processing time and size of the intersection. If processing time rises, intersection size escalates accordingly because vehicles need to initiate communication much farther than before in order to get the timely reservations. As an alternative, we can also apply upper bound on the processing time of scheduling.

Scheduling defines the crossing sequence of the vehicles through the intersection. Scheduling policy as one of the most important factors of intersection management has a great impact on vehicles throughput. Additionally, when it comes to selecting the right scheduling policy, we need to consider fairness and communication overhead in order to avoid long waiting times and secure efficiency. Here, we exploit different algorithms that are classified into three classes namely optimization-based, heuristic and FCFS for resource reservations and TP in order to secure traffic properties such as safety, infotainment, ecology and efficiency. The FCFS scheduling mechanism operates as the name suggests. The first vehicle that arrives at the intersection is the first one that is processed. Several publications benefited from FCFS algorithm in their works. Among the scheduling policies, FCFS algorithm satisfies fairness though its performance dramatically deteriorates with respect to the intersection density as it scales. Heuristic approaches do not necessarily aim to provide an optimal but to offer a fast solution. They seem to be capable of meeting a trade-off between the two essential elements namely throughput and fairness. Besides, they can even reach higher throughput with a limited delay compared to FCFS. Conversely, in optimization-based policies, the processing to seek the optimal scheduling is time-consuming though they can provide better throughput comparatively. Furthermore, it might degrade when the intersection density expands. On the other hand, analytical solutions can resolve this problem for heuristic and optimization-based approaches. The main purpose of the optimization-based method is to reduce the mean travel time of the entire intersection as opposed to FCFS policy. However, some approaches have followed some other auxiliary optimization goals such as passenger infotainment, fuel consumption, communication efficiency, acceleration/deceleration, or velocity. The sequence of vehicles approaching does not necessarily correspond to the their crossing order. Numerous papers have studied and applied the optimization-based methods as scheduling policy at non-signalized intersections to enhance the throughput [17], [26]–[30]. Efficient scheduling policies that have little waiting and processing times are still open to research.

C. INTERSECTION MODELING

In the literature, researchers have addressed the modeling of the intersections from two perspectives that can be helpful for collision detection as shown in Fig. 1 and Fig. 2.

1) SPATIO-TEMPORAL (ST) RESERVATION

Space-time occupancy is a type of cooperative resource reservation that deals with intersection resource scheduling regarding time slots and space tiles. Here, intersection is discretized into a grid of cells such that the route of each vehicle features a list of grid cells that it occupies at each timestamp along its path through the intersection. When the intersection is modeled with cells, vehicles should reserve cells along their path for a specific time period and pass the intersection according to their reservation. This method is collision free and can be deployed in a centralized or distributed fashion and merged with optimization techniques to increase throughput or other metrics. Basically, FCFS is the dominant algorithm in the centralized version. ST resource reservation is carried out via either vehicle agent or infrastructure. The aim of this approach is to prevent vehicles to be in a common cell simultaneously. Depending on the intensity of the cases, the granularity of grid partitioning changes. For example, the entire intersection area can be a collision area or smaller tiles can model the intersection in more details which leads to higher algorithm complexity. Occupancy grid solution has less computational overhead compared to the other due to its straightforward conflict areas checking until it is limited to a few collision cells.

2) TRAJECTORY PLANNING (TP)

In this approach, instead of using an occupancy grid for the intersection zone, vehicles follow pre-defined travel trajectories while crossing the intersection resulting in the determination of collision points. TP is divided into two groups, namely safe pattern and priority-based. Typically, TP can be combined with other safety parameters like acceleration/deceleration and speed to maximize optimization and efficiency.

3) INTERSECTION MANAGEMENT (IM) GOALS

IM goals are classified into different classes including safety, efficiency, environment and infotainment as illustrated

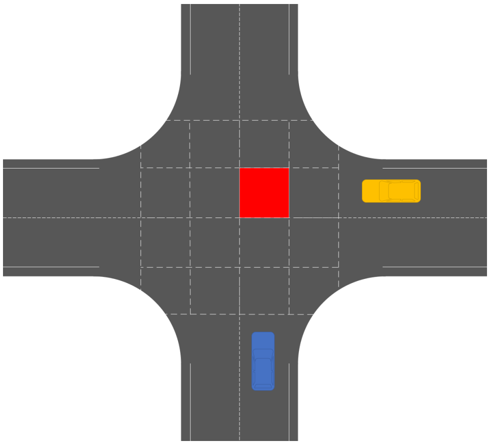

FIGURE 1. Grid representation of the intersection area.

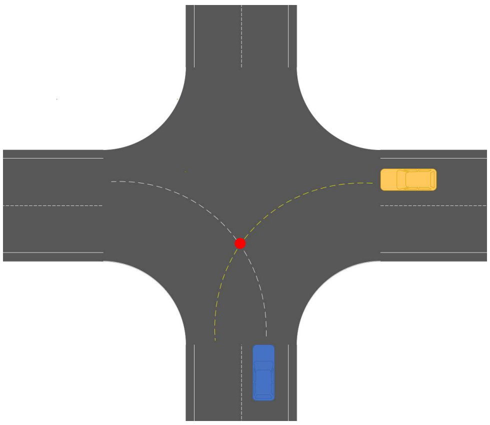

FIGURE 2. Trajectory representation of the intersection area.

in Fig. 3. Besides, some goals are categorized into several sub-classes. In particular, the environment is divided into fuel consumption and emission. Efficiency is decomposed of delay, throughput, congestion sub-goals while safety pertains to collision avoidance. Based on the application, researchers have examined one or several goals in their studies on IM.

III. SIGNALIZED INTERSECTIONS

Invention of traffic lights has definitively revolutionized intersection safety and traffic flow. During the last decade, quite a number of noticeable works have been conducted to improve traffic lights functionality. They span a wide range of approaches such as mathematical models [52], max and back pressure [53]–[55], and agent-based learning methods [31]–[33]. Among the proposed solutions, vehicular wireless communication has exhibited superiority over the traditional methods due to their wider detection area and more detailed conveyed information. Moreover, in V2X communications, vehicles can collaborate for intersection coordination.

Signal phase and timing (SPaT) control of the traffic lights is recognized as the simplest optimization-based method and can produce reasonable throughput [34], [36]–[38], [56]. In these approaches, the infrastructure designates an optimal trajectory to the vehicles so that they catch the green light. Liu *et al.* [34] proposed a two speed optimization algorithm to minimize delay and travel time of the CVs. Fayazi *et al.* [36], [37] investigated the optimal scheduling arrivals of the CVs with Mixed Integer Linear Programming (MILP) and using an intersection controller. This helped to prevent collisions and minimizes travel time, fuel consumption and average number of stops at the intersection. In [36], they proposed a variant of the MILP controller introduced in [37] for mixed traffic flow management. Concerning delay, the proposed method had better performance than normal signalized intersections. Ashtiani *et al.* [38] followed the similar optimization-based approach as [36], [37] for a grid of intersections that resulted in positive influence on fuel consumption and mobility of the traffic. Furthermore, Chang and Park [41] availed an optimization-based system to control the traffic signals at the intersection. Here, in each lane, vehicles formed a group using V2V communication and estimated the traffic density (queue length) by a group leader that resulted in lower waiting time. Afterwards, an algorithm determined the signal cycle length and green light via V2I communication and the received information from the group leader. Xie and Wang [42] developed a smart decision assist system on-board of vehicles at a signalized intersections to guarantee safety and reduce unnecessary stops. The proposed system was supported by V2I communication and made use of a probabilistic sequential process for proper stop/go decisions that utilized the integrated information from the intersection and vehicles.

Furthermore, Wang *et al.* [43] focused on infotainment, safety and efficiency and developed a V2I driving assistance system for the signalized intersection. The proposed system could provide advisory passing speed, warnings in terms of traffic light violation and rear-end collision, and automatic braking. Likewise, Meng and Cassandras [39] developed a system based on V2I that adapted the speed of the AVs according to the information received from the traffic light such that they could cross the signalized intersection non-stop. Their design also led to reduction in fuel consumption, travel time, and delay. With a similar approach, Zhao *et al.* [44] developed a cooperative optimal speed advisory system to spare fuel consumption at the signalized intersections. Wang *et al.* [48] studied a different method and devised a cluster-based cooperative application for CAVs. In the proposed system, vehicles formed clusters in order to pass through the signalized intersection with less pollution, fuel consumption and better throughput. Moreover, Saust *et al.* [49] deployed a cooperative V2I system to minimize delay, emissions and fuel consumption by regulating traffic signal control as well as driving patterns of the vehicles. This approach optimized the longitudinal and lateral movement strategies of the AVs using a max-min ant system at the signalized intersection.

Shen *et al.* [35] made use of centralized MPC-based mechanism and provided a platform for CAVs to approach the

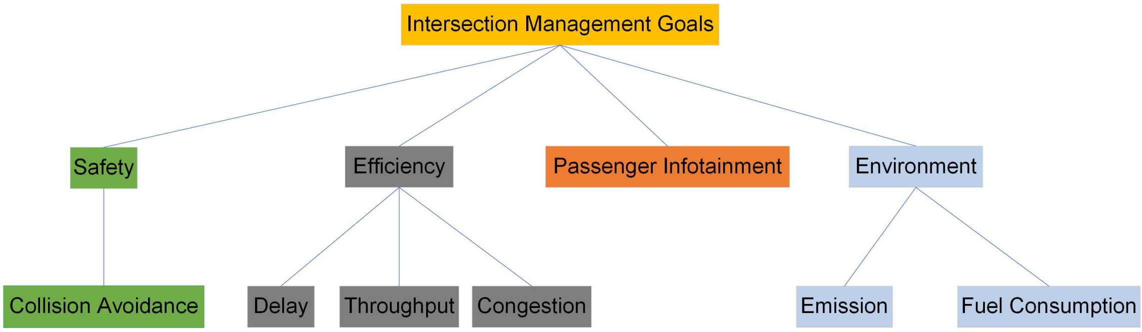

FIGURE 3. Intersection management goals.

TABLE 1. Summary of literature reviews on signalized intersections.

Literature	Architecture Type	Scheduling Policy	Intersection Modeling	Intersection Goal
[31]–[33]	V2V	Optimization	TP	Efficiency
[34], [35]	V2I	Optimization	TP	Efficiency
[36]–[39], [40]	V2I	Optimization	TP	Safety + Efficiency + Environment
[41]	V2I + V2V	Optimization	TP	Efficiency
[42]	V2I	Optimization	TP	Safety + Efficiency
[43]	V2I	Optimization	TP	Safety + Efficiency + Infotainment
[44],	V2V	Optimization	TP	Environment
[45]–[47]	V2I	Optimization	TP	Environment
[48]	V2V	Optimization	TP	Efficiency + Environment
[49], [50], [51]	V2I	Optimization	TP	Efficiency + Environment

signalized intersection with a smooth speed. Gutesa and Besenski [50] developed a centralized IM mechanism for CAVs based on trajectory planning at the signalized intersection. A control algorithm allocated the optimal path considering various inputs such as vehicle's position, speed, signalization status and current traffic at the intersection. This approach resulted in lower delay, travel time and fuel consumption of the vehicles. Zhu *et al.* [40] studied a safe eco-driving IM model for hybrid electric CAVs using a safe novel off-policy-based reinforcement learning (RL) algorithm at the signalized intersection. The proposed model was based on V2I communication and optimized the vehicles trajectories such that fuel consumption and travel time were reduced significantly. The model improved the mean speed in comparison to the traditional vehicles. In addition, some other researchers like Mandava *et al.* [45] along with Kamalanathsharma and Rakha [46] employed V2I technology and focused on dynamic programming and optimization of individual vehicle velocity trajectory to pass through the intersection by saving fuel up to 12-14 and 30 percent respectively. In another approach, Asadi and Vahidi [51] used a centralized architecture and model predictive controller. In this effort, they could reduce fuel consumption and CO2 emissions by 47 and 56 percent while considering travel time efficiency. Du and Pisu [47] deployed an energy efficient IM mechanism for CVs driving on two-lane road and crossing multiple intersections. The MPC, speed control and lane changing discretion were adopted to minimize the fuel consumption of the vehicles. A summary of literature reviews on signalized intersections is presented in Table 1.

IV. SEMI-AUTONOMOUS INTERSECTIONS (Hybrid)

Intersections are still shared between autonomous connected and human-driven vehicles. Hence, there should be some control mechanisms such as traffic lights or on-board sensors for human-driven vehicles to control them. Recently, hybrid intersections are absorbing more attention where they incorporate human-driven and autonomous vehicles traffic. This section deals with the articles that have addressed such intersections and the proposed methodologies when two types of vehicles share the same intersection.

Pourmehrab *et al.* [56] studied joint SPaT and TP optimization for human-driven vehicles and AVs respectively. The system showed better travel time compared to the conventional methods. Qian *et al.* [57] presented a priority-based TP and integrated legacy vehicles that were controlled by traffic lights at a hybrid intersection. If a non-cooperative vehicle and an autonomous vehicle approached the intersection from different roads, the manual one received the lower priority and could pass the intersection once the connected vehicle has passed the conflict area. In case they were on the same road, a virtual platoon was constructed where an autonomous vehicle was followed by the legacy one to cross the intersection. Verma and Vecchio [59] employed a semi-autonomous control system, a hybrid model in which some vehicles were equipped with a cooperative active safety system and others were human-based vehicles. Moreover, Dresner and Stone [15] treated vehicles and intersections as autonomous agents for autonomous intersection management (AIM). A query-based reservation approach plus an FCFS policy were used to coordinate the autonomous CVs through the intersection (pass or stop). They also integrated human-driven vehicles in the system that followed the traffic lights rules. In terms of safety and delay, the proposed system outperformed traffic lights. Inspired by the AIM system of this approach, Hausknecht *et al.* [60] managed a grid of connected intersections. They extended their work by integrating various navigation policies to dynamically change the planned vehicle route (reversing lanes direction) and decrease its delay. In an analogous research, Sharon and Stone [62] modified the system with a distinction to [15]. In contrast to FCFS reservation model proposed in [15], given that an autonomous connected vehicle with a red light was present, the intersection manager did not revoke its reservation unless there was no other vehicle with a green light at the intersection. This method improved the performance of the intersection for hybrid traffic. Another extension of [15] was presented in [63], where different types of semi-autonomous vehicles with features like cruise control received reservations similar to the CAVs. Shen *et al.* [64] deployed a FCFS-based centralized hybrid intersection system where on-board units (OBUs) were proposed for non-autonomous vehicles to communicate with the controller using different signals like pass and stop. Further, Sharon *et al.* [65] designed a centralized hybrid intersection management protocol that involved autonomous and manually operated vehicles. They used FCFS algorithm for CVs to traverse the intersection.

In another research work, Li and Zhou [61] designed a V2I-based optimization platform that improved intersection capacity, mobility and delay via dynamic signal timing policies. They used MILP, a search algorithm like sequential branch-and-bound (BB) to find the optimal phases at hybrid intersections. Similarly, Lin *et al.* [29] developed a centralized intersection coordination method where the road segment was split into three virtual sections of core, buffer and free areas. CVs speed and time adjustments were assigned based on the buffer allocation mechanism in the buffer area. Then, they were allowed to pass the core area (intersection area) with the constant speed. Human-driven vehicles trespassed in the free area. This method was able to promote delay, mobility and fuel consumption compared to the traffic light system. To deal with the mixed traffic, Onieva *et al.* [67], [68] proposed an efficient multi-objective algorithm, a fuzzy rule-based system for hybrid intersections involving manual and CAVs where the speed of the CAVs was controlled in order to avoid collisions with manually driven vehicles. Additionally, Fayazi and Vahidi [70] devised a vehicle-in-the-loop (VIL) simulation platform using bi-directional cellular communication wherein the infrastructure received the vehicles' information and scheduled the optimal arrival time and speed based on the MILP algorithm.

Likewise, Liu *et al.* [66] deployed a safe IM framework for hybrid traffic. They used V2I communication and model predictive control (MPC) for permission assignments of AVs whereas for human-driven vehicle, traffic lights operated with simple coordination protocols. Sayin *et al.* [73] exploited an information-centric V2I-based IM system which integrated useful information that can be provided exclusively by the driver and not the sensors. In this heuristic method, in the vicinity of the intersection, drivers reported their utility functions that they intend to maximize using an payment-based incentive mechanism called Vickrey-Clarke-Groove. Then, the roadside unit prioritized the intersection usage accordingly and maximized the sum of all utility functions (social welfare) which was used to enhance the transportation quality. Ahn *et al.* [69] used a centralized intersection controller namely supervisor that overrides the autonomous vehicles in case of crash detection. The supervisor coordinated the traffic with the help of an interior point and active set technique at the semi-autonomous intersection including one manual and two autonomous vehicles. Additionally, Sinha *et al.* [74] introduced a new virtual traffic lights (VTLs) extension model to enhance its functionality. It embodied VTL-enabled, ordinary vehicles and also an infrastructure to ensure safe, smoother traffic flow. Cheng *et al.* [72] employed an approach based on heuristic RL to plan safe optimal trajectories of the CAVs and human-driven vehicles at the signalized intersection. Wang *et al.* [58] proposed a V2I-based traffic control system for CVs and human-driven vehicles at the hybrid intersection. This scheme could detour the CVs traffic with respect to congestion in the roads and outperformed traditional methods in terms of delay and travel time. Fu *et al.* [71] developed a centralized multi-intersection coordination platform based on C-V2X communications and resource reservation for CAVs. The goal was to enhance fault tolerance and traffic efficiency over conventional systems. Besides, authors could also simulated remote driving with lower delay. Table 2 summarizes the hybrid intersections approaches.

V. AUTONOMOUS INTERSECTIONS

Non-signalized intersections reside no traffic lights or any other controller. Eye contact or hand signaling are the simplest way of safe passage through such intersections. Introduction of V2X communications paved the road for easier and more accurate vehicles interactions. Particularly in non light of sight or obstructed situations, vehicles avoid collisions by exchanging traffic information. In this regard, agent based methods are extensively used especially for the V2V architecture. An agent is a computational autonomous unit that fulfills certain objectives in a certain ambiance [75]. An agent can be a vehicle, a traffic light or an infrastructure that gathers information to coordinate the vehicles passing. In this section, AIM methods are discussed in details in different categories with respect to the goals they serve.

A. SAFETY

Traffic safety is known as the most remarkable application of wireless vehicular communication. In this context, we must protect not only cars but also VRUs such as motorcycles or cyclists. In accidents, pedestrians and cyclists as VRUs

TABLE 2. Summary of literature reviews on semi-autonomous (hybrid) intersections.

Literature	Architecture Type	Scheduling Policy	Intersection Modeling	Intersection Goal
[56], [57], [58]	V2I	Optimization	TP	Efficiency
[59]	V2V	Optimization	TP	Efficiency
[15]	V2I	Optimization + FCFS	ST	Safety + Efficiency
[60], [61]	V2I	Optimization	TP	Safety + Efficiency
[62], [63]	V2I	Optimization	ST	Safety + Efficiency
[64], [65]	V2I	FCFS	TP	Safety + Efficiency
[29]	V2I	Optimization	TP	Efficiency + Environment
[66]–[69]	V2I	Optimization	TP	Safety
[70], [71]	C-V2I	Optimization	TP	Efficiency
[72]	V2I	Heuristic	TP	Safety
[73]	V2I	Heuristic + Optimization	TP	Efficiency
[74]	V2I+V2V	Optimization	TP	Safety + Efficiency

are more exposed to fatal and serious injuries. As an example, 2.6 million pedestrians and cyclists were involved in 5.9 million crashes in the European Union in 2013 [76]. The accident rate of this group is growing with 75 people casualties and 750 injuries every day on European roads [77]. Nowadays, safety related solutions to diminish the risk of accidents for VRUs are being neglected [78]. Publications regarding VRUs with emphasise on wheel-based VRUs are summarized in section VI. To provide traffic safety, there is a demand for the vehicles to communicate traffic information. Road traffic safety applications lie in two categories; V2I and V2V applications. V2I safety spans a wide range of applications comprising red light violation and curve speed warning, stop sign gap assist, spot weather impact warning, reduced speed/work zone warning and pedestrian in signalized crosswalk warning [79]. V2V safety related applications encompass intersection movement assist (IMA), left turn assist (LTA), blind spot/lane change warning (BSW/LCW), do not pass warning (DNPW) and vehicle turning right in front of bus warning [79]. Forward collision warning (FCW), emergency electronic brake lights (EEBL), traffic signal violation [80], [81] or even VTLs [82], [83] are other examples of this kind of applications. Among them and especially in an urban environment, intersection collision/assistance is of great significance [84], [85]. It is due to the fact that the large extent of accidents around 40 percent occurs near or at the intersections [86].

Researchers have proposed several approaches to ensure collision avoidance at the intersection. Today, VTLs can replace physical ones as vehicular communications enable vehicles to exchange traffic information. Ferreira *et al.* [83] designed a system where a VTL protocol coordinated the traffic flow. In the proposed system, VTL leader was selected using V2V communications to undertake traffic signaling and controlling the intersection. Once the light was green for the VTL leader, it preferably handed over the responsibility to the new leader closest to the intersection. Besides, some researchers established their safety methodologies based on the prediction of risk, collision probability calculation or movement-based techniques. Tu and Huang [87] introduced ‘‘Forwards’’, a distributed collision warning system for map-free intersections. It took advantage of a triple kalman filter that employed GPS and sensors data to estimate the vehicle mobility state information. Collision avoidance was done based on the received information of each vehicle via DSRC. Gabarron *et al.* [88] planned vehicles trajectories in a way to become collision free while traveling at high speeds. To this end, they utilized multi-objective optimization based on lateral motion of the vehicles. Chen *et al.* [89] examined the effect of different intersection collision warning systems (ICWSs) (audio and visual) on intersection accidents. Their system was based on DSRC and could reduce the drivers' reaction times as well as crashes by 40 to 50 percent. Additionally, Lu *et al.* [90] utilized a V2V protocol that defined the vehicles passing sequence based on the traffic rules at the non-signalized intersection. Besides, an algorithm was used to determine a safe deceleration value for yielding vehicles to avoid collisions. Belkhouche [91] employed a cooperative optimal approach for conflict resolution of autonomous vehicles at an non-signalized intersection. Collisions were detected using speed ratios, then a fast algorithm was used to compute the optimal actions according to cost function which is formulated in terms of current speed deviations. Riegger *et al.* [92] developed a V2I-based MPC method for autonomous vehicles at the intersection zone. They availed convex optimization to formulate the problem to provide optimal trajectories and avoid collisions.

Furthermore, Altchø *et al.* [93] employed a supervisor at the intersection that availed mixed-integer quadratic programming (MIQP) to manage and manipulate the control inputs of the semi-autonomous vehicles and safely navigate them through the intersection. In another article, Jiang *et al.* [94] presented a distributed optimization algorithm which was a sort of augmented Lagrangian based alternating direction inexact Newton method (ALADIN) that coordinated the vehicles passing with the presumption that the order of precedence was provided. Here, every vehicle executed locally the control problem and shared the departure and arrival information with its neighbors to prevent collisions. Furthermore, Rahmati and Talebpour [4] investigated a decision-making platform based on the game theory for CAVs focusing on the left-turn maneuvers under assumption of being unprotected. This study tried to characterize vehicles interactions and behaviors at the intersection and to estimate the real choice of the driver at the respective situation. Murgovski *et al.* [95] optimally modeled the safe passing order of the AVs with a centralized control using a Convex function. Malikopoulos and Zhao [96] exploited an analytical rear-end collision avoidance system with application of Euler-Lagrange equation for CAVs. Shi *et al.* [97] benefited from the closed-loop optimal control mechanism for AVs to avoid rear-end collisions in each lane in addition to the conflicts inside the intersection zone. Moreover, Yu and Petnga [98] introduced a multi-agent V2V-based scheme for AVs to predict and avoid different kinds of collisions using machine learning techniques and two spatio-temporal algorithms. Nekoui *et al.* [99] developed a warning system based on V2I to avoid collisions at the intersections. Red light violation for an approaching vehicle was calculated depending on the position, speed and time to the intersection. In case of a high crash probability, the driver and other vehicles were warned. Fu *et al.* [100] analyzed an algorithm that considered the vehicles' state data to detect hazardous situations and warn the drivers using V2V and dynamic Bayesian networks (DBNs). In addition, Joerer *et al.* [101] assessed the drivers's safety at an intersection in a suburban area by measuring two types of V2V beaconing warning messages namely simple and one-hop relaying. They showed that one-hop relayed beaconing can significantly improve the driver's safety at the intersection. In [85], they addressed vehicular communication aspects and studied two congestion control methods including Transmit Rate Control (TRC) and Dynamic Beaconing (DynB) in urban and rural intersections. Rate adaption of these algorithms were in accordance to different situations and aimed to meet the safety requirements of vehicular use cases. In their other work [102], they analyzed the intersection collision avoidance system for two approaching vehicles and derived the likelihood of collisions between the two with respect to their future trajectories.

There are some papers that reviewed the intersection collision avoidance from a risk estimation perspective. In this regard, Baek *et al.* [103] proposed an approach composed of vehicular communication and multiple in-vehicle sensors to estimate the vehicles trajectories and warn the driver to avoid collision using Kalman filter. Raut and Bajaj [104] employed a collision avoidance framework based on V2I and V2V to estimate the crash probability at the intersection. In [105] an efficient algorithm based on V2I and V2V was presented to assess the risk, warn the driver and mitigate collisions at the intersection using Dynamic Bayesian Networks (DBNs) and state information of the vehicle. Xia *et al.* [106] proposed V2V-based efficient warning algorithms for two collision scenarios, namely rear-end and intersection with respect to the information captured from the vehicle state. Additionally, authors in [107] focused on calculation of the collision probability of two vehicles' trajectories at the intersection with the help of their speed, position, motion capture device, intention of the driver and V2V communication. Hafner *et al.* [108] developed a V2V application that automatically controlled the longitudinal movements of two vehicles at the intersections. Collision avoidance was based on the calculation of a capture set which is a collection of all situations in which the system is unable to prevent a collision [109]. Their system could prevent collisions under desirable communication conditions. Lefèvre *et al.* [110] proposed the intention and expectation comparison for risk assessment at an intersection. Moreover, Liebner *et al.* [111] evaluated collision risks using drivers' intent inference at intersections while Oh and Kim [112] used vehicle's trajectory data for risk estimation of the rear-end collisions. Weidl *et al.* [113] utilized Bayesian networks to predict collision risks at the intersections from data comprising vehicle self-awareness and localization, and infrastructure sensors.

In another approach, Goldhammer *et al.* [114] installed diverse types of sensor networks including signal phase tapping, cameras, laser scanners, and also a V2I unit at an intersection. Collision avoidance was achieved via cooperation and calibrated alignment of these sensors. In [115], researchers employed an efficient frontal crash detection and avoidance system. Here, the authors designed a probabilistic algorithm and a decision-making protocol to predict trajectories, assess the threats and mitigate collisions based on a Kalman filter by using Euclidean space. In another article [116], a V2V-based collision warning framework was proposed where future vehicles trajectories were predicted using a Kalman filter to estimate the collision risk. Wang *et al.* [117] implemented a spatio-temporal technique to warn three types of drivers; negative, normal and positive of potential accidents earlier, on-time or with delay respectively with respect to the safe braking distance. A V2I-based collision detection algorithm at T-shaped junction was proposed in [118] that benefited from Location Based Services (LBS) that contains IMU and GPS technologies to collect vehicle state information at T-shaped intersections. In another research [119], a V2V-based collision warning approach was studied where vehicles left-turn trajectories were predicted at T-shaped junctions based on LBS and Kalman filtering. Kwon *et al.* [120] implemented some collision prediction algorithms at the intersection where road sensors sent position and velocity of the approaching vehicles to the infrastructure via a sensor network. Then, the infrastructure broadcast the state information to the other vehicles so that they could locally calculate the collision probability accordingly. Salim *et al.* [121] proposed a centralized approach and a safe communication protocol where an infrastructure agent received status messages from the vehicle agents, learns, detects and warns the drivers of the collisions.

Furthermore, a novel collision predication algorithm was investigated in [141] using V2V and based on comparison of dynamic thresholds for the minimal distance between vehicles to warn the drivers with normal or emergency warnings. Malinverno *et al.* [132] introduced an effective cellular vehicle-to-infrastructure (C-V2I) scheme for collision avoidance (CA)/collision warning (CW) for human-operated and

TABLE 3. Summary of literature reviews on safe autonomous intersections.

Literature	Architecture Type	Scheduling Policy	Intersection Modeling
[4], [83], [87]–[91], [94], [96], [110]–[112], [116], [122]–[124], [114], [119] [85], [97], [98], [100]–[102], [106]–[108], [115], [121], [125]–[127]	V2V	Optimization	TP
[117]	V2V	Optimization	ST
[92], [93], [95], [99], [121], [128]–[130], [114], [118], [120], [131]	V2I	Optimization	TP
[104], [105], [113]	V2I + V2V	Optimization	TP
[132]	C-V2I	Optimization	TP
[133], [134]–[136]	V2I + V2T	Optimization	TP
[137]	T2T	RCAS	TP
[138]	T2T + V2T	RCAS + PTC	TP
[139]	T2I + V2I	Optimization	TP
[140]	T2I + V2I	PTC + Optimization	TP

AVs at the intersection. Colombo and Wymeersch [128] deployed a V2I-based CA system under contained communication conditions using a wireless network where the infrastructure could override the vehicles' input if necessary. Another CW solution based on V2V was introduced in [126] that relied on the computation of time and distance to the intersection. Basma *et al.* [129] exploited a V2I-based CA system where four wireless sensor networks (WSNs) installed on each road monitored the passing vehicles, transmit the information to the base station wirelessly. Then, if a conflict was imminent, the base station would communicate with the warning system fixed at each intersection side via wireless or wired connection to warn the drivers. Similarly, authors in [130] presented an empirical novel centralized CA system called iICAS that inherited the same concepts with one distinction. In addition to issuing a public warning, the system could directly warn the vehicle at risk. Miller and Huang [122] deployed a V2V-based CW test-bed with customizable parameters such as communication range and latency, coefficient of friction, vehicle speed, driver reaction time and position accuracy. In addition, Guzman *et al.* [125] addressed a V2V-based intersection safety application via a test field where an emergency vehicle was prioritized to cross the intersection. Suzuki *et al.* [124] investigated the distributed CA/CW using Very High Frequency (VHF) in Non-line of sight (NLOS) situations. Mobility information were periodically broadcast by vehicles and if a potential crash was detected, a warning message was sent out to the vehicles at risk. In [127], authors mainly addressed the accuracy enhancement through development of a cooperative vector-based CW solution considering curve and intersection scenarios.

Not many papers can be found that deal with trains or trams collisions. Choi *et al.* [134]–[136] analyzed the direct and indirect vehicle-to-train (V2T) communication for collision avoidance at a railroad crossing between a train and a vehicle in rural and suburban areas from different perspectives. Avoiding train to train collision using a rail collision avoidance system (RCAS) was published in [137]. They investigated the train to train (T2T) communication and RCAS for trams where it warned the driver if there was a potential collision with another tram. Collision was calculated based on the predicted trajectories of both trams and velocity and position were the parameters to find the crash prediction. Authors in [140] proposed a positive train control (PTC)-VANET integrated system to reduce conflicts at rail road intersection. Barkouk et el. [138] performed an overview on RCAS and also PTC systems for V2T and V2V applications. Mäder *et al.* [139] exploited a train to infrastructure (T2I)/V2I based smart and safe railway crossing. In this system, the approaching train/tram and the vehicles periodically sent mobility information to the cloud infrastructure. Then, the traffic controller computed collisions and estimated the train arrival time and sent advisory speeds or stop commands to the vehicles depending on the train distance to the intersection and the vehicles' positions. In [133], researchers employed an audio visual CW framework for rail-highway crossing by using V2T and V2I communication. In case a crash with the train was predicted, speed deceleration is triggered for the vehicles to decrease the collision probability. Ghoul and Sayed [131] focused on a V2I-based trajectory planning system and implemented the optimal speeds for CVs using deep RL and a rule-based strategy to bring safe passage of the vehicles at the intersections. Table 3 shows the literature addressed the safe autonomous intersections.

B. EFFICIENCY

Many methods have been introduced by researchers for improvement of the intersection efficiency from different aspects such as throughput, delay or congestion remedy as follows.

Malikopoulos and Zhao [142] employed a decentralized optimal lane and order control framework for each CAV to cross the intersections. Qiao *et al.* [151] developed a virtual roundabout for the management of AVs at the intersection. This system outperformed FCFS and traffic lights in properties like traffic congestion and safety distance. Vasirani and Ossowski [160] studied a computational market strategy in which driver agents trade the capacity use of the intersection with IM agents. This showed a more efficient behavior compared to the popular traffic lights. In their following research [161], they analyzed a double V2I-based scenario with the reservation control model proposed by [15]. Firstly, they performed reservations on an auction-based policy in a single intersection. Secondly, they suggested a novel competitive market-based distributed approach for traffic assignment for multiple intersections. In the latter, they made use of bidding rules including travel time and price for driver's path selection such that drivers with higher travel time could send higher price bids thereby reducing their delay. Finally, a combination of both strategies were proposed that could drastically decrease the travel time. Further, ShangGuan *et al.* [162] proposed a novel V2I-based optimal control scheme based on time delay petri nets (TdPN). The proposed method resulted in better performance compared to the traditional signal phase systems for non-signalized intersections. Yan *et al.* [163] exploited a V2I-based approach to attain an optimal passage sequence and minimize the crossing times for the autonomous vehicles at isolated intersections based on dynamic programming. In another approach [172], the authors designed a genetic algorithm to find an optimal crossing order for several adjacent intersections in collaboration with dynamic programming and heuristic small extra time (SET). They showed the inferiority of conventional methods like fixed-cycle time and adaptive control in comparison to the branch and bound, genetic, dynamic programming algorithms, and heuristic SET.

Moreover, Wu *et al.* [171] developed different traffic control mechanisms namely; V2V and V2I to navigate the vehicles as fast as possible through the non-signalized intersection. The authors took advantage of the Timed Petri Net Model and dynamic programming for the simulation and concluded that a global approach is the most efficient solution. To achieve the best passing order, Wu *et al.* [164] introduced an innovative scheduling model based on dynamic programming. In their system, intersection and vehicles were considered as machine and jobs respectively and could efficiently handle normal congested situations. The authors extended their work in [152] where they introduced an Ant Colony System (ACS) to control the vehicles individually on the basis of localization and vehicular communication technologies. Their system outperformed the traditional adaptive controller and traffic lights. Besides, their scheme could find the minimum travel time of the vehicles and evacuate their sequence of arrivals for numerous lanes and vehicles in an optimized manner. Further, Zhang *et al.* [165] utilized a V2I priority-based reservation scheduling mechanism named PriorFIFO for traversing of autonomous CVs. In a later research [166], the authors inherited the concepts of the previous work and adopted a cooperative V2I service-oriented ST reservation scheme for vehicles passing called csPriorFIFO. Here, all traffic participants, objects and the intersection environment were modeled to ensure the QoS of the highest priority vehicles. Wei *et al.* [153] employed a reservation-oriented control scheme named Batch-Light. A conflict matrix decision greedy algorithm was proposed to provide more reservations with specific fairness. Besides, the k-Shift optimization algorithm was used to increase the possibility of more unlucky vehicles traversal through the intersection via deceleration or acceleration. The proposed system performed more efficiently than traffic lights and FCFS systems. Au and Stone [146] proposed a motion planning heuristic approach to minimize the stopping time of the vehicles at the intersection and to increase throughput. The earliest arrival time was scheduled by the infrastructure based on the highest vehicle's speed. This method outperformed the optimal heuristic methodology in [147] in terms of throughput, mean delay, and efficiency.

Furthermore, Au *et al.* [167] leveraged the liveness and deadlock free features into AIM by introducing a batch-based reservation policy. Perronnet *et al.* [154] exploited a hierarchical deadlock free architecture for a grid of intersections via three routing policies including congestion avoidance, shortest path and reservation which depend on the context of the traffic. The system diminished delay and computational overhead. In another approach, Carlin *et al.* [155] utilized an auction-based policy where the system collects all bids from total roads to coordinate the vehicles passing sequence at the intersection. The system maintained fairness by keeping a logical travel time for low-budgets vehicles. Wuthishuwong and Traechtler [156] deployed a graph-based traffic coordination method in a network of autonomous intersections to balance the traffic density and elevate the throughput using a consensus discrete time algorithm and Greenshield's model. Additionally, Guler *et al.* [157] developed a holistic approach to find the optimal sequence times of entry and exit of the vehicles using an iterative algorithm that reduces delay and number of stops. An extension of the work of Guler *et al.* [157] was proposed by Yang *et al.* [148]. The authors utilized an algorithm for trajectory assignment to three classes of vehicles including conventional, connected, and automated vehicles based on the collected information from all vehicles in the range of the infrastructure. They used a branch and bound algorithm and a Kalman filter to discover the optimal path of the vehicles after the determination of the coming/leaving times. A centralized routing mechanism using an iterative algorithm was employed in [168] to reduce delay, travel time and increase the throughput for a grid of intersections. Philippe *et al.* [158] introduced a "profitability collectives" algorithm based on game and optimization theories using multi-agents to distributively coordinate the CVs at the intersection with a high level of performance. Ameddah *et al.* [143] presented a V2V-based mechanism to manage the vehicles crossing based on their priorities in addition to other parameters such as density, distance of the vehicle to the intersection and direction. The proposed system enhanced travel time and throughput.

In addition, Li and Liu [173] created a heuristic IM scheme for AVs under a V2I environment where a dynamic state list and a lane collision matrix were employed to determine the real-time lane occupancy and passing order of the vehicles. The proposed system outperformed adaptive and static traffic light methodologies with less computational overhead and could enormously increase fairness and diminish average delay. Rapelli *et al.* [174] developed a distributed heuristic-based virtual traffic light mechanism to coordinate

TABLE 4. Summary of literature reviews on efficient autonomous intersections.

Literature	Architecture Type	Scheduling Policy	Intersection Modeling
[142]–[145]	V2V	Optimization	TP
[146], [147]	V2I	Heuristic	TP
[148], [149], [150]	V2I	Optimization	TP
[151]–[159]	V2V	Optimization	ST
[160]–[170]	V2I	Optimization	ST
[171]	V2I + V2V	Optimization	ST
[172]	V2V	Optimization + Heuristic	ST
[173]	V2I	Heuristic	ST
[174]	V2V	Heuristic	TP

the vehicles at the intersection. This solution could minimize the evacuation time, emissions and smooth the traffic flow. In [149], a centralized intelligent traffic light solution was devised over a content-based architecture called named data networking (NDN) to coordinate the vehicles and reduce congestion and waiting time at the intersection. Further, Chou *et al.* [159] proposed a strategy such that the VTL cycle was adapted according to the vehicle type and traffic density using V2V communication. The proposed approach increased the speed and throughput of the intersection. Authors in [144] suggested a V2V-based scheme where the traffic light listens to the information exchanged between vehicles and adapts its timing based on the traffic congestion near the intersection. In a different approach, Zhu *et al.* [169] employed a centralized reservation-based IM system and designed a novel strategy to assign passing permission to the vehicles with minimal delay called Look-ahead Intersection Control Policy (LICP). The results demonstrated its superiority over FCFS. In addition, a novel V2V-based IM algorithm was presented in [145] where the problem was modeled as a new version of mutual exclusion and was more efficient than adaptive traffic lights. Li *et al.* [170] made use of a sustainable time-space reservation-based IM solution in terms of emissions, fuel consumption and number of stops to coordinate the passing order of AVs at the intersection using V2I communication. Wu *et al.* [150] employed a congestion free traffic signal control scheme for CAVs where traffic was dynamically controlled using multi-agent RL in a grid of six intersections. In the proposed system, communication was handled between traffic lights and vehicles. Table 4 presents the articles for the efficient autonomous intersections.

C. SAFETY AND EFFICIENCY

To achieve a trade-off between safety and efficiency boosts the usability of existing IM methods. This section introduces the literature that addressed these goals.

Vehicle crossing scheduling can take advantage of robot motion planning methods such as path-velocity decomposition for multi-robots environment. Firstly, this method identifies and fixes the Communication Anomalies and Channel Optimization path of each robot. Afterwards, velocity adaptation is applied via input controls so that they traverse the intersection safely. Gregoire *et al.* [27] advocated a mathematical model based on the previously mentioned method. They adopted the vehicles' priority to build a graph containing the passing order of the robots and later they opted for a heuristic algorithm to plan relatively optimal and deadlock-free paths based on the priority graph leading to lower trip time and safe traversal of the vehicles. Further, in [175] they addressed priority based robot motion planning at a controlled intersection. In the proposed system, a control law included the proprieties and managed the robots within the intersection to avoid collisions. Ghaffarian *et al.* [176] introduced a V2I-based traffic controller that utilized integer linear program (ILP) to calculate optimal and safe passing orders of the vehicles trajectories while ensuring maximal throughput. Researchers in [177]–[179] studied sequence-based protocols for safe TP in cooperative real intersection. Vehicles negotiated the right of way individually with the controller with regard to a passing sequence to increase the throughput. In an different approach, Lee and Park [17] utilized a cooperative V2I control system wherein an optimization algorithm (nonlinear constrained) could alter each autonomous vehicle's maneuver to avoid collisions by removing conflicting trajectory overlaps at the intersection. Azimi *et al.* [180] exploited a family of V2V-based IM protocols. They also provided an efficient collision detection algorithm to prevent accidents at the intersections. The system was based on V2V communication and time-space resource reservation. In another research [181], they developed two safe deadlock-free novel IM protocols based on distributed ST method. They added parallelism and accurate vehicle models to maximize the vehicles progression and concurrent crossing inside the intersection, decrease delay and improve throughput. In a later work [182], they adopted the similar approach by applying their protocols in the previous work in [181] for autonomous roundabouts by introducing a new collision detection algorithm. Authors in [183] studied an additional protocol that was analogous to one of the presented protocols in their former works [181], [182] in terms of parallel progression. But the advantage was that the lower-priority vehicle was allowed to first pass the intersection if its arrival time to the common collision area was shorter than the vehicle with the higher priority.

Furthermore, Fok *et al.* [184] developed a safe cyber physical test-bed that consisted of several robotic mini vehicles that all were equipped with sensors and could communicate using 802.11g Wi-Fi technology. The aim was to evaluate and compare six ST-based V2V and V2I policies with the existing intersection management rules such as stop signs and traditional traffic signals. The simulation results demonstrated less travel time and delay compared to the state of the art techniques. Quinlan *et al.* [185] implemented a mixed intersection testbed where a bunch of virtual vehicles in the simulation interacted with a real autonomous vehicle at an real intersection based on a centralized ST reservation approach using FCFS. Simulation results showed that vehicles traversed the autonomous intersection safely with better throughput compared to the conventional methods. Ahmane *et al.* [186] modeled ST resource reservation via Petri Nets based control policies for intersection management using V2I. Approaching vehicles requested ST reservations and right of way order was granted based on the timed Petri Net for intersection crossing in a safe and efficient manner. Additionally, in [187] a cooperative optimization algorithm was used for an optimal safe crossing order of the vehicles with minimal travel time. Kloock *et al.* [188] analyzed the safe and efficient intersection management using distributed model predictive control (DMPC) scheme. Vehicles followed predefined routes and priorities were applied to them based on their reaction times to stop before the intersection in case they could not pass the intersection with the adjusted speed. In [189], a ST-based TP system was developed to achieve safety and lower delay and intersection efficiency. They utilized priority-based and discrete forward-rolling optimal control (DFROC) algorithms to navigate the CVs through the intersection. The authors of [190] also studied the linear programming approach for CAVs and could solve the optimization with respect to the travel time by considering the traffic flows of each lane.

Besides, Timmerman and Boon [191] investigated different platooning algorithms for vehicles that could minimize mean delay, provide fairness and safety. Guney and Raptis [192] harvested the optimal heuristic-based coordination solution for AVs using an particle swarm optimization (PSO) algorithm and FCFS policy to remove collisions and diminish the delay at the intersection. Further, Xu *et al.* [193] coordinated the safe passing order of the CAVs based on some heuristic strategies as well as Monte Carlo tree search (MCTS) where the leaf node yields the optimal solution. Buckman *et al.* [194] made use of a heuristic centralized coordination based on the revised FCFS algorithm for navigating the vehicle through the intersection safely. In this work, the agents' order was swapped having a social psychology metric that could reduce delay while improving the utility function of every vehicle agent. Stevanovic and Mitrovic [195] deployed a heuristic-based system where neighboring lanes direction were altered thereby less conflicts happened at the intersection using a reservation-based algorithm. Similarly based on a heuristic approach, Belkhouche [196] addressed the optimal time and cost efficient conflict resolution of the vehicles with the help of Lagrangian function and safety margins through V2V communication. With a different approach, Tachet *et al.* [197] proposed a slot-based intersection framework. Having received the requests, the BATCH algorithm heuristically re-ordered the vehicle's arrival at the interaction after a period of time instead of immediate assignment of the velocity to them in order to achieve safe and more efficient scheduling output. Furthermore, in [198] a heuristic approach was presented introducing a singular entrance scheduling scheme based on the reservation at intersections. To find the optimal sequence of vehicles arrival, a genetic algorithm was used and also vehicles were allowed to approach the intersection with the desired speed. Besides, a red-black tree was created to store and manage the reservations. Elhadef [199] employed an adaptive V2I-based system and took advantage of a locking technique where the algorithm allows a vehicle to pass the intersection when it locks its conflicting lanes. This mechanism could satisfy fairness, safety and liveness to the vehicles.

In addition, Fajardo *et al.* [200] showed the superiority of FCFS performance over traffic lights in terms of delay and safety via simulation. Researchers in [201]–[203] took advantage of multi-agent reservation schemes based on V2V communication to improve traffic congestion and delay while ensuring safety. Adams and Rutherford [204] exploited a cooperative variant of the centralized AIM problem proposed in [15] to increase safety and reduce delay around common locations (way-points). This multi-agent TP mechanism was more efficient that traffic light systems. Moreover, in [205], WIN-FIT, an innovative reservation policy was used in which autonomous vehicles built dynamic groups and the winner was allowed to safely cross the intersection. Besides, specific vehicles in the other groups could pass through the intersection during the unused periods by the winner group. This solution could greatly lower the delay and improve the throughput. Aoki and Rajkumar [206], [207] designed a configurable synchronous intersection protocol (CSIP). It was the resilient and robust version of the Ballroom intersection protocol (BRIP). In contrary to BRIP, CSIP satisfied the safety concerns in terms of localization inaccuracies, control faults, and flexible inter-vehicle distances for each intersection depending on safety requirements. CSIP resulted in no accident occurrence, maximizing throughput and minimizing delay compared to traditional intersections. Besides, Elhenaway *et al.* [208] adopted a game theory techniques to find the best heuristic-based solution for navigation of AVs with the minimal delay at collision free intersection. With a similar method, Zohdy and Rakha [209] introduced a centralized heuristic approach for AVs that are armed with cooperative adaptive cruise control (CACC). The authors benefited from game theory to minimize the overall delay and collisions at the non-signalized intersection. Savic *et al.* [210] proposed a distributed V2V algorithm to prevent collisions and reduce delays. This approach was resistant to communication-failures in a great extent and met safety and liveness requirements for AVs.

In another research work, Abdelhameed *et al.* [211] studied a hybrid fuzzy-genetic controller to manage the vehicles' flow at the intersections. The system comprised an intersection manager and vehicle agents for vehicles coordination and control and could enhance throughput, mean and peak delay, predicted collision avoidance and intersection utilization. Moreover, a reservation method was employed in [212] for autonomous control of the emergency evacuation at the intersection. The proposed system was conflict free and improved speed, delay, travel time, and safety. Müller *et al.* [213] developed a centralized urban solution that scheduled the safe and optimal arrival time of the AVs at the intersection by means of MILP and ensured minimum delay. Chai *et al.* [214] assigned slots to the approaching AVs beforehand to cross the intersection in an optimal manner with the least delay, collision free and nonstop. In a certain distance from the intersection, IM calculated and sent out the target state of every vehicle based on two novel algorithms. One is called LOOSE which was used to improve safety, and the other one is named COMPACT which aimed at efficiency enhancement. Additionally, Kamal *et al.* [215] presented a coordination framework for CAVs to safely and quickly cross the intersection using MPC. Likewise, Kim [216] made advantage of MPC for safe TP of the vehicles. Moreover, they established some V2I and V2V coordination protocols for inter-vehicle safety, lane changing, and also intersection passing. Similarly, Katriniok *et al.* [217] designed a system based on distributed MPC to manage the priority of the AVs passage in a safe and efficient way at the non-signalized intersections. Perronnet *et al.* [178] deployed a sequence-based strategy for AVs that was resilient to communication latency and could ensure safe crossing of the vehicles with minimum delay. Lamouik *et al.* [218] employed a multi-agent coordination system using deep neural networks and reinforced learning (RL) in an autonomous environment. The proposed system offered safe a rapid intersection passing.

In addition, De Campos *et al.* [219] focused on a decentralized coordination of the traffic for conflict resolution. Decisions were made using a combination of model-based heuristic and sequential optimal control. In another work, Ze-hua *et al.* [220] availed a discrete control method based on a hybrid automation model to increase the cooperation among AVs by altering their maximum and minimum velocities and avoiding collisions. Furthermore, to elevate cooperation and efficiency in particular zones, they presented market mechanisms. In a different approach, Zheng *et al.* [221] proposed a delay-tolerant IM protocol in terms of communication. Besides, a framework was devised for safety, performance and liveliness analysis of the protocol and showed that the system was collision free and decreased delay compared to the traffic lights. Gregoire and Frazzoli [222] employed an efficient and safe hybrid V2I/V2V approach for AVs coordination at the intersection. A centralized job scheduler planned the crossing time for each vehicle with maximum speed while a distributed controller guaranteed this time and conflict free passing of the vehicles. Besides, Zhang *et al.* [223] designed and uniformly modeled centralized and decentralized reservation-based mechanisms for AVs to safely cross the intersection. Aloufi and Chatterjee [224] presented a system that scheduled the AVs crossing based on production line technique. The proposed system eliminated conflicts and decreased waiting time. In addition, they utilized KNN to predict the vehicles that make right-turns. A heuristic ST approach was studied by Chouhan and Banda [225] to prevent collisions and to minimize delay at the intersection. The system outperformed FCFS, traffic lights, and also the CIVIC algorithm [17] from the average delay perspective. Moreover, Creemers *et al.* [226] optimized the passing order of the vehicles with the help of a centralized controller supervising the access of the vehicles to the interaction using MPC. With respect to the average delay and throughput, the system was more effective than traditional traffic lights and FCFS. In [227], a distributed collision resolution strategy was utilized to navigate a group of CAVs safely through the intersection. In the proposed mechanism, optimization runs locally on each vehicle such that vehicles estimate the desired time and speed to traverse conflict zones along their path based on the received information from other vehicles. Their objective was to decrease delay and improve throughput of the traffic.

Another work on MILP was performed by [228] to boost the crossing time and to ensure safe traffic flow at the autonomous intersection. Simulation results demonstrated that this approach is better than the coordination algorithm based on discrete-time occupancy trajectory [229] and traffic lights in terms of throughput and delay. To significantly increase the throughput together with safety and efficiency, Mo *et al.* [230] benefited from multi-agents RL to formulate vehicle scheduling. They introduced V2V, collision set strategies, low-complexity algorithms and handled the multiple-collision-set coordination. Further, Steinmetz *et al.* [231] centrally harmonized the vehicles passage by a collision-aware resource allocation (CARA) mechanism that was self-triggered and considered communication constrains. A dynamic scheduling solution for AVs based on queuing theory was used in [232]. Rate stability theorem and low-complexity Lyapunov theorem-based algorithms were used to obtain higher quality of service (QoS), delay, throughput, and road stability. In [233], a heuristic approach based on various game theory techniques was utilized to improve throughput and avoid accidents. Additionally, Cruz-Piris *et al.* [234] adopted a genetic algorithm to automatically optimize crossing of both manual and AVs. The authors made use of a cellular automation simulator to increase throughput. Likewise, Gonzalez *et al.* [235] used a cellular automaton model and suggested a fault-tolerant rule-based distributed coordination system for AVs. The system outperformed traffic lights from the throughput viewpoint. An efficient V2I autonomous intersection scheduling protocol based on TP was developed in [236] to ensure safety with minimum delay. In the proposed system, the infrastructure collects vehicles' information to plan collision free trajectories and assign relative proprieties with the lowest delay using a window searching algorithm. Then, vehicles individually adapt their velocity using dynamic programming to cross the intersection.

The authors in [237] availed a heuristic approach and modeled the order of the vehicles as multi-agent Markov decision processes (MAMDPs) via RL at autonomous intersections. They particularly used a decentralized coordination multi-agent learning approach to mitigate collisions and reduce delay. Further, Mirheli *et al.* [238] developed a distributed coordination scheme to ensure that CAVs trajectories have no near crash situations. They used mixed-integer nonlinear programs (MINLPs) for optimization. The proposed approach was efficient in terms of travel time and throughput. Wuthishuwong and Traechtler [239] designed an V2I based intersection scheduling method using discrete mathematics for modeling the passing sequence and trajectory calculation via dynamic programming. The system had less waiting time than traffic lights. He *et al.* [240] used an efficient and collision-free solution that coordinated the approaching AVs from all directions in such way that they were allowed to travel on any entering lane and land on any exiting lane of the intersection. Here, travel time and throughput were lower than traditional traffic lights. A scheduling mechanism to resolve conflicts and maximize throughput for AVs was employed in [241]. Platooning and individual-based vehicle arrival models were developed utilizing a heuristic algorithm which aimed to optimally schedule the arrival time of every vehicle. The proposed solution outperformed traffic lights. Furthermore, Aoki and Rajkumar [242] devised a heuristic-based system where self-driving AVs could safely cross the dynamic intersection that are not shown in a map using sensors and V2V communication. They introduced a cyber traffic light that acted as an intersection coordinator in congested periods and increased traffic throughput. Katriniok *et al.* [243] introduced a distributed MPC system that could designate speed advice to the vehicles and safely schedule the vehicle passage through the non-signalized intersection. This method optimized the traffic flow and they also accounted for the driver reactions in terms of uncertainties.

In [244], the authors studied a V2V TP based regime where each vehicle solved a non-linear MPC using the proximal averaged Newton method for optimal control (PANOC) and sent its planned path to other vehicles. Feng *et al.* [245] employed a joint optimal control on both signal and trajectory using dynamic programming and control theory respectively with a goal to optimize fuel and travel time. In addition, Azimi *et al.* [246] introduced the ballroom intersection protocol (BRIP) for intersection management. They used a ST method and aimed to maximize the concurrent passage of vehicles through the intersection. The proposed system was deadlock free and vehicles could pass the intersection in a specific time with a constant velocity and non-stop. Moreover, the method was V2X independent and could increase the throughput. In [247], a V2X scheduling algorithm for collision avoidance was used based on the modeling of autonomous intersection to the scheduling sections (absolute value programming) in addition to the time occupancy of the vehicles. The proposed method was applicable with and without platoons and could reduce delay and increase throughput. Moreover, authors in [248] adopted a framework based on discrete-time occupancy trajectory (DTOT) where the intersection assigned modified DTOTs (time slots) to the formerly built queue of vehicles whose proposed DTOTs collide with each other. The described system performed based on the FCFS strategy in order to safely steer them through the intersection. A safe V2V interaction scheme was proposed in [249] to smoothly navigate the vehicles by means of speed adjustment with respect to the leading vehicle.

Additionally, Englund *et al.* [250] deployed an intersection cooperative speed limit advisory application based on V2I and wave control mechanism. In this approach, already speed-harmonized grouped vehicles on the same road organized groups with other vehicles on other roads such that their arrival time were managed, traffic flow was coordinated and collisions were avoided. Bian *et al.* [251] exploited a distributed IM mechanism by employing two offline and online algorithms to model the intersection with virtual belts and apply them in a real-time manner for safe and efficient vehicles TP through the intersection. In [261], an efficient rule-based application was deployed using V2V to avoid collisions based on distance, time to intersection indices, road and vehicle priorities. Basjaruddin *et al.* [262] utilized a multi-agent cooperative V2V scheme to ensure safety and alleviate travel time at the intersection. Moreover, Elleuch *et al.* [263] investigated a cooperative collision avoidance system using real-time databases and V2V communication to reduce computation time and ensure safety. Each vehicle's database preserved the local and surrounding vehicles information, and as the vehicle approached the intersection, it referred to its database and selected the objective vehicles to run the system. Safe and efficient IM scheme based on VAIMA was introduced in [264], an algorithm that provided fairness and improved passage time, traffic capacity by considering driver intention and V2V communication. Molinari and Raisch and Raisch [265] devised a V2V-based IM solution where safe and optimal vehicles trajectories and also crossing sequences were computed and determined using MPC and vehicles dynamics respectively. With a heterogeneous solution in [266], authors utilized a CA clustering platform using Wi-Fi and LTE channels. Wi-Fi was utilized for communication inside the clusters while LTE was used for transmission of safety messages among clusters. The system was efficient in terms of reception rate and delay.

Furthermore, Anadu *et al.* [257] developed a collision detection and avoidance system using mini robots equipped with sensors, micro controllers, V2I and V2V communication at the intersection. Lu and Kim [267] proposed an IM coordination genetic algorithm that optimized the vehicles passing order in a way that emergency vehicles traversed the intersection with the highest priority and with the lowest negative impact on travel time of the other vehicles. Road throughput and capacity paradigms as two efficient policies were presented in [123] for safe driving in different environments including intersection for AVs. The proposed approach benefited from V2V and in-vehicles sensors. With a different approach, Bazzi *et al.* [268] exploited a VTL-based approach using V2V where the first priority was allocated to the closest vehicle to the intersection which was then handed over to the next one. Abdelhameed *et al.* [252] benefited from a centralized multi-agent IM solution for AVs suing Fuzzy and proportional–integral–derivative (PID) controller. The collision of trajectories was predicted via Euclidean distance between the two vehicles and the intersection utilization for linear and especially fuzzy controller outperformed traditional traffic lights in terms of delay and throughput. Further, in [269], the authors built a V2V heuristic scheduling algorithm where the neighboring vehicles exchanged information and only the leading approaching vehicle cooperated with other leaders to safely traverse the intersection with minimal delay. Milanés *et al.* [270] made use of V2V and a Fuzzy logic controller to acquire the position and speed of the vehicles, predict the collision point at the intersection and adjust the speed of the vehicle without right of way to yield. Additionally, a V2V-based heuristic algorithm including shuffled frog leaping and genetic algorithms was proposed in [274] to plan the AVs trajectories such that safe and fast mobility was guaranteed. Ferreira and D'Orey [271] investigated the good performance of VTL in terms of emissions and speed based on V2V communication.

Vieira *et al.* [258] presented an IM method through visible light communication (VLC) under vehicular environment. In the proposed system, streetlights, traffic lights, RSU and vehicles were interconnected using VLC. Relative speed and distance were derived from the exchanged messages such that the RSU could optimally coordinate the safe vehicles crossing with the minimal delay. Pei *et al.* [259] studied cooperative multi-intersection management using V2I communications and a distributed ST method to ensure traffic efficiency and safety for CAVs at the intersections. Moreover, Xu *et al.* [260] introduced a safe and efficient cooperative multi-intersection scheduling scheme for CAVs. the proposed system was based on multi-agents and V2I communications and benefited from deep RL and fastest crossing time point algorithm (FCTP) to increase throughput and travel time of the vehicles. Zhang *et al.* [253] utilized a safe V2I framework based on CNN and a sequential based algorithm to coordinate the optimal crossing time and order of CAVs. The proposed model improved delay and speed in comparison to FCFS policy and traffic lights. Further, Worrawichaipat *et al.* [256] proposed a decentralized ST agent-based IM algorithm for CAVs that provided safe crossing of CAVs while the obstructions are present at the intersection incurring low traffic throughput. Their system behaved more efficient than FCFC and traffic lights methods. Regnath *et al.* [272] proposed a reservation-based decentralized IM scheme that planned safe trajectories for CAVs and ensured better performance in terms of delay compared to the traffic lights and priority roads. Qian *et al.* [254] developed an IM technique based on two mixed-integer nonlinear programs where vehicle trajectories, departure and signal times were centrally optimized so that safety was ensured and travel times were shortened for CAVs. In addition, Wu *et al.* [273] introduced a cooperative distributed collision-free framework for CAVs by formulating the scenario as a multi-agent RL problem. The proposed method could manage dynamic quantity of vehicles to pass through the intersection with efficient trip time. Ma and Li [255] utilized a centralized AIM based on two different reservation strategy for automated and CVs to minimize the travel time and avoid collisions. The proposed system used MILP for trajectory planning whereby instead of using predetermined arrival time and speed of the vehicles, they were optimized dynamically along the path. This method was able to assign a new trajectory to the vehicles with new arrival speed and time in case of sharp or sudden changes in the traffic condition at the intersection. Literature regarding the safe and efficient autonomous intersections are provided in Table 5.

D. EFFICIENCY AND ENVIRONMENT

Some researchers have proposed various IM methods in order to achieve the goals environmental benefits and efficiency.

Jin *et al.* [275] used a V2I approach that slightly varied from [284] with an optimal scheduling policy. The authors optimized the leaving times of the vehicle agents using linear programming and big M method at the intersection. The system aimed to reduce emissions, fuel and travel time. In another heuristic-based research [278], they followed a similar approach as [284] without the concept of platoons. They implemented a centralized solution based on the combination of priority, FCFS, and lane based polices where vehicles with higher priorities were served earlier. Similarly, Xu *et al.* [276] proposed a V2I based system which concurrently optimized the AVs' arrival time and signal timing to reduce travel time and total fuel consumption at the intersection. Furthermore, in another article, Tlig *et al.* [279] presented a multi-agent two-level decentralized scheme that optimized the traffic flow speed at the network level so that AVs were allowed to cross the intersection nonstop with minimum energy consumption. Mahbub *et al.* [280] devised a decentralized energy-optimal framework for two adjoining intersections using interior boundary conditions. They could provide safe efficient trajectories for the CAVs and diminish the environmental impacts and travel time compared to signalized intersections. In [281], the authors tried to coordinate the vehicles crossing based on optimism of the travel time and fuel consumption using MILP. Additionally, Hafzulazwan [282] conducted the similar approach with the goal of reaching the optimized fuel consumption and acceleration or deceleration. In [283], an architecture was proposed where a manager controlled all the traffic lights. In the coverage area of the traffic lights, vehicles establish direct communication via V2I communication by sending their requests. Otherwise, vehicles ad-hoc communication with the front vehicle that

TABLE 5. Summary of literature reviews on safe and efficient autonomous intersections.

Literature	Architecture Type	Scheduling Policy	Intersection Modeling
[17], [175]–[179], [199], [211], [213] [226], [236], [239], [250]–[252], [253]–[255]	V2I	Optimization	TP
[180]–[183], [189], [205], [206], [256] [201]–[203], [207], [212], [245], [246]	V2V	Optimization	ST
[184], [223], [247]	V2V + V2I	Optimization	ST
[216], [222], [257], [258]	V2V + V2I	Optimization	TP
[186], [214], [229], [231], [259], [260]	V2I	Optimization	ST
[178], [187], [188], [190], [191], [204], [210], [215], [243], [244] [217], [218], [220], [224], [227], [228], [230], [232], [234], [235], [123] [238], [240], [249], [261]–[267], [268]–[271], [272], [273]	V2V	Optimization	TP
[194], [196], [208], [233], [237], [241], [242]	V2V	Heuristic	TP
[209]	V2I	Heuristic	TP
[195]	V2V	Heuristic	ST
[197], [198], [225]	V2I	Heuristic	ST
[200]	V2V	FCFS	TP
[185], [248]	V2I	FCFS	ST
[221]	V2I	Optimization + FCFS	TP
[27], [193], [219], [274]	V2V	Optimization + Heuristic	TP
[192]	V2V	Heuristic + FCFS	TP

TABLE 6. Summary of literature reviews on ecological and efficient autonomous intersections.

Literature	Architecture Type	Scheduling Policy	Intersection Modeling
[275], [276], [277]	V2I	Optimization	TP
[278]	V2I	Heuristic + Optimization + FCFS	TP
[279]–[282]	V2V	Optimization	TP
[283]	V2I +V2V	Optimization	TP

was linked to the traffic light were performed. Afterwards, requests were forwarded to the controller to find the optimal green light timing and reduce emissions. Zhao *et al.* [277] presented an centralized optimal coordination framework for CAVs in the roundabout. Performance of the system was also investigated under mixed traffic in the roundabout. The propose method significantly diminished trip time and energy consumption for CAVs whereas under the hybrid traffic situation it was not so effective and stable in congested traffic conditions. Table 6 summarizes the articles regarding efficient and ecological autonomous intersection.

E. SAFETY, EFFICIENCY, AND ENVIRONMENT

This section introduces works that focused on safety, efficiency and environment. To fulfill safety and optimize energy consumption, Makarem and Gillet [285] availed their modified version in [286] and investigated the intersection coordination via distributed navigation function method for AVs. In this heuristic approach, heavier vehicles consuming more energy were prioritized to pass the intersection before others to ensure energy optimization. The systems were more energy efficient compared to the traffic light. With a similar concept in [287], they added inertia and intention of the vehicles to the shared information in order to alleviate the system performance from intersection capacity, fuel consumption, average speed, and traffic smoothness perspectives. Kamal *et al.* [288] utilized a centralized approach based on MPC to safely coordinate the AVs. The proposed system optimally computed the vehicles trajectories and enabled smooth flow of the traffic with high throughput, less delay and fuel consumption. Furthermore, a V2V IM method for AVs based on multi-agent was developed in [294]. A collision free sequence order of the vehicles was determined with respect to their future paths. Besides, velocities were adjusted to ensure safe passing in addition to less energy consumption and delay. Tlig *et al.* [295] defined an agent at each intersection to locally synchronize the arrival time and also the speed of the other AVs vehicles agents thereby they could safely cross the intersection without stopping and consume less energy. In another research work [296], a novel algorithm was proposed that took control of the speed to safely and efficiently route AVs in the non-congested traffic. Mirheli *et al.* [297] developed a control logic via dynamic programming and benefited from look-ahead mechanism based on a tree search algorithm to suggest near-optimal maneuvers for AVs. Compared to the signal control, the proposed method was able to maximize throughput, minimize travel time and fuel consumption, avoid collisions and smooth the traffic flow at the intersection.

Additionally, Malikopoulos *et al.* [304] investigated a distributed optimal control scheme based on FCFS for CAVs to minimize fuel, travel time, energy consumption while satisfying safety and maximizing throughput. The system behaved more efficiently compared to the signal control. Jin *et al.* [284] employed V2I communication to form a safe multi-agent intersection management framework where

TABLE 7. Summary of literature reviews on safe, efficient and ecological autonomous intersections.

Literature	Architecture Type	Scheduling Policy	Intersection Modeling
[285]–[287]	V2V	Heuristic	TP
[288]–[292], [293]	V2I	Optimization	TP
[26], [30], [294]–[303]	V2V	Optimization	TP
[304]	V2V	FCFS	TP
[305]–[308], [309]	V2I	Optimization	ST
[310]	V2V	Optimization + FCFS	TP
[307]	V2V + V2I	Optimization	ST
[284]	V2I	Optimization + FCFS	ST
[311]	V2I	Optimization + FCFS	TP

passages of vehicles platoons were scheduled using FCFS and suggested reservation time slots. Here, the traffic performance indicated higher values compared to the traffic lights in terms of delay, travel time, fuel consumption, and emissions. The proposed system exhibited robustness to density. Besides, in comparison to the non-platooning system, the communication load significantly declined. Bashiri and Fleming [305] deployed the similar approach as [284], a platooning-based mechanism for IM and and benefited from reservation and two policies based on classical stop-sign that outperformed it in terms of delay. In their latter work [306], they made use of a greedy-based cost function and reservation based policies to devise a centralized scheduling strategy for vehicles platoons to safely traverse the intersection with minimum delay and fuel consumption which was more effective than traffic lights. In a different approach, Medina *et al.* [298] exploited a decentralized virtual platooning control mechanism. Here, vehicles in different lanes and future directions cooperatively formed a platoon to safely cross the intersection with high throughput and less fuel consumption. This method showed better performance than traditional traffic lights. Moreover, Bichiou and Rakha [26] presented an optimization algorithm based on control theory to control CAVs. The proposed method considered weather conditions as well as vehicle dynamics and except for computational expenses, it demonstrated better performance compared to the existing conventional IM methods in terms of delay, emissions and fuel consumption. In another article, Philip *et al.* [289] studied a collaborative approach between RSU and AVs in terms of their lane speeds to elevate intersection efficiency and reduce fuel consumption. To this end and to reach a close-optimal result, a consensus-based algorithm with constant step-size gradient was used.

Moreover in [290], a collaborative method was adopted that optimized both CAVs speed and signal timing simultaneously to achieve lower travel time and fuel consummation. The authors of [310] relied on V2V communication for their system. They considered the intersection as a conflict zone and allowed only one vehicle to pass the intersection at a time based on the shortest arrival time and FCFS. Speed adjustment was performed for vehicles with lower priority to reach the clear intersection. The proposed system outperformed FCFS and traffic lights in terms of emissions, fuel consumption, travel time and speed. Further, Bento *et al.* [307] developed a global agent-based IM system supported by V2V and V2I using a ST reservation scheme that aimed to decrease ecological impact, collisions, and congestion. Here, they developed a traffic simulator to evaluate the reservation-based scheme for roundabouts and crossroads management. ST cell reservation was performed via an infrastructure agent to minimize conflicts, congestion and environmental impacts. The introduced system also supported V2V communication. A different centralized ST approach of their work including a small number of legacy vehicles not supporting V2X communication was introduced in [309]. Simulation showed good performance in terms of travel time, energy-saving, and flow rate. They could integrate all intersection types including roundabouts. Zohdy and Rakha [291] utilized an optimization framework that evoked the concept of cooperative adaptive cruise control where an intersection manager assigns an optimal safe speed to the AVs so that they can pass through the intersection having lower delay and fuel consumption.

In addition, Zhang *et al.* [300] deployed an optimal decentralized approach for CAVs crossing two neighbor intersections applying the Euler-Lagrange equation and optimal dynamic speed that yielded continuous traffic flown, collision avoidance, and lower travel time and fuel consumption. Researchers in [301] conducted an analytical research on the optimal control of the intersection using a similar approach. The authors of [302] availed three techniques (Genetic Algorithm (GA), Active-set Method (ASM), and sequential quadratic programming (SQP)) for optimal scheduling CVs in a corridor of intersections. In the proposed system, delay, rear-end collisions, emissions and fuel consumption declined. Zohdy *et al.* [30] launched an optimization tool to navigate AVs through the intersection. They used cooperative adaptive cruise control as TP method to prevent crashes and reduce delay and fuel consumption. Du *et al.* [311] focused on a rule-based V2I-based IM framework using FCFS. Under low traffic, cooperative speed synchronization was applied while in congested times, virtual platooning was used to coordinate the vehicles passage through the intersection. The system was able to spare energy, increase the intersection capacity and decrease travel time in both cases. In addition, in [292], an intersection coordination approach for AVs using MPC and V2I communication was presented to plan safe trajectories with high mobility and minimal energy and ecological impact. Munst *et al.* [303] benefited from a VTL framework based on a cloud manager and V2I communication where the vehicle state information were augmented by the cloud and suggestions were sent to the vehicles at the intersection. This work aimed to improve traffic flow, safety and fuel consumption. Huang *et al.* [308] implemented a reservation-based test-bed under V2I communication where priorities were assigned based on vehicle classes in terms of unstoppable, stopping and others. The system showed better performance in terms of delay, emission, and fuel consumption compared to conventional control methods. Chen *et al.* [293] aimed to find an optimal speed of the CAVs to minimize their fuel consumption and travel time by use of a safe centralized intersection coordination method. Safe, efficient and ecological approaches applied at autonomous intersections are shown in Table 7.

F. SAFETY, EFFICIENCY, AND INFOTAINMENT

In this section, we explore the literature that aimed to boost safety, passenger infotainment and efficiency. Krajewski *et al.* [312] investigated a decentralized graph-based solution for vehicles longitudinal trajectories optimizations by usage of dynamic programming at intersections. The system outperformed manual vehicles and non-cooperative AVs. To achieve the aforementioned three goals, Dai *et al.* [313] implemented an automated optimal intersection control framework. An intersection control model was transformed to the convex optimization problem to schedule the smooth vehicle passage. Further, Mladenovi¢ and Abbas [314] utilized a conflict free cooperative self-organizing control scheme for AVs at the intersections. The proposed method was based on the adjustment of the vehicle's velocity trajectory and priority assignments that provided less waiting time, delay, and travel time. In [315], they relied on a self-organizing priority-based agent-based IM approach for AVs using V2V. Vehicles trajectories were planned according to the social priority and considering vehicles speed calculation. The system resulted in infotainment, safety, and efficiency. In addition, Wuthishuwong *et al.* [316] established a V2I-based system that determined the safe time and trajectories for AVs using discrete mathematics, dynamic programming, and a node reservation algorithm at a one-way intersection. Lower waiting time, smooth traffic flow, and safe crossing were maintained in the system. Table 8 describes the literature that cared for safe, efficient and passenger infotainment at autonomous intersections.

G. SAFETY, ENVIRONMENT, AND INFOTAINMENT

In [299], the authors extended their decentralized control framework from [300] by integrating left and right turns and took into account the passenger discomfort optimization in turnings in addition to ecological (fuel consumption) and safety goals.

TABLE 8. Summary of literature reviews on safe and efficient autonomous intersections with infotainment aspects.

Literature	Architecture Type	Scheduling Policy	Intersection Modeling
[312]–[315]	V2V	Optimization	TP
[316]	V2I	Optimization	TP

H. SAFETY, EFFICIENCY, ENVIRONMENT, AND INFOTAINMENT

It is quite idealistic if IM can take into account all these objectives and generate a trade-off between them. To ensure safety and alleviate fuel consumption, travel time, traffic flow, emission, and driver infotainment level, Ding *et al.* [317] studied a safe centralized approach for IM for AVs by transforming the problem to a nonlinear constrained programming. Cao *et al.* [323] implemented a multi-agents routing strategy in a semi-decentralized fashion using the route assignment problem solved by infrastructure agents. In addition, Qian *et al.* [319] adopted a decentralized MPC scheme using a priority-based scheduling scheme for AVs to smoothly and safely coordinate them through the intersection while minimizing pollution, mitigating gridlocks and saving energy. In [320], the proximity of the intersection was analytically formulated as three zones and an optimization algorithm was performed based on Pontryagin's minimum principle (PMP) and the Euler-Lagrange equation to coordinate the CAVs at the intersection. The system followed multi-objectives including fuel reduction, driver infotainment, safety and efficiency. Furthermore, Azimi *et al.* [3] proposed V2V ST-based protocols to provide safety, infotainment, environmental sustainability, and boost the throughput at intersections and roundabouts using speed optimization of the vehicles. FCFS policy, road priorities, and vehicle identification number (VIN) were applied for safe crossings of the vehicles. The authors of [321] studied a greedy iterative algorithm and a composite policy to organize multi-intersection networks via trajectory optimization and route planning for CAVs. This framework ensured efficiency, safety, environment sustainability and passenger infotainment. In [322], a ST Fuzzy-based algorithm for roundabouts management using V2V and V2I communication and connected and non-CVs was proposed. The reservation was adaptive based on the vehicles speed and could reduce travel time, emissions, congestion, energy and increase driving infotainment. Furthermore, Zhang *et al.* [318] adopted a novel V2I-based AIM system for CAVs that planned safe and optimal trajectories of the vehicles considering factors such as travel infotainment, fuel consumption, speed and acceleration. The proposed scheme took advantage of a priority-based mechanism that improved the traffic efficiency and reduced the delays of emergency vehicles at the whole intersection zone. Literature concerned about autonomous intersections with multi-objectives is presented in Table 9.

VI. VULNERABLE ROAD USER (VRU)

Intersection users incorporate not only vehicles but also VRUs such as bicycles, scooters and motorcycles. In spite

TABLE 9. Summary of literature reviews on multi-objective autonomous intersections.

Literature	Architecture Type	Scheduling Policy	Intersection Modeling
[317], [318]	V2I	Optimization	TP
[319]–[321]	V2V	Optimization	TP
[3]	V2V	Optimization + FCFS	ST
[322], [323]	V2I + V2V	Optimization	TP

of the significant importance of VRUs as one the most paramount components of roads users, majority of the researchers have focused on the intersection management solutions for vehicles and rarely investigated the VRUs safety in the traffic. In the literature, researchers have reduced the likelihood of crashes for VRUs at the intersections from various perspectives. Research on intersection management for VRUs has been limited mostly to safety concerns such as warning or detection. For example, the application of different sensors is a traditional method that has been widely used. However, sensors are not suitable for non-line of sight situations and should integrate other technologies like DSRC or LTE. Other emerging solutions such as wearable devices and cellphones still need more research. Researchers in [324] proposed a CA algorithm based on vehicle to bicycle (V2B) communication at an autonomous intersection. Additionally, authors in [325] presented two cases for collision avoidance of bikes/pedestrians at the intersection; either WiFi communication between bikes/pedestrians and infrastructure so called B2I/P2I whereby the RSU relayed the information via DSRC/WAVE to the vehicles, or more efficient option which involved direct communication using DSRC/WAVE between the two target groups as vehicle to pedestrian (V2P)/V2B communication.

There are some projects that investigated the safety of road users from the experimental approach. RedEye [326] exploited a system where scooter rider decelerated and warned the nearby vehicles when it violated the red light. It also received the warning from other RedEye riders using smartphones. SPaT control of the traffic light was used as an optimization tool at the signalized intersection. VRUITS [327] was a project that investigated the mobility, infotainment and safety of pedestrians, bikes, moped and motorcycles under various scenarios via ITS applications and through V2I communication in addition to B2I, P2I and moped/motorcycle to infrastructure (M2I) communications. They introduced the intersection as the most dangerous collision point basically in poor visibility. BikeCOM project [328] utilized smartphones to establish a communication between a cyclist and vehicle driver's phone to exchange safety relevant data and warn both the cyclist and the driver of the potential threat. Moreover, PROSPECT project [329] analyzed the cyclist to vehicle collisions in different use cases from the vehicle's perspective. They discovered that intersections mostly contribute to the accidents. In addition, cyclist direction, driver's intention, road topology and traffic rules influence were also studied. As further efforts in the VRUs field, the aim of the in-Dev project [336] was to improve the safety of VRUs by investigating accident causation for VRUs through developing a toolbox consisting of socio-economic factors. Finally, XCYCLE [330] intended to enhance the cyclist detection in terms of active and passive, and warn the driver and cyclist of a danger at the intersections through effective mechanisms.

Some papers have considered heterogeneous solutions as an alternative or addition to the pure classical 802.11p technology. In V-Alert [334], short-and long-range communication were combined giving more time to VRUs and drivers to take actions for collision avoidance especially at the intersections. In their proposed system, on one hand, vehicles periodically sent position information to the RSU using 802.11p. Then, it relayed the information to a central server via LTE. On the other hand, similarly, bicycles sent information to the proxy bike through a WiFi network namely bike to bike (B2B) communication so that it later would transmit all the positions information via LTE to the central server known as cellular-B2I or (C-B2I) communication. Therefore, with the dissemination of the safety messages to the vehicles and bicycles group, imminent conflicts were prevented. Besides, in the proposed scheme, pedestrians and motorcycles could be integrated. Thielen *et al.* [78] introduced a heterogeneous approach using an RSU to communicate between a cyclist and a vehicle. Cyclists sent safety messages to the RSU through Wi-Fi. Afterwards, ITS-G5 was used to relay the information to the vehicles in the vicinity. Further, Anaya *et al.* [335] designed a system named "MotoWarn" that targeted both cyclists and motorcycles. In regard to the cyclist, it incorporated the iBeacon technology and Bluetooth to notify the vehicles about the nearby cyclists. The vehicle was loaded with a Bluetooth interface to receive the iBeacon messages from the cyclists. Concerning the motorcycle, it established a one-way 802.11p based communication to send the safety information from the motorcycle to the vehicle (M2V) whereby the vehicle could predict the collision and notify the driver.

In the literature, a combination of human or sensor-based methods and ITS-G5 has also been introduced to address the collision avoidance. Kwakkernaat *et al.* [331] proposed a system that the vehicle was aware of the cyclist via exchanging safety messages based on ITS-G5. It then merged this acquired information with the data it received from the vision sensors to outperform the reliability of them. Inspired by [102], Segata *et al.* [333] explored the vehicle cyclist intersection collision avoidance based on calculation of the collision probability and informed the vehicle driver to avoid the accident. To avoid arbitrary collisions with bicycles, a treat assessment using vehicle dynamics along with longitudinal and latitudinal movements of the vehicle have been modeled by Brännström *et al.* [332]. Summary of literature reviews on VRUs is shown in Table 10.

VII. CHALLENGES

Intersection management resiliency should be enormously observed since it is directly associated with human lives.

TABLE 10. Summary of literature reviews on VRUs.

Literature	Architecture Type	Scheduling Policy	Intersection Modeling	Intersection Type	Intersection Goal
[324]	V2B	Optimization	TP	Autonomous	Safety
[325]	P2I/B2I + V2B/V2P + V2I	Optimization	TP	Autonomous	Safety
[326]	V2B	Optimization	TP	Signalized	Safety
[327]	V2I + P2I + B2I + M2I	Optimization	TP	Autonomous	Safety, Efficiency, Infotainment
[328]–[333]	V2B	Optimization	TP	Autonomous	Safety
[334]	C-V2I + B2B + C-B2I	Optimization	TP	Autonomous	Safety
[78]	V2I + B2I	Optimization	TP	Autonomous	Safety
[335]	V2B + M2V	Optimization	TP	Autonomous	Safety

There are many factors and challenges that contribute to the robustness of the intersections operation as mentioned below.

A. SENSORS

Sensors play an important role in data fusion from the vehicles in the surroundings. They have many variations and deployment methods as follows [337]. Vision and sound sensors (ultrasonic and acoustic), remote sensing sensors like infrared, laser scanners, radar, Lidar, and RF/Wi-Fi/LTE transceivers, contact-based sensors including inductive loops, magnetic sensors, strain gauge, piezoelectric, fiber optic, pneumatic, seismic and vibration, off-road sensors such as unmanned aerial vehicles (UAVs), GPS, and mobile apparatus. All these miscellaneous sensors have various features such as coverage range, accuracy and light sensitivity. Thus, right usage or combination of sensors are necessary to be considered for better coordination of the traffic at the intersection [338].

B. INFORMATION MANAGEMENT AND SHARING

There exist some challenging features in VANETs such as high mobility, speed and fast topology change that might impact traffic safety and efficiency. In such a dynamic network, vehicles need to be very responsive and process the information rapidly. Apart from local processing in the vehicles or pre-processing sensors for delay-sensitive applications, edge, fog and cloud computing are other alternatives for data processing by bringing the computation and storage source closer to the vehicles at different levels. This will decrease the perception and processing time of a hazardous situation which is essential for safety critical applications [338]. In addition to the location where vehicular information processing takes place either locally, on intermediate nodes or at the receiver side, there are other factors that highly influence the system performance and should be meticulously observed. These factors include data format, dissemination frequency and type of information that are shared among vehicles in different scenarios. Consequently, the challenging task is to elaborate a concrete model that entails the whole environment characteristics adjacent to the intersection [25].

C. PLANNING UNIVERSAL SCHEME

Majority of developed IM frameworks have been devised and tested for a particular scenario. Therefore, they only work properly under the given circumstances and can not be generalized to other scenarios. However, road network involves plenty of scenarios that are hardly managed by a single solution. Hence, it is recommended to design a universal approach such that it is adaptable to different situations and is capable of meeting many cooperative IM goals [25].

D. HETEROGENEOUS COLLABORATION

Vehicular traffic includes various vehicle types and brands with distinctive characteristics and constraints encompassing vehicle dynamics, sensors, communication equipment and so on. Thus, it is demanding to work on a generic standard that facilitates heterogeneous vehicles to collaborate with one another in an efficient way.

E. VEHICLE CLASSIFICATION

Distinctive safety characteristics of heterogeneous vehicles such as speed, acceleration, deceleration, reaction distance, breaking distance, stopping distance, and braking lag distance highlights the necessity of vehicle classification especially in safety critical IM applications. Gholamhosseinian and Seitz [337] introduced VANETs as a potential approach for vehicle classification that took into account mobility and physical parameters of the vehicles. In their investigation, VANETs were introduced as an identical solution that could classify vehicles globally and in a real-time manner. In their next research [339], they presented a VANET-based methodology to classify heterogeneous classes vehicles with respect to their safety parameters such as acceleration, deceleration, braking distance, stopping distance and also braking lag distance of heterogeneous vehicle. Moreover, other important parameters like velocity, load sensitivity, and reaction time were taken into consideration.

F. QUALITY MEASUREMENT

In order to fully exploit the advantages of cooperative IM, it is suggested to measure the quality of cooperation at the intersection. This topic has rarely gained attention in the literature. Measurable parameters, quality model, scope of quality rating, and responsible authority are open concerns in this area that require careful consideration [25].

G. EXTERNAL FACTORS

Researchers are recommended to consider different weather and road/rail conditions such as dry, wet, icy, snowy and oily as underlying factors in their IM solutions. These factors can drastically impact traffic safety and efficiency. Additionally, they can directly affect travel time, speed, fuel consumption, throughput of the vehicles at the intersection. Further, from the safety perspective, inclement weather conditions might influence vision, vehicle's braking system, friction coefficient of the road/rail surface, and driver reaction time of different vehicles [339].

H. INTERSECTION TYPE

Generally, intersections are classified into several categories like crossroad, roundabout, X,Y and T-intersection, ramp merge, deformed and misaligned intersections. Topology of intersection plays a vital role in IM such that it is defined according to a specific scenario and its particular traffic condition.

I. LOCALIZATION FAULTS

Simultaneous Localization and Mapping (SLAM) [340] is one of the advanced techniques used in many papers to minimize the localization error. Since this method is not flawless, a larger ST occupancy must be reserved by the intersection manager in order to certainly prevent conflicts inside the intersection. The size of this safe margin is dependent on the localization algorithm, maximum speed, and also the accuracy of the vehicle sensors. In this context, [15] considered a safety space around the vehicles to compensate localization errors in sensors perception. Authors in [196] accounted for a safety boundary for inter-crossing time of the vehicles to overcome position uncertainties.

J. COMMUNICATION ANOMALIES AND CHANNEL OPTIMIZATION

Communication delay, range and rate play critical roles in the intersection management efficiency, safety and scalability. Network delay is mainly proportional to the total number of CVs and their transmission packets. The processing capacity of the intersection is derived according to the communication rate and also the traffic information that it receives from each vehicle. Vehicle's safety extremely depends on the reliability and timely reception and transmission of the information. Vehicles and infrastructure exchange information and should receive the safety information in a suitable distance from the intersection so that they can timely stop or slow down to avoid collisions. Haas and Hu [341] assessed the communication performance of their systems by inserting collisions with high and constant velocity ($> 7\ m/s$) to the collision free routes of the vehicle and determined the probability of collision avoidance. This approach showed some drawbacks in terms of realistic radio propagation models and low speed crash situations. Zinchenko *et al.* [342] addressed the reliability of V2V DSRC-based communication at the application level. They considered information freshness, path prediction error and communication range as their performance metrics and developed some realistic scenarios at the intersections and found out that traffic congestion, obstruction, intersection location, and topology are important factors to gain application reliability.

In terms of channel optimization or information dissemination range, some approaches have been proposed for VANETs to diminish collisions on the roads. Tang and Yip [343] researched a collision avoidance system based on the time-to-avoid collision metric considering warning interval and reaction time as well as different deceleration rates. For normal and poor channel conditions, DSRC transmission delays of 25 and 300 *ms* were assumed respectively. This approach might not be a comprehensive strategy due to size of fixed delays. Furthermore, the behavior of the other intersecting car should also be considered to reach a sustainable safety. Sepulcre *et al.* [344] launched an empirical tests for an intersection collision warning system. They realized that the beacon rate of more than $2Hz$ is required for a perfect warning reception. Besides, authors evaluated the challenging case where a node at the intersection tried to congest the channel. Their work lacked the impact of congestion on the beacon rate as well as the latest congestion control methods. Zinchenko *et al.* [345] investigated the impact of various densities on static beacon intervals of 5, 10 and 15 Hz and figured out that information freshness of 0.2 second is not reachable for the rate 5Hz. To examine this V2X reliability test, they moved the receiver along the road while the transmitter was maintained at different fixed locations. Moreover, by analyzing different scenarios, they discovered that better communication performance is acquired when the intersection is fully surrounded by buildings in contrast to the situations where there is no building or they are placed on merely two corners. The reason lied in shadowing effects and partitioning of interference domain by the buildings. Joerer *et al.* [346] proposed a V2V situation-based rate adaption solution for endangered vehicles at the intersection to support vehicular safety. They applied this adaption on two congestion control mechanisms namely TRC and DynB and concluded that it can increase the situation awareness. To mitigate collisions, there are some approaches [347]–[349] and in [350]–[353], the improvement of channel load, beaconing or information dissemination range were suggested.

K. SYNCHRONIZATION

To guarantee safety, it is imperative for the intersection participants to be accurately synchronized. In Crossroads [354] and its variation Crossroads+ [355], synchronization and time stamping between infrastructure and vehicles were proposed as a reservation-based policy. Here, after clock synchronization of all vehicles with the infrastructure, they shared their status information with that. Afterwards, the infrastructure sent ''time to actuate'' and a constant speed to every vehicle so that it could initiate to speed up or slow down at the relative time to adapt to the announced velocity. The system showed notable efficiency. They considered an upper bound for the round trip delay and delegated ''time-to-actuate'' for vehicles to behave in a deterministic manner. In [356], the authors concentrated on a progressive data synchronization strategy in order to prevent redundant transmissions of the vehicle agents at the autonomous intersections via bandwidth optimization and decreasing the data transmission.

L. VEHICLE DYNAMICS AND MODEL MISMATCH

Basically, the estimation of the vehicle's future trajectories at the intersection area demands vehicle modeling. Researchers have modeled vehicles differently ranging from simple models like one-dimension to more complex ones such as bicycle and 4-wheel considering air drift, road slope, and mass models. The one-dimension model is the simplest model that takes into account the velocity and longitudinal movement of the vehicle. It lacks the ability to capture the vehicle's movement in 2D space which is not so accurate. On the contrary, longitudinal and latitudinal positions of the vehicle are considered in the 4-wheel model. Additionally, velocity, heading and steering angle are also considered [15]. The bicycle model represents an abstract variation of the 4-wheel model where two virtual wheels at the center of the vehicle represent the model. Other complex models can more precisely model the vehicle's behavior by considering additional features such as friction coefficient, mass, air drift, and road slope [357]. Specifically, parameters such as mechanical efficiency of the drive-line, wheels torque, tire radius, gravitational acceleration, aerodynamic drag coefficient, rolling resistance, and the road slop are taken into consideration. However, these models have enormous computational overhead and are not feasible in dense situations.

The real vehicle and the considered vehicle model should match to avoid crashes at the intersection. Furthermore, other external perturbations like wind may affect the normal vehicle behavior. In [16], a safe intersection crossing protocol was carried out by assigning two parameters arrival time (FCFS) and velocity from the infrastructure to the approaching vehicles based on the received information from them. The authors proposed a system called RIM that utilized a ST-based IM method for CAVs coordination at the intersection. They studied the impact of confined external turbulence and demonstrated that model mismatch can be sorted out with better throughput if a vehicle tracks a reference position profile rather than a velocity one. The velocity reference model (assignment method) is robust for an ideal situation where there is no external disturbances. The system showed better throughput than existing IM methods. Qian *et al.* [358] suggested a control method for CAVs to reduce congestion, travel time and ensure safety at the intersection. The optimal strategy was operated by an intersection manager and it was based on the TP by grouping the vehicles according to their longitudinal dynamics. Chen *et al.* [359] constructed a distributed IM scheme for CAVs that employed safe geometric topology of the vehicle platoons with efficient merge and splitting of the groups. Authors considered vehicle dynamics, car-following model and topology of communication in their research to prevent collisions and improve velocity. The proposed model outperformed FCFS from the energy consumption and travel time perspectives. Liu and Kamel [360] utilized an optimal cruise control methodology based on swarm algorithm, V2I and V2V communications to provide energy efficiency, lower trip time, passenger infotainment, higher throughput and safety for platoons of vehicles. They also considered vehicle dynamics and various constraints such as speed limit, engine power limit and stop-free strategy.

Researchers in [361] and [362] addressed measurement and input uncertainties via some approximation algorithms for collision avoidance heuristically. They utilized a centralized solution and verification problem and aimed to robustly avoid the (invariant) Bad Sets or dangerous situations for multiple vehicles (agents) at the intersection. Li *et al.* [363] employed a heuristic approach and various game theory techniques to model the vehicle behavior and dynamics and find the best heuristic-based solution for a collision free intersection. Further, Bian *et al.* [357] studied the safe and efficient cooperation of vehicles at non-signalized intersections via partitioning the tasks into vehicle's position and velocity observation, safe arrival time optimization, and trajectory control areas. To this end, they designed distributed algorithms for every one of these tasks.

M. UNCERTAINTIES AND OTHERS FACTORS

Formal methods can not always guarantee safety for intersections. Because vehicles might disregard the rules and deviate from VTL signals, the planned trajectory or ST reservation. Additionally, an approaching emergency vehicle can cause a disruption of the normal intersection management. Reasons may originate from IM crash, mechanical failure or sudden vehicle beak down, communications failure, distorted information, human behavior or control reasons. This might also happen at hybrid intersections where the behavior of human-driven vehicles is unpredictable. Here, sound fault tolerant mechanisms are needed to detect the selfish actions or other uncertainties. Some researchers have worked on this area. Recently, Khayatian *et al.* [364] proposed a resilient and robust algorithm for intersection management. In the studied system, a rogue vehicle that does not follow the IM rules was detected. Then, IM broadcast a warning message to all vehicles and a big margin is accounted between the passing time of them to ensure safety. Dedinsky *et al.* [365] utilized a vision-based monitoring system to inform the IM in case a rogue vehicle appears or any other fault happens in the trajectories of the approaching vehicles to the intersection. In [366], a collision avoidance system based on the cooperative resource reservation was proposed. In the proposed system, an evasion plan database was considered for unexpected situations like accidents or vehicle mechanical failures. In this case, the intersection manager could recover the possible paths for the involved vehicles.

Furthermore, the authors of [367] proposed a hybrid control of a centralized and distributed architecture for intersection management. The centralized section assigned time slots to the approaching vehicles whereas the distributed one ensured safety by allowing vehicles to optimally adjust the control inputs. Hafner *et al.* [109] studied the collision

TABLE 11. Summary of literature reviews on robustness and resiliency challenges for IM.

Challenge Domain	Literature
Sensors	[338]
Information Management and Sharing	[25], [338]
Planning Universal Scheme	[25]
Vehicle Classification	[337], [339]
Quality Measurement and Heterogeneous Collaboration	[25]
External Factors	[339]
Localization Faults	[15], [196]
Communication Anomalies and Chancel Optimization	[341]–[353]
Synchronization	[354]–[356]
Vehicle Dynamics and Model Mismatch	[16], [357], [361]–[363], [358]–[360]
Uncertainties and Unexpected Situations	[28], [108], [109], [364]–[370]
Recovery	[371], [372]
Security and Privacy	[373]–[375]

avoidance between two vehicles via control methods and vehicle states at the autonomous intersection. They availed capture sets to prevent vehicles to enter the bad sets at the same time whereby collisions occurred. In later work [108], they used the same concept but considered communication delay and model uncertainty in their experiment. In a similar work, Campos *et al.* [368] addressed the same problem from the distributed perspective such that instead of globally preserving the capture and bad set, each vehicle maintained its local individual sets (optimization) that helped it to pass the intersection and avoid collisions. In the next paper [369], they developed their work with receding horizon control scheme. Moreover, authors in [370] proposed a decision-making system where a malicious vehicle does not hold to the intersection rules. In contrast, other vehicles play games according to their priority sequences which are based on the right of way rules and compute the related Nash equilibrium as their control input for decision orders. Hubmann *et al.* [28] presented a safe model especially for uncertain maneuvers along the AVS path due to noisy sensor or drivers intention via usage of POMDP (partially observable Markov decision process) and V2V to seek an optimal acceleration.

N. RECOVERY

When the abnormal situation at the intersection is resolved, it should possess a recovery plan to resume its regular operation and avoid any deadlocks. However, in some conditions like intersection blockage, vehicles must have embedded recovery systems to find a reroute. Li and Wang [371] developed four cooperative safe and time-optimal algorithms at a blind intersection based on spanning tree paradigm. In their proposed methods, a recovery plan was also considered to provide a new crossing schedule for the vehicles in situations where an obstacle like a pedestrian abruptly appears on the road or a pedestrian suddenly tries to pass the intersection. In another effort, Dresner and Stone [372] utilized a collision-free centralized-based ST method at a hybrid intersection using FCFS for AVs, and a similar mechanism for human driven vehicles. In this multi-agent based system, recovery performance of the system was also analyzed when vehicles experienced mechanical failures.

O. SECURITY AND PRIVACY

Authenticity of information that are exchanged among vehicles is of crucial importance. authentication source, correct information interval in case of false information dissemination are other challenges that should be addressed. Lefèvre *et al.* [373] studied the impact of privacy strategies on V2X communication. In cooperative vehicular wireless communication, security is one of the important concerns since malicious information can lead to disaster especially at crucial places such as intersection. In spite of its significance, there has been few efforts in the literature that addressed the security of the intersection management systems. Today, CVs as well as intersection management systems are prone to cyber attacks [376]. Attacks can target the wireless channel [376] in terms of Bluetooth, IEEE 802.11 or cellular communications. Besides, they might physically install harmful applications [377] or access the vehicle's controller area network (CAN) bus [378]. Bentjen [374] examined two scenarios where the system was attacked:

1) *Sybil Attack* which deals with false or multi-reservations at a moment. They used FCFS and exhibited that traffic jams mostly occur when some reservations have the most number of the collisions with other trajectories. Other types of Sybil attacks are discussed in [379]: Nuisance which stands for delay in communication, Herding which tricks the intersection to control various vehicles and Carjacking that implies single or multi vehicle speed spoofing [374].
2) *Squatting Attack* which enforces a vehicle to stop inside the intersection. Thereby, the intersection manager is compelled to notably lower the speed of other vehicles resulting in traffic congestion.

These problems might be mitigated as follows; defining a lower bound on the speed of approaching vehicles for a squatting attack, detecting vehicles by ambient sensor deployment or providing every message with a distinctive signed certificate in terms of Sybil attach. In another approach,

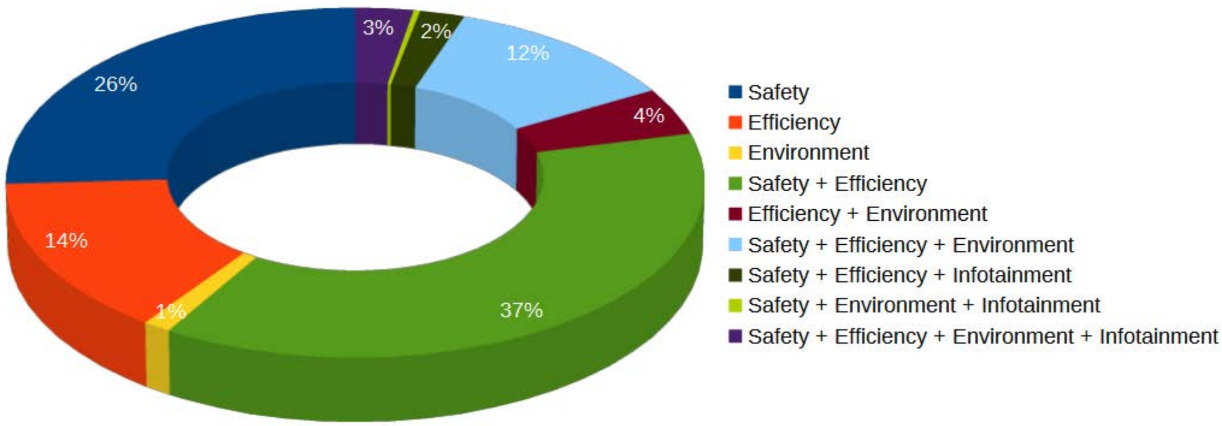

FIGURE 4. Distribution of intersection management goals.

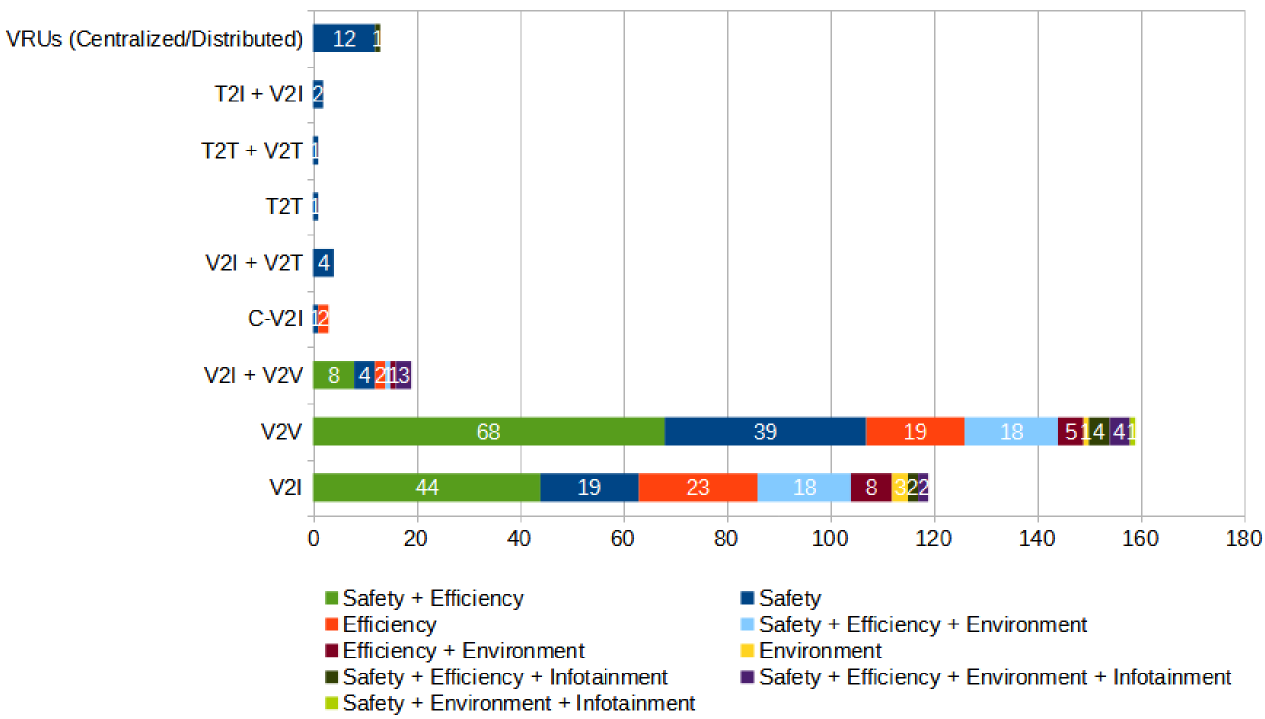

FIGURE 5. Distribution of literature based on the intersection management goals and architecture.

Chen *et al.* [375] manifested a spoofing attacker effect on the intersection manager. They investigated that a malicious vehicle can trick the system and cause congestion by sending false information to the intersection manager. Table 11 lists the literature that addressed different performance challenges for IM.

VIII. SUMMARY

In summary, Fig. 4 illustrates the percentage of nine types of IM goals. Overall, the most significant goals addressed in the literature which accounted for 37 and 26 percent were safety plus efficiency along with safety respectively. In addition, the proportion of efficiency comprised 14 percent while IM approaches with safe, efficient and environmental friendly goals showed only a slight decrease to 12 percent. Five remaining goals inclusively covered 10 percent of the literature. Efficient and ecological IM approaches contained 4 percent of all publications similar to multi-objective solutions that incorporated 3 percent of entire research works. Moreover, IM methods considering safety, efficiency and infotainment aspects contributed to 2 percent of the literature. Lastly, apart from scant number of IM methods that addressed safe, ecological and infotainment goals, 1 percent of the literature focused on environmental concerns.

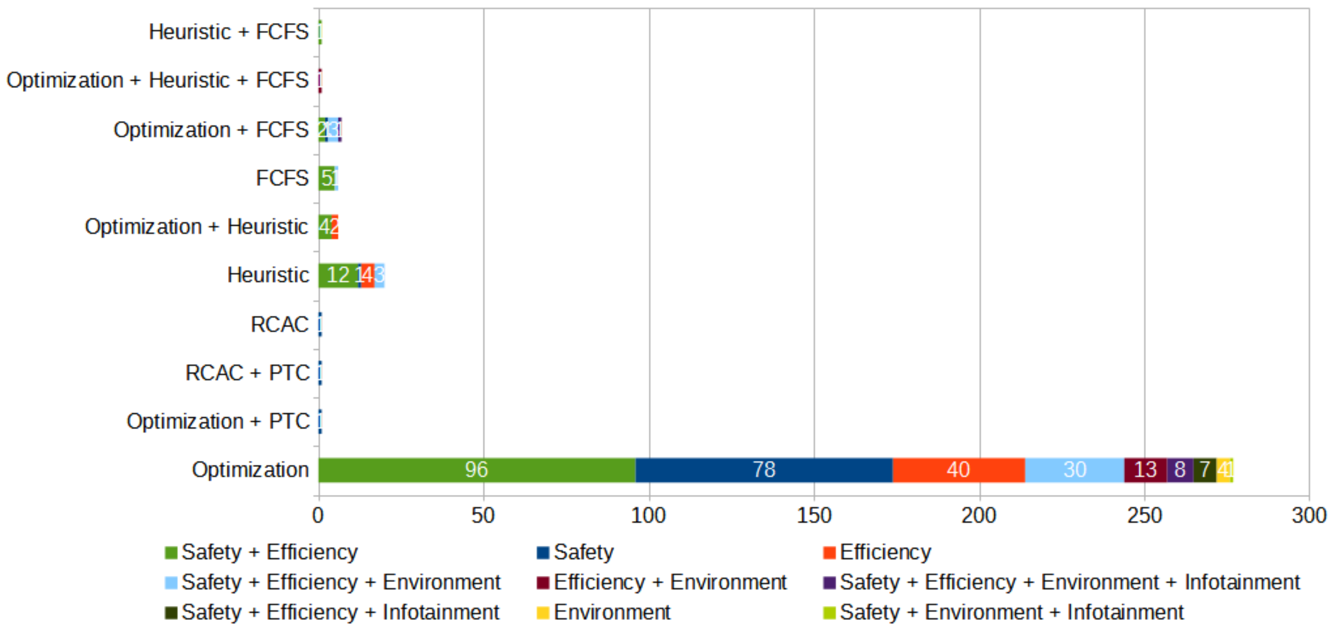

FIGURE 6. Distribution of literature based on the intersection management goals and coordination method.

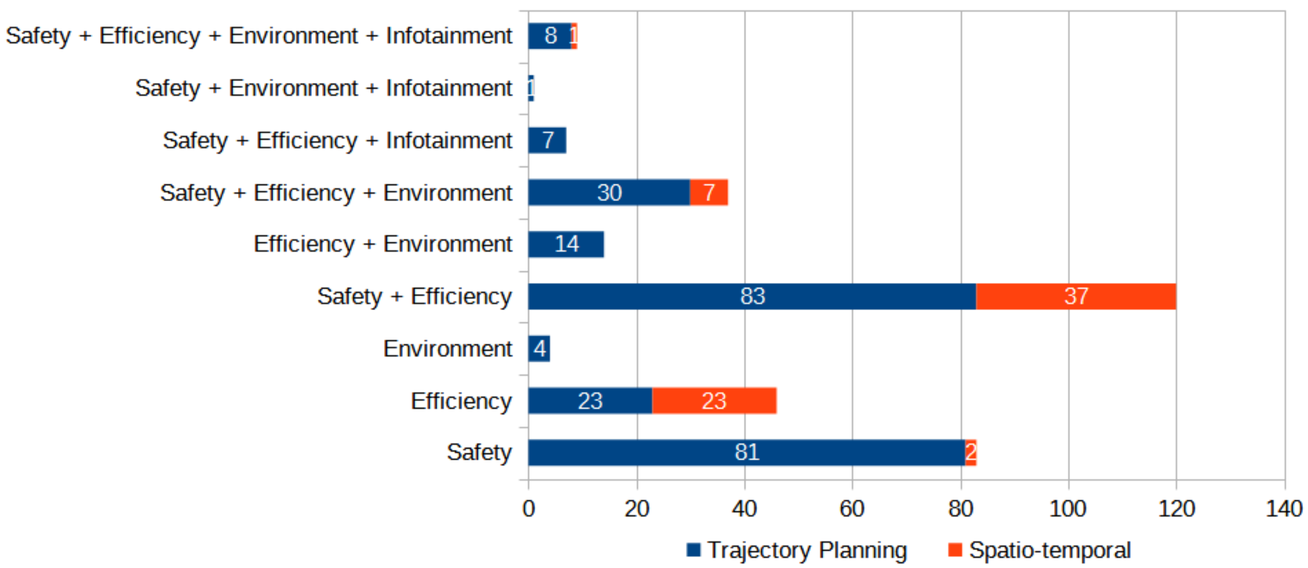

FIGURE 7. Distribution of literature based on the intersection management goals and intersection modeling.

Fig. 5 illustrates the literature that investigated the IM from an architecture perspective. Overall, V2V comprised the majority of articles including 68 papers on safety plus efficiency followed by safety with 39 papers. Safe, efficient and ecological V2V-based approaches comprised similar number of articles as efficient ones, with 18 and 19 papers respectively. The other four goals with a total of 15 papers rarely contributed to the literature. In terms of V2I-based IM methods, which is the second most prevalent architecture, 44 papers focused on safety plus efficiency while 23 articles addressed efficient V2I-based IM techniques. Besides, safe, efficient and environmental centralized methods showed similar contribution as safety-driven goals with 18 and 19 efforts respectively. Among the remaining four goals with 16 papers, efficiency and environment category held the majority papers with 8, followed by environment by 3 relevant articles. Multi-objective V2I-based schemes along with articles involved in safe, efficient plus infotainment shared identical amount of literature, each with 2 publications. Furthermore, combination of V2I and V2V-based methods with sum of 19 articles was the next favorite architecture used for IM. Next, VRUs such as bikes, motorcycles, pedestrians, scooters, with various forms of centralized and decentralized architectures mostly dealt with safety issues, while one out of

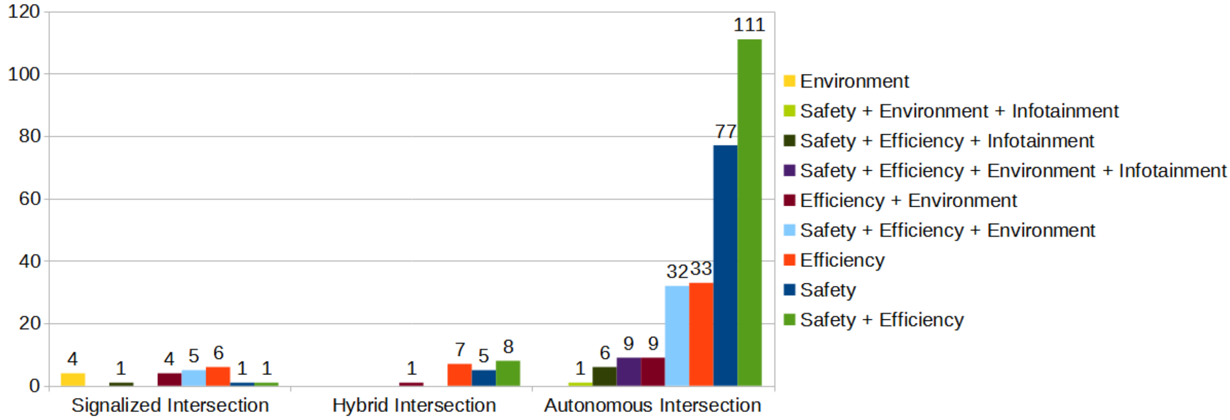

FIGURE 8. Distribution of literature based on the intersection management goals and intersection types.

13 reviewed papers examined safety, efficiency and infotainment goals at once. Furthermore, researchers scarcely used other types of architectures in their works.

With regard to the coordination methods, as it is shown in Fig. 6, optimization-based policies with 277 articles was by far the most commonly used method. Here, 96 papers addressed safety plus efficiency while 78 and 40 papers were interested to conduct their research on safety as well as efficiency respectively. Moreover, 30 out of 63 remaining articles concerned safety, efficiency and environment. Besides, 13 researchers explored optimal efficient and ecological IM whereas only 8 works were dedicated to multi-objective optimization-based IM strategies. Further, 7 researchers took advantage of optimization methods to provide a safe and efficient IM considering infotainment aspects. All the 4 environmental-friendly approaches benefited from optimization algorithms for traffic management at the intersections. In addition, heuristic-based approaches incorporated 20 papers while other mechanisms did not have noticeable contribution to the literature.

In terms of intersection modelling, as it is illustrated in Fig. 7, most of the publications were keen to use TP instead of ST technique. There were only two exceptions; one was efficiency where TP and ST intersection modellings revealed analogous participation of the literature, each with 23 papers. The second one was demonstrated in safe and efficient IM frameworks where 37 out of 120 corresponding efforts exploited ST.

The last figure exhibits the distribution of IM goals with respect to three different intersection types. Comparably, as shown in Fig. 8, ample amounts of efforts have been discussed for AIM rather than hybrid or signalized IM. Among all works that tackled IM for heterogeneous CVs, signalized intersections with 22 and semi-autonomous intersections with 21 articles held marginal amount of studied articles in this survey.

IX. CONCLUSION

In near future, cooperative traffic coordination methods using wireless vehicular communications promise to raise the performance of the IM. In this paper, we presented a comprehensive survey on current solutions for the IM under connected vehicles environment. Heterogeneous classes of vehicles such as trams/trains, VRUs, and other types of vehicles were discussed in our research. We studied signalized, hybrid and autonomous intersections with respect to diverse criteria including various intersection modeling, three substantial scheduling policies, different architectures and four major goals that they serve based on the application scenario. We emphasized on the autonomous intersections and investigated the relevant proposals in details in terms of safety, efficiency, environment and infotainment. Further, we explored IM attempts for VRUs as one of the most important road users with the focus on wheeled and motorized vehicles. Besides, we described numerous parameters that influence the IM performance from the robustness and resiliency points of view. Finally, multiple analyses were conducted to compare and visualize the results.

To the authors knowledge, this paper is the first one that systematically addressed the cooperative IM from different aspects such as heterogeneous vehicles, diverse intersection management goals and also variations of the intersections. We reviewed most of the published papers in well reputed libraries. The initial research discovered more than 1200 papers, which we eventually narrowed down to around 379 papers by eliminating trivial candidates. Compared to the existing surveys, we markedly considered more relevant and recent articles and endeavoured to present a comprehensive reference in the area of IM. In our study, we observed that most of the researchers tend to apply optimization-based scheduling methods rather than FCFS and heuristic coordination mechanisms such that around 277 papers generally benefited from this method. Further, compared to other methodologies, V2V-based architecture seemed to be more widespread as the corresponding literature demonstrated superiority over V2I-based methods with 159 articles compared to 119. With regard to the intersection modeling, TP was more common than ST reservation mechanism in all mentioned goals where this modelling method was rarely favored for IM systems except for safe and efficient IM ones in addition to safe proposed IM solutions that more extensively utilized such a method in their works. Furthermore, the evaluation results indicated that majority of researchers opted for a combination of safety and efficiency as their goals towards the management of the intersections. Safety, efficiency and a mixture of the aforementioned goals with environment were ranked subsequently. Last but not least, due to our research, most of the researchers were highly inclined to adopt AIM as apposed to signalized or hybrid intersections.

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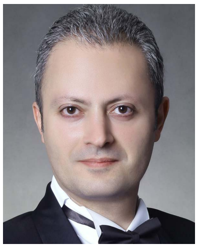

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