Cooperative Intersection Management: A Survey

Lei Chen, *Member, IEEE*, and Cristofer Englund

***Abstract*—Intersection management is one of the most challenging problems within the transport system. Traffic light-based methods have been efficient but are not able to deal with the growing mobility and social challenges. On the other hand, the advancements of automation and communications have enabled cooperative intersection management, where road users, infrastructure, and traffic control centers are able to communicate and coordinate the traffic safely and efficiently. Major techniques and solutions for cooperative intersections are surveyed in this paper for both signalized and nonsignalized intersections, whereas focuses are put on the latter. Cooperative methods, including time slots and space reservation, trajectory planning, and virtual traffic lights, are discussed in detail. Vehicle collision warning and avoidance methods are discussed to deal with uncertainties. Concerning vulnerable road users, pedestrian collision avoidance methods are discussed. In addition, an introduction to major projects related to cooperative intersection management is presented. A further discussion of the presented works is given with highlights of future research topics. This paper serves as a comprehensive survey of the field, aiming at stimulating new methods and accelerating the advancement of automated and cooperative intersections.**

***Index Terms*—Cooperative intelligent traffic systems, C-ITS, cooperative intersection management, VANET, V2V, V2I, V2P, V2X, mathematical optimization, multi-agent system, trajectory planning, motion planning, collision avoidance.**

I. Introduction

INTERSECTION management is one of the most challenging problems within the transport system for keeping traffic safety and smoothing traffic flow. Although intersections take a relatively small part of the entire road system, it accounts for a significant part of traffic accidents. According to the EU community road accident database CARE, intersection related fatalities accounts for more than 20% in the EU during the last decade (2001–2010) [1]. Similar ratio is shown in the United States where 40% of the crashes and 21.5% of the traffic fatalities are intersection related [2]. Intersections are bottlenecks of traffic flow. The introduction of traffic lights has helped to improve the traffic condition at intersections, and systems such as the Sydney Coordinated Adaptive Traffic (SCAT) system [3], SCOOT [4], as well as RHODES [5] have tried to improve the efficiency by adapting the traffic signals based on traffic estimation. Even though, due to the fact that majority of traffic lights are not dynamically adapted to real time traffic, the effects of traffic lights are far from explored. Occasionally, traffic lights with improper signal setting may be the causes of congestion. Meanwhile, traffic safety and efficiency are closely correlated. While some literatures suggest that congestion level has little impact on accidents [6], [7] on motorways, others show accident frequency increases with congestion level for both motorways and intersections [8]–[10]. For intersections with low congestion level, possibilities of severe crashes with casualties are higher because of head-on crashes and involvement of vulnerable road users (VRUs). While for high congestion level, similar to other traffic situations, accidents are usually less serious, e.g., mostly involving property damages, but frequency of accidents are higher as drivers get easily distracted. Therefore, traffic safety and efficiency need to be jointly considered.

Recent advancements of information and communication technologies (ICT) have enabled new methods, such as the prevalence of intelligent transport systems (ITS) for intersection management. Vehicles nowadays are equipped with advanced sensors that provide much more detailed environmental information, enabling richer perception of local surroundings. Such information is then shared among vehicles through vehicular ad hoc networks (VANETs), where vehicles communicate with each other through vehicle-to-vehicle communication (V2V) and with intersection infrastructure through vehicle-to-infrastructure communication (V2I) (V2V and V2I are together referred to as V2X). Vulnerable road users (VRUs) such as pedestrians are also considered through vehicle-to-pedestrian (V2P) communications. This enables global environmental perception for vehicles on other road users both within and beyond the line of sight. Furthermore, the real-time information exchange enables connection and cooperation between road users, infrastructure and control centers, forming cooperative ITS (C-ITS).

To support the development of C-ITS, the Institute of Electrical and Electronics Engineers (IEEE) published Wireless Access for Vehicle Environments (WAVE) specification through e.g., IEEE 1609 standards [11]. The standards include the usage of IEEE 802.11p based Dedicated Short Range Communications (DSRC) and define related architectures and functionalities. The Society of Automotive Engineers (SAE) specified messages and data elements to support DSRC based ITS applications in the standards SAE J2735 [12], J3067 [13], J2945 [14] and its extensions such as J2945/1 [15]. In 2014, a basic set of standards on C-ITS was confirmed by the EU standardization organizations. The concept of ITS-Station was defined and a communication architecture, within which the EU DSRC specification, i.e., ITS-G5, together with

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L. Chen is with Viktoria Swedish ICT, 417 56 Gothenburg, Sweden (e-mail: lei.chen@viktoria.se).

C. Englund is with Viktoria Swedish ICT, 417 56 Gothenburg, Sweden. He is also with the Department of Intelligent Systems, School of Information Technology, Halmstad University, 301 18 Halmstad, Sweden, and the SAFER Vehicle and Traffic Safety Centre, Chalmers University of Technology, 402 78 Gothenburg, Sweden (e-mail: cristofer.englund@viktoria.se).

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networking and transport protocol, newly introduced facility services, security mechanism, and a set of ITS applications were specified [16]. Applications such as intersection collision warning and cooperative intersection management have been considered. Those above standards focus mainly on 802.11p based communications. While in the cellular communication industry, the 3rd Generation Partnership Project (3GPP) also starts works on Long Term Evolution (LTE) networks for V2X [17], [18]. Besides, the International Standardization Organization (ISO) has also published the Communications Access for Land Mobiles (CALM) specification through e.g., ISO 21217 standards [19], that allows different radio technologies access to the ITS-Stations. Meanwhile, the deployment of C-ITS also gradually takes shape with numerous research and demonstration projects, especially the on-going Ann Arbor connected vehicle test environment in the United States, and the cross-border C-ITS corridor connecting Rotterdam, Frankfurt and Vienna in the EU.

The standardization, research and demonstration effort on C-ITS, together with the advancements of vehicle control technologies, intersection safety and efficiency can be improved significantly. Problems of the hidden vehicles, e.g., vehicles are blocked by buildings or trees thus are beyond the line-of-sight of other drivers, will be solved and intersection passing will be jointly optimized through negotiation and cooperation between road users and infrastructure, leading to a fully cooperative intersection management (CIM) that contributes to both traffic safety and efficiency.

Intersections are of two main categories, i.e., signalized and non-signalized. Signalized intersections have traffic lights, where traffic passes an intersection according to light signals. While non-signalized intersections typically have yield or stop signs or in some cases, no signs at all. In the case of signalized intersection, CIM allows vehicles to communicate with infrastructure for traffic perception, intersection passing negotiation, in-vehicle signage, etc. Accurate traffic perception of infrastructure enables more intelligent traffic signal phase setting, while negotiation allows vehicles to take an active role for intersection management and thus a flexible and cooperative intersection control. In the case of non-signalized intersection, CIM helps the drivers with a detailed and global view of intersection environments for decision-making. In case of autonomous vehicles, CIM allows vehicles to communicate with each other and negotiate intersection passing, and drive through without human intervention.

This paper is motivated by the challenge of intersection management and also by the intensive research effort towards future cooperative and automated intersections. A detailed review of cooperative intersection management systems enabled by ITS, together with a brief discussion on the main methodologies and techniques, as well as a summary of worldwide projects are presented and discussed. In Section II, major intersection modeling methods are presented. A brief introduction of major CIM methods and their common assumptions are given. In Section III, a short discussion on signalized intersection management is presented. In Section IV, a detailed discussion on non-signalized intersection is presented. Section IV covers majority and up-to-date works on CIM enabled by vehicle communications, expanding from earlier studies to the state-of-art ones. Major mechanisms and techniques are discussed in detail. Following the discussion, a summary of projects on CIM is given in Section V. In Section VI, a further discussion on the presented works is given with highlights on future research topics. Section VII concludes the paper.

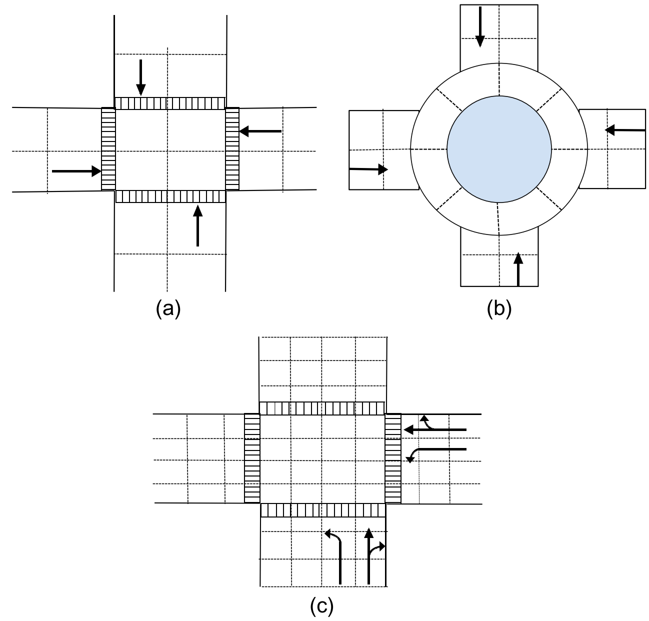

Fig. 1. Illustration of intersection discretization. Intersections are discretized into a grid of tiles (cells). a) a four-way intersection with single straight traffic from each direction. The intersection is discretized into 20 tiles. b) a four-way intersection with straight, left-turn and right-turn traffic. The discretization is in more detail with 64 tiles. c) A roundabout discretized into 24 tiles.

II. Intersection Modeling and Traffic Coordination

An intersection is a shared resource that a limited number of vehicles want to utilize at the same time, thus intersection occupation needs to be scheduled and coordinated. Based on the surveyed works and to facilitate the future discussion, major intersection modeling methods, traffic coordination methods, as well as common assumptions are presented.

A. Intersection Modeling

1) Space and Time Discretization: Discretization has been widely used for solving resource allocation and scheduling problems. It transforms a continuous problem into its discrete counterpart so that methods such as scheduling, discrete optimization can be applied. In the case of intersection passing, the problem can be considered as a discretized resource allocation and optimization problem, where time slots and geographical space are discretized and allocated to passing vehicles with objectives on maximizing certain utilities, e.g., traffic efficiency.

Depending on the types of intersection, space discretization details can be different, as shown in Fig. 1. In general, higher granularity, e.g., smaller tiles, helps to model the intersection in more detail, but it introduces higher complexities for algorithm design.

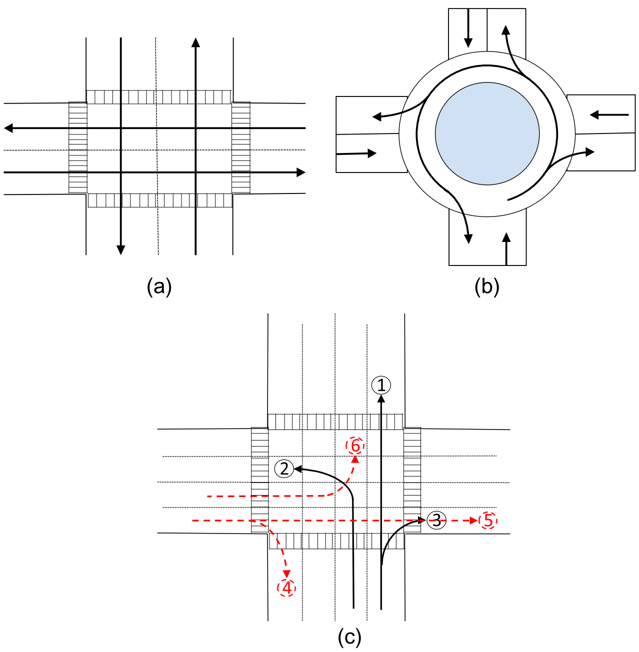

Fig. 2. Trajectory illustration. a) a four-way intersection with no turns allowed, each entrance is associated with one trajectory, i.e., a straight travel route. b) a four-way multi-lane intersection, each entrance is associated with three trajectories, i.e., straight, left-turn and right-turn. c) a typical roundabout, where each entrance is associated with four trajectories, i.e., right-turn, straight, left-turn and U-turn.

2) Trajectory Modeling: An intersection is a well-regulated zone where vehicles generally follow certain patterns during passing, e.g., travel routes, regardless of signal existence. Illustrated in Fig. 2, depending on the rules of intersection passing, the trajectories for vehicles from different directions with different intentions follows "pre-defined" routes. Assuming that a travel trajectory is followed, it is easy to identify trajectories that are in conflict with (or cross) each other or not. Non-conflict trajectories can form a so-called safe pattern, within which vehicles are able to pass the intersection safely. Shown in Fig. 2(b), trajectory sets $\{1, 2\}$, $\{2, 3\}$, $\{2, 4\}$, etc., form safe patterns, while $\{2, 5\}$, $\{2, 6\}$, etc., do not.

Trajectory planning has been widely used for managing and coordinating air traffic, such as in [20]–[22], and for vehicle collision avoidance, such as in [23], as well as robotic motion planning [24]. The aim is to plan trajectories for different moving objects in a conflict-free fashion. Typically, in a more abstracted way, trajectory planning can be formulated as travel route planning to minimize trajectory overlap based on the number of vehicles and their intentions. If combined with the vehicle control parameters, the problem can also be modeled in more detail such as optimization of vehicle control parameters, e.g., velocities, acceleration/deceleration, to ensure the safety, and to maximize objectives such as efficiency.

3) Collision Region Modeling: Assuming that vehicles within an intersection follow travel routes as planned, the potential collision regions can be predicted by combining the above discussed space discretization and trajectory modeling. Therefore, during the resource reservation, only the potential collision regions need to be considered. This helps to reduce the complexity of the time slots and space reservation problem.

It is worth mentioning that the presentation of the above modeling methods is not for differentiation, but rather to give an illustration on how CIM is approached by majority of works. There are no strict boundaries between them. As can be interpreted, collision region based modeling is a sub-set of the one on time slots and space discretization, while a trajectory can be modeled as a number of consecutive tiles. It is also noticed that all above illustrations are mainly for clarifying the modeling concept. For modeling a realistic intersection, local traffic regulations need to be followed.

B. Traffic Coordination Methodologies

Generally speaking, depending on the existence of a central control unit, CIM can be classified as being centralized and distributed. Cross-disciplinary techniques are applied for approaching the CIM problem.

Centralized CIM relies on a coordination unit that collects information and gives instructions to vehicles on when and how to pass through the intersection. The coordination unit is usually an intersection manager, a traffic light, etc. Based on information from road infrastructure and received from wireless communications, the coordination unit makes decisions centrally.

Distributed CIM involves no central units. Vehicles communicate with each other and form a VANET. Decisions are made locally by each of the vehicles based on the observation of the environment through the VANET. Communications also allow vehicles to negotiate with each other and with road infrastructure for most efficient intersection passing. In some cases, though no fixed coordination units are present, a temporary unit e.g., a vehicle leader selected by negotiations among vehicles coordinates the intersection traffic temporarily. In this context, the system can be considered as hybrid since both distributed and centralized processes are involved.

Besides coordination architecture, cross-disciplinary methods such as mathematical optimization, multi-agent systems (MAS) are widely applied for traffic coordination at intersection. Mathematical optimization, such as linear programming (LP), integer linear programming (ILP), dynamic programming, meta-heuristics, aims at decision factors to optimize objectives under certain constraints. In the case of time slots and space allocation, decision variables are space tile and time slot allocation for each vehicle. While in the case of trajectory planning, they are intersection passing sequences. With the development of vehicle control technologies, decision variables can be in much more detail. Optimal vehicle maneuvers such as braking, throttle, acceleration and deceleration, can also be considered as variables. The sets of constraints for CIM may include safety requirements such as safe headway, speed limits; vehicle control limitations such as acceleration and deceleration limits, maneuvering capabilities. And objectives for CIM can be defined such as maximizing traffic flow or minimizing intersection passing time.

Agent based methods are also widely applied, especially for distributed CIM. An agent is an computational unit with high degree of autonomy that acts automatically to achieve certain goals under a certain environment [25]–[27]. Multi-agent

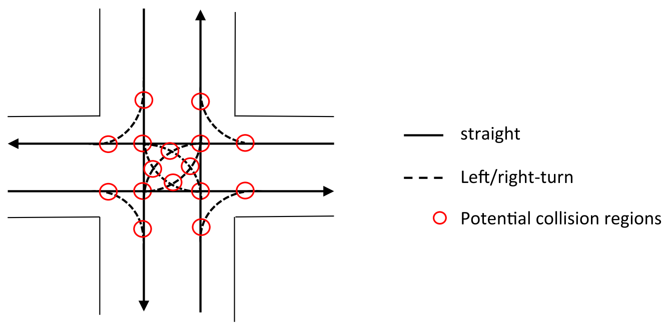

Fig. 3. Illustration of collision regions. Intersections are modeled by combining the space discretization and trajectory modeling, where only the collision regions need to be considered. Instead of discretizing the whole intersection, there are in total 16 collision regions that need to be reserved and allocated.

systems (MAS) are systems with more than one agent, where agents interact and coordinate their behaviors for achieving common goals. The domain of transportation suits the agent methods well as transport system is highly dynamic and all related players e.g., road users and infrastructure must coordinate with each other, either actively such as by negotiating or passively by simply following rules. An agent in such a system can reside in a single player such as a vehicle or a traffic light that has a certain level of autonomy. It can also reside in a system such as an intelligent traffic scheduler at the road control center. On the one hand, agents collect information and make decision themselves, e.g., how to pass through the intersection safely and efficiently. On the other hand, agents must communicate and interact with other agents, e.g., a vehicle must follow the traffic lights and coordinate with other vehicles for intersection passing.

C. Assumptions

Intersection traffic coordination involves road users, e.g., vehicles, vulnerable road users (VRUs), and infrastructure. Majority works on CIM focus on vehicle coordination and are from a high level with many hypotheses. To facilitate the discussion, common assumptions are discussed below.

- Intersection geometry: As illustrated in Fig. 1, Fig. 2, and Fig. 3, intersection is discretized and vehicles are assumed to follow exactly passing rules such as travel routes.
- Communication devices: It is assumed that both vehicles and intersections are equipped with communication devices that are used for information exchange.
- Communication performance: It is assumed that communications between vehicles and infrastructure are ideal, e.g., no packet loss, negligible latency.
- Vehicle behaviors: It is assumed that vehicles are able to follow instructions such as the driving plan from the intersection controller or mutually agreed by vehicles. No overtaking, reverse or lane-changing are considered in CIM.
- Vehicle status and dynamics: Vehicles are assumed to be highly automated. They are usually assumed with same settings such as length, width and dynamics such as velocity, acceleration, and deceleration.
- Uncertainties: Unless works are specifically for dealing uncertainties such as works presented in Section IV-D, control and human uncertainties are not considered.
- VRU involvement: In non-signalized CIM, VRUs are seldom considered during the coordination process. As presented in Section IV-E, works on VRUs focus on detection and collision avoidance.

It is noticed that the above assumptions are commonly applied by many of the CIM methods, while detailed hypotheses in each work vary. Being aware of this helps to understand the methods and evaluate the practicalness.

III. Signalized Intersection

The introduction of traffic light has proven to help improve the traffic flow and intersection safety. Significant works have been done to improve the traffic light control algorithms. Major research areas including mathematical model [28]–[33], fuzzy logic [34]–[36], rolling horizon approach [37], Markovian-based control [38], neural networks-based control [39], Petri Net-based control [40]–[42], queue theory [43], as well as agent-based learning methods [44]–[47]. More recently, studies on a network of signalized intersections based on max pressure and back pressure were presented in e.g., [48]–[50]. Those methods focus on providing algorithms that enable smart traffic lights. Knowledge on the traffic queues at the intersection, as well as turn probabilities and saturation flow rates are necessary inputs.

Earlier in 1992, Bell stated in [51] the issues with intersection control and mentioned that signal control alone could not solve the growing problem of urban congestion. Nowadays, the ever-increasing traffic has made intersections more and more bottlenecks in the traffic system. Conventionally, traffic queue detection is through e.g., loop detectors, surveillance devices such as in SCAT, SCOOT, and RHODES. With the prevalence of ITS, vehicular communications were considered for more accurate traffic queue estimation. In [52], the authors presented an agent-based traffic controller that was able to adapt to the real-time traffic situation. In [53] optimization algorithms were developed for minimizing the average traffic queue length by giving green light to the lanes with the largest traffic queue. In those works, traffic information was collected by communications between vehicles and infrastructure. It has been shown that wireless communication has clear advantages over traditional loop detectors as the detection area is significantly larger, and the transmitted information is in more detail.

Besides data collections, efficient V2X communication allows vehicles to take a more active role in intersection passing such as negotiating with infrastructure for green lights. In [54], the authors proposed vehicle-infrastructure mechanism, where a group of vehicles negotiated with the intersection controller for green light. Traffic queue estimation was done by vehicles themselves. While waiting for the green light, vehicles exchanged information via V2V and grouped themselves based on their intended travel directions. Each group selected a group leader that took charge of traffic queue estimation of its group by communicating with newly arriving vehicles. Traffic queue lengths of all groups were then exchanged with the intersection controller for negotiating signal phases of green light. When the green light period came, e.g., traffic on the cross road was emptied, the group leader stopped accepting new vehicles from joining and the queue length was used as a basis for the intersection controller to allocate green light time. By constant information exchange and accurate estimation of the queue, vehicles actively affected the traffic scheduling at the intersection and helped to improve the traffic flow.

Signalized intersection management includes also VRUs. Provided that pedestrians follow the traffic lights, the problem can be considered as signal phase optimization including VRU traffic such as in [55], [56]. The aims, among others, are to integrate pedestrian traffic into signal phase optimization for smarter traffic lights to improve pedestrian safety and to balance traffic between vehicles and VRUs, etc. Pedestrian flow observation can be based on press buttons, camera and sensor detection [57]. With communications, VRUs may take an active role for intersection passing. In [58], [59], a two-way communication pedestrian unit was developed. It was used for both requesting green light and providing feedback to pedestrians.

IV. Non-Signalized Intersection

Non-signalized intersections have no traffic lights or any other controlling facilities. Traditionally, drivers need to interact with each other through eye-contact for safe passing. With vehicle communications, driver interactions are easier and more accurate. Detailed vehicle information and driving intentions of passing vehicles especially those that are not within the line of sight, e.g., blocked by buildings or trees, can be shared among drivers for better decisions. In [60], an early concept based on vehicular networks for intersection collision warning was proposed and tested. Critical factors such as communication range, latency, vehicle speed, driver response time, location accuracy, were identified. Similar method was used in [61], where the authors studied communication scenarios for the cases of V2V-only and V2X. Platoon concept, where vehicles drive closely as road trains, was used in [62] for CIM. Vehicles approaching an intersection firstly communicated with each other and formulated a virtual platoon and then platoon controllers coordinated the intersection passing. A map-free intersection collision warning system called Forwards was presented in [63], where DSRC was used for information exchange among vehicles and a triple Kalman filter was used for estimating vehicles states for collision avoidance. Cooperative speed harmonization for intersection traffic merge, where V2I communications were used for in-advance speed advisory, was presented in [64]. The method introduced so called speed waves, where vehicles on the same road were firstly organized into groups with an advised speed and then groups from different roads took turns arriving at the intersection, thus avoiding congestion and improving traffic flow.

Those above-mentioned works give a quick look into the application of communications for CIM. While in the following part, major methods for non-signalized intersection including cooperative resource reservation, trajectory planning, virtual traffic lights, as well as dealing with critical situations, e.g., vehicle and pedestrian collision avoidance, are discussed in detail.

A. *Cooperative Resource Reservation*

As discussed in Fig. 1, intersection can be modeled with tiles. In cooperative resource reservation, vehicles need to reserve the tiles on their planned route for certain time slots. Once the tiles and time slots are granted, vehicles can pass the intersection according to the reservation. By doing this, it can be guaranteed that space tiles will be allocated in a non-conflict way, i.e., one tile will not be allocated to more than one vehicle at the same time slot. Besides, the allocation can also consider the traffic situation and employ other optimization objectives to improve intersection performance such as to maximize the traffic flow or to minimize the energy consumption. Depending on the involvement of infrastructure, cooperative resource reservation can be classified as centralized, where intersection infrastructure is responsible for allocating time slots and space tiles; and distributed, where vehicle themselves negotiate the resource reservation. Agent-based methods are used for cooperative resource reservation, where agents that reside on vehicles and infrastructure perform resource reservation and grant.

1) Centralized Cooperative Resource Reservation: For centralized cooperative resource reservation, two types of agents are introduced, i.e., vehicle agent (VA) residing at a vehicle and intersection reservation agent (RA) residing at infrastructure. A vehicle requests reservation of tiles through its VA when approaching an intersection by sending related information including arriving time, velocity, driving intentions, and vehicle dynamics, etc. The RA simulates passing schedules e.g., tiles and time slots needed for passing the intersection. During the simulation, the RA checks if the requested tiles have already been reserved by another vehicle at corresponding time slots for conflict detection. If no conflicts are found, reservation will be granted. Otherwise, the reservation request will be rejected and the vehicle needs to send a new one. Once a tile is granted, the vehicle must be able to determine whether it can follow the reservation and drive through. If not, the vehicle should cancel the reservation and request a new one.

In [65], cooperative resource reservation was studied with a simple intersection as the one in Fig. 1(a). Besides common assumptions, it was assumed that once reservation was granted, vehicle kept the same speed until intersection was passed. Simulation was done with comparison to two other intersection management methods, overpass and traffic light. It was shown that performance of the cooperative resource reservation was a good approximation to that of the overpass method and was two to three times better than the traffic light method. Following this preliminary study, the authors proposed improvement methods in [66], together with a communication protocol. Besides resource reservation, the protocol was able to model different intersection control policies such as overpass, stop sign, and traffic lights. To simulate the overpass, the RA accepted all requests and confirmed as they were. For modeling the stop sign, confirmation was given only to vehicles that stopped at the intersection, while any other vehicles were rejected and had to stop. In the case of modeling traffic lights, RA compared the

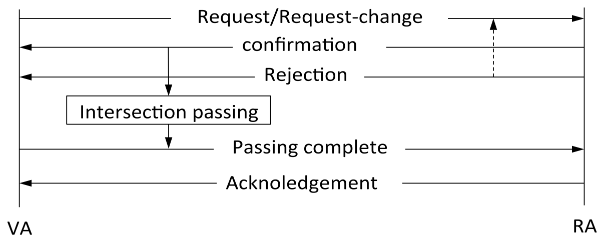

Fig. 4. Interactions between vehicle agent (VA) and reservation agent (RA).

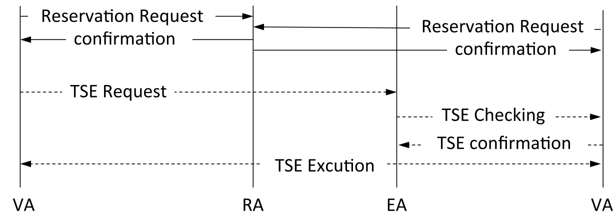

Fig. 5. Resource reservation and time slot exchange.

traffic light status with the reservation requests and only allocated tiles that were on a travel route with the green light status. The study considered more practical scenarios that allowed left-turn and right-turn traffic. Instead of assuming that vehicles kept the same velocity, the work allowed the vehicles to accelerate within the intersection. Detailed interactions between the VA and the RA were described and implemented as shown in Fig. 4.

Following the above study, further improvements were done in [67] by 1) incorporating the human-drivers into the system and 2) considering high-priority vehicles such as ambulances, and police cars. To incorporate human in the driving loop and utilize the current infrastructure as much as possible, the authors proposed traffic light models and integrated them into the resource reservation system. An adjustable light policy First-Come-First-Serve light (FCFS-light) was implemented. The policy emulated an intersection managed by both traffic light and the cooperative resource reservation mechanism. When allocating space tiles, the RA checked statuses of both tile occupation and traffic light. Only tiles that were on a route with green light could be reserved and allocated. To facilitate emergency vehicles, a FCFS-EMERG policy was proposed. If the RA detected an emergency vehicle in a lane, FCFS-EMERG set green light to that lane and red lights to all other lanes, thus only reservation requests from vehicles at the same lane with the emergency vehicle were granted.

In [68], the author proposed timed Petri Net-based control policies for CIM to deal with resource reservation. Vehicle requested the right-of-way (time space resources) when approaching the intersection. Based on timed Petri Net, the intersection controller generated passing sequences with an objective to minimize the instant queue length. The right-of-way information was then sent to vehicles and shown by on-board systems. Both simulation and demonstration works were done based on the method.

Other works on cooperative resource reservation can be found in e.g., [69]–[71]. Readers are referred to [72] for a comprehensive discussion over the topic.

Simulation and prototyping works have been conducted on cooperative resource reservation. In [73], a mixed reality testing system was developed for realistic demonstration. The system involved a real vehicle at a realistic intersection, and a simulation platform representing the intersection. A number of virtual vehicles were created for passing the intersection, where one of the virtual vehicles served as a proxy vehicle corresponding to the dynamics of the real vehicle, thus connecting the virtual and physical world. Despite the identification of large variations of errors e.g., GPS, noisy sensor data, communication instabilities, the reservation-based CIM was shown to outperform traditional system such as traffic signals and stop signs. In [74], mini vehicles were used for demonstrating the cooperative resource reservation scheme, where V2X communications was implemented with 802.11g Wi-Fi.

A traffic simulator, ISR-TrafSim,[1] was developed for testing the reservation-based CIM in [75]. Two types of intersections, roundabouts and crossroads intersections, were considered and different interaction procedures were applied. In the case of roundabouts, vehicles sent information to the intersection agent to notify driving intentions. While in the case of crossroads, the intersection agent itself detected driving intentions of vehicles. In both cases, the intersection agent was responsible for time slots and space tiles allocation. The simulator was later extended in [76] for legacy scenarios with low percentage of cooperative vehicles.

2) Centralized Cooperative Resource Reservation With Economic Incentive: In principle, centralized cooperative resource reservation follows FCFS as vehicles firstly arrive at the intersection send reservation requests first. Since intersection resources are shared, from an economical perspective, road users may value intersection occupation differently. For example, a person who rushes to an airport may value the intersection passing time more than daily commuters, thus they may want to pay for priorities for passing the intersection. In [77], [78], the authors proposed a time slot exchange (TSE) method that enabled vehicles to exchange reservations with a valuation-aware fashion. Simply speaking, it allowed vehicles to trade reserved resources for passing the intersection. By doing this, drivers had incentives to exchange their granted reservations so that an overall satisfaction could be achieved without compromising the traffic efficiency. To enable TSE, besides the VA and RA, a third agent i.e., the exchange agent (EA) was introduced for time slot exchange. The EA resided at infrastructure side in parallel with the RA. While the RA aimed to maximize utilities such as traffic flow, the EA aimed to accomplish as many reservation exchanges as possible.

TSE worked as a second step of the cooperative resource reservation method for vehicles having reservations already granted. Shown in Fig. 5, VAs firstly reserved time slots for space tiles. Afterwards, reservations were exchanged mutually between VAs through EA according to their valuations. Compared with the previously discussed cooperative resource reservation, it was shown that average waiting time was reduced significantly, especially for vehicles arriving on short notice with high valuations.

[1] http://www2.isr.uc.pt/~conde/isr-trafsim/

In [79], the authors proposed an auction-based CIM called initial time slot auction (ITSA). Instead of following a FCFS principle, the RA auctioned time slots and allocated them to the vehicle with the highest bid. The authors proposed two variants of ITSA, basic ITSA and ITSA with subsidies. In the basic ITSA, the intersection firstly initiated a second-price sealed-bid auction [80] for all registered vehicles entering the intersection. It then allocated the next time slot to the vehicle with the highest bid, while the vehicle needed only to pay the second highest bid according to the auction rule. For this scheme, only vehicles with their preceding vehicles having time slots allocated could bid and only one vehicle from each direction was allowed to bid. In such a case, if a vehicle had no time slot allocated, all its succeeding vehicles couldn't influence the outcome of the auction. To deal with this, ITSA with subsidies was proposed, where vehicles were allowed to subsidize their predecessors so that they could bid in groups instead of individually. In this case, the group with the highest bid was allocated time slots together. Simulation studies showed that ITSA achieved significantly lower average waiting time in comparison to the original cooperative resource reservation method. Furthermore, ITSA with subsidies performed even better regarding average weighted waiting time than that of ITSA.

3) Distributed Cooperative Resource Reservation: Cooperative resource reservation has also been considered in the form of distributed CIM where no infrastructure support is needed. Earlier in [81], [82], a distributed reservation scheme was proposed based on collision regions as shown in Fig. 3. The concept of token was introduced for resource reservation and occupation. Each of the collision regions was associated with a token and at each time only one vehicle could hold the token and thus occupying the region. The vehicle holding the token constantly broadcast the occupancy information until it left the region and released the token. Meanwhile, other vehicles continuously listened and detected the token availability for avoiding conflict. The method was proven to be deadlock-free and collision-free through Petri Net models. To be more flexible and adaptive to traffic conditions, the authors also proposed a priority based fairness token reservation mechanism, where vehicles on highly congested roads or vehicles of special types such as emergency vehicles, police vehicles may request higher priority for intersection passing.

In [83], a distributed reservation protocol was proposed. The protocol introduces two sets of messages, *claim* and *cancel* for the purpose of resource reservation and release. The *claim* messages were used to claim the occupation of tiles that formed an intersection passing trajectory. All other vehicles detected reservation statuses and avoided tiles that were already reserved. As interpreted, resource reservation and allocation were made at the vehicle side, thus no infrastructure support was needed. To facilitate the vehicle priorities, *claims* were allowed to dominate each other, e.g., if two claims were in conflict with each other, the one with a higher priority was able to dominate the one with a lower priority. Therefore, if a vehicle arrived and sent *claims* for certain tiles with a higher priority, the vehicle with a lower priority *claims* on those tiles had to release the reservation. A vehicle constantly listened to messages when approaching an intersection but only started to make reservations within a certain distance. It compared its own planned passing trajectory with all received *claims* from other vehicles. If there were no conflicts, it started broadcasting *claim* messages containing reservation information of the tiles within its planned trajectory. Unless there were *claims* with higher priorities, the vehicle reserved the tiles until it passed the intersection, and then canceled the reservations by sending out *cancel* messages. A preliminary study showed that the average delay was improved in comparison to the traffic light scheme and the four-way stop sign scheme.

Similar works can also be found in [84]–[86], where a family of distributed reservation protocol were presented for intersections and roundabouts with detailed message specifications. In [84], the authors introduced *stop* and *clear* messages for resource reservation and release. In a later work [85], the messages were modified to *enter*, *cross*, and *clear* for similar purposes. While in the former no vehicle models were considered, in the latter vehicle dynamics, e.g., acceleration, deceleration, were considered. Vehicles approaching the intersection broadcast *stop* messages for occupying tiles on its passing trajectory. Other vehicles evaluated the availability of the tiles before they started to pass the intersection. In addition, a *generic* message set was used for periodically broadcasting basic vehicle information for vehicles to keep safe distances. The message was formatted according to the Basic Safety Message (BSM) specified in SAE standard J2735 [12] for DSRC.

B. Trajectory Planning

Cooperative resource reservation methods deal with intersection resource scheduling regarding time slots and space tiles. Since a travel route at an intersection consists of a number of consecutive tiles, as modeled in Fig. 2, another major method for intersection management is trajectory planning.

1) Trajectory Planning Using Safe Pattern: As shown in Fig. 2, vehicles having their passing trajectories within a safe pattern can be scheduled simultaneously. The problem of CIM falls then to identify safe patterns based on the traffic flow and then to schedule them efficiently. In [87], [88], a cooperative scheduling algorithm was presented, where vehicles within a safe pattern were scheduled to pass an intersection simultaneously. A zone was defined before the intersection where trajectory planning was performed by negotiations between vehicles via V2V. Vehicles were labeled according to the time they entered the zone and shared their planned trajectories with each other. One of the vehicles, also referred to as a vehicle leader in other works, was responsible for the trajectory planning. The work described the scheduling problem as a spanning tree and proposed algorithms for minimizing the executing time e.g., time used by all vehicles to pass the intersection. Information exchange was done with a timely fashion and was assumed to be error-free. Clearly, the scheduling framework was hybrid as negotiation was distributed, while scheduling was done centrally at the vehicle leader. The authors used a rather simple method for leader selection, where the vehicle that firstly received all the available information was chosen as the vehicle leader. In an autonomous intersection where no centralized controllers are involved, vehicle leaders behave as temporary controllers for all the involved vehicles, thus vehicle leader selection is one of the challenging problems that needs further exploration.

In [89]–[91], centralized machine scheduling algorithms were designed for minimizing evacuation time of intersection vehicles. Based on vehicle information collected through V2I, an intersection controller calculated the scheduling strategy, and instructed vehicles about the passing sequences. Traffic flows from different lanes were grouped into families based on safe patterns. At each scheduling step, one family was chosen. For each lane, if the vehicle nearest to the intersection was within the chosen family, it would be scheduled. In [90], general four-way multi-lane intersections were studied and a dynamic programming algorithm was developed for solving the trajectory planning problem. The algorithm was polynomially bounded by the number of vehicles but was exponential in the number of lanes. Therefore, only scenarios with limited numbers of vehicles and lanes could be solved. For improving the computing efficiency and being inspired by solution algorithms for the traveling salesman problem (TSP), an ant colony algorithm was developed in [92] to approach the problem. Besides simulation, prototyping works of the algorithms were done in e.g., [93]–[95].

Similarly in [96], an intelligent ILP-based traffic controller (SI^2BTC) was designed. The scheduler firstly collected vehicle information through the VANET and generated a snapshot of the intersection. It then employed an ILP model for calculating optimal passing sequences. The objective of the ILP model was set to maximize the capacity i.e., the number of passing vehicles. Weighted cost functions were used to consider factor such as vehicle priorities or delay. The constraints were defined to guarantee safety based on safe patterns. The authors considered different scenarios based on the information availability of priorities and queue length i.e., priority-aware and non-aware, as well as queue-length-aware and non-aware. The results were compared with a fixed timing traffic light controller and showed clear benefits regarding vehicle waiting time and queue length at the intersection.

With the concept of safe pattern, only vehicles within a safe pattern can be scheduled simultaneously. This may not be the most efficient solution regarding traffic flow. In [97], the authors presented a cooperative vehicle intersection control (CVIC) system for trajectory planning irrespective whether vehicles were within a safe pattern or not. The problem was formulated to find optimal vehicle maneuvers to minimize the length of overlapping trajectories, with constraints on acceleration, deceleration, speeds, and the required headway. The optimization problem was a non-linear constraint optimization algorithm, and three different searching algorithms, i.e., active set method, interior point method, and genetic algorithm, were implemented. Those algorithms took vehicles' arriving states, e.g., speed, acceleration, and deceleration, as an initial solution and ran in parallel to solve the same optimization algorithm. The first solution achieved was used by the controller to construct passing sequences. Newly arrived vehicles were constantly included into the optimization algorithm and up-to-date passing sequences were used by vehicles for intersection passing. CVIC was simulated with a hypothetical four-way intersection with single through from each approach. The results were compared with the conventional actuated intersection control and showed that stop delay, total travel time, as well as emissions were reduced.

2) Trajectory Planning Based on Priority Graph: Robot motion planning methods were applied for coordinating vehicles to pass intersections. A common way for multiple robot motion planning is path-velocity decomposition. Paths for each of the robots are firstly identified and fixed, and then control inputs adapt the velocity for intersection passing safely and efficiently. In [98], the authors presented a mathematical framework based on path-velocity decomposition for coordinating intersection vehicles. For identifying paths, the authors adopted the notion of priority to define the relative order between vehicles for intersection passing. A priority graph was then constructed including priority relations between all involving vehicles. Based on a fixed priority graph, motion planning algorithms were proposed for optimal trajectories. The method was studied with simulation in [49] with consideration on vehicle dynamic constraints e.g., speed limits, acceleration and deceleration limits. The simulation confirmed safety effects, however, deadlocks might arise on high traffic densities. Furthermore, it was assumed that vehicles followed the control plan with no considerations on control uncertainties. In [99], the authors revisited the priority-based methods for robot motion planning. Control uncertainties were considered with the introduction of a feedback control law that was used to preserve the priorities within the fixed priority graph and avoid collisions within the intersection. Further in [100], the authors considered the existence of non-cooperative vehicles. It was assumed that legacy vehicles were able to keep safe distances from their leading vehicles. Under such assumption, traffic light was used for guiding legacy vehicles. If a legacy vehicle and an autonomous vehicle were on different paths, the legacy one was assigned with low priority and allowed to enter after the autonomous vehicle passed the collision region. On the other hand, if they were on the same path, a virtual platoon was formed where the legacy vehicle followed the autonomous vehicle to pass the intersection. Human behaviors were not considered for legacy vehicles.

3) Trajectory Planning Based on Collision Region: Collision region-based intersection modeling has also been used for trajectory planning. In [101], the authors presented a linear programming formulation for autonomous intersection control (LPAIC) that was able to obtain exact optimal solutions for scheduling vehicles at intersections. Firstly, a lane-based traffic flow model was presented with the aim to find the optimal time schedule to minimize the total travel time. To deal with conflict trajectories a number of nonlinear constraints were proposed to guarantee the single-occupancy of collision regions. The constraints were then relaxed to be a set of linear equations, and the nonlinear optimization formulation was transferred to a linear one. Similar to other studies, lane-changing was not allowed, as the constraints for lane-changing were not yet able to be linearized. The formulation was applied to three scenarios, within which a four-way four-lane isolated intersection was used. It was shown that LPAIC outperformed traffic light control based on actuated longest queue first.

In [102], a special scenario was considered, where an intersection having several travel routes crossed at a single point, e.g., single collision region. The authors formulated the intersection passing as a *maximal controlled invariant set* problem. With initial states of the vehicles as inputs, the problem aimed to determine the largest set of states in which a control sequence exists for avoiding collisions. It was claimed that the problem was NP-complete while no formal proof was provided. The authors thus proposed an approximation algorithm that had time complexity as a polynomial of a degree associated with the number of vehicles. Following this, a least restrictive supervisor was designed to make sure that the driver input wouldn't lead into collisions. Otherwise, a safe input would be suggested. Besides safety, the supervisor was also able to cooperate with other controllers for evaluating driver inputs to achieve secondary objectives such as efficiency and fuel consumption. The work assumed perfect information exchange, e.g., accurate sensor data, no communication loss. To be more practical, the authors revisited the same problem and designed similar algorithms in [103] for dealing with imperfect information of control system. A *maximal robust controlled invariant set problem* was considered. The output was the largest set of states that admitted a valid control for collision avoidance accounting for any admissible disturbance. This eventually was used for a robust controller that was able to deal with system uncertainties.

C. Virtual Traffic Light

With a high penetration of vehicle communications when most vehicles are able to exchange information, physical traffic lights can be eliminated. Instead, a virtual traffic light (VTL), that resides at each of the vehicles creates traffic light signals and coordinates the intersection passing. In [104], the authors presented the concept of VTL and verified the performance by simulation of the city of Porto with the DIVERT simulator [105]. The proposed VTL procedures at an intersection included roughly the following stages:

- VTL leader selection: When approaching an intersection, vehicles kept tracking others within their vicinity through wireless communications, and a VTL leader was chosen cooperatively. It was then responsible for creating VTL signals and temporally controlling the intersection passing. For facilitating the signal transmission, it was preferable that the VTL leader was the one that was stopping and was the nearest vehicle to the intersection.
- VTL signal construction and dissemination: Similar to an intersection agent, a VTL leader created traffic light signals according to pre-defined rules and then broadcast them to all involved vehicles.
- VTL leader handover: Once the green light phase was granted to the lane that the current VTL leader was on, a handover of VTL leader was triggered. The new leader would be e.g., the one closest to the intersection, or the one chosen by a new round of leader negotiation.

The simulation results in [104] was based on the study from a city level. The results showed very positive improvements where traffic flow was increased and vehicle emissions were reduced.

In [106], the authors addressed one of the key topics of VTL, VTL leader negotiation, with special consideration on the message losses caused by unstable communications. The problem was considered as a 1-of-n selection problem and solved via a round-based algorithm, where one single leader was selected by all the n involved processes (vehicles) through rounds of communications. Communication failure may cause massive message losses, resulting in that some vehicles failed to involve in the selection procedure, referred to as disagreements of the leader selection. The work presented methods for calculating possibilities of disagreements. In general, disagreement probabilities relied on the number of involved vehicles, the number of communication rounds and the possibility of communication failure. Two types communication failures were considered, i.e., symmetric failure where all intended receivers failed to receive a message; and asymmetry failure where only a sub-set of vehicles failed to receive a message. Based on this, the authors proposed optimistic and pessimistic decision criteria. In the optimistic decision, all vehicles with complete views (receive information from all other vehicles) assumed that all other vehicles also had complete views. While in the pessimistic decision, vehicles having complete views pessimistically considered that other vehicles didn't have complete views unless they could confirm during the communication rounds. The work focused on the optimistic decision criteria and analyzed disagreement possibilities regarding the number of vehicles and number of communication rounds.

D. Intersection Collision Avoidance

CIM methods that have been discussed above generally assume that vehicles follow decisions, e.g., resource reservation, planned trajectories or VTL signals. This assumption might not always hold due to many factors such as driver behaviors, communication instabilities or mechanical failures. Therefore, collision avoidance is critical in some situations and should be considered as an indispensable part within CIM. A number of works have been dedicated to this.

Formal methods with provable safety have been studied for CIM to guarantee collision-free intersections, where communication failure, noisy information, and mechanical failure are considered. In [107], a hybrid architecture was proposed for intelligent intersection management with provable system-wide safety. Both centralized control and distributed control were involved. For centralized control, the intersection controller was responsible for allocating time slots for each of the approaching vehicles. While for distributed control, vehicles had freedom to adjust their control inputs to make sure perpetual safety, e.g., collision avoidance both in short term and long run. To do this, each vehicle maintained an updated infinite horizon contingency plan, and distributed it among others at each sampling instant. A partial-order relation between vehicles was defined which specified for each vehicle a set of vehicles whose worst-case behaviors it should protect itself against. The work aimed at providing provably safe designs for intersection safety, however, due to the difficulties for mathematical evaluation, the performance was verified through simulation.

A similar concept has been used in [108], where an evasion plan for avoiding collisions was proposed to deal with emergency situations such as when vehicles lose control due to e.g., mechanical problems. The methods was based on cooperative resource reservation, while additional functionalities for the intersection manager were introduced for calculating back-up passing plans with consideration of a finite types of mechanical failures of each vehicle on each of the travel route at each time slot. The results were incrementally updated and stored in an evasion plan database. In case of emergency situations, e.g., vehicle failures, accidents, the intersection manager immediately stopped granting reservations and retrieved feasible trajectories for the involved vehicles. For demonstrating the efficiency, two robots were used. One of them broke down by simulated mechanical failure and the second was redirected to a safe passing plan from the evasion plan database, thus avoiding a collision.

In [109], the authors studied formal control methods for guaranteeing collision-free intersections. As modeled by the collision region in Fig. 3, if no lane-change is allowed and vehicles follow pre-defined intersection passing paths, the potential collision locations are known a priori. Whether a collision will happen depends on the states, e.g. placements, velocities, vehicle control sequences. In this work, the authors modeled potential collisions by a set of displacements of vehicles, referred to as a *bad set*. To prevent two vehicles entering the *bad set* at the same time where collision would happen, a *capture set* was proposed. The *capture set* denoted a real-timely updated set of vehicle displacements that no control could prevent vehicles entering the *bad set* under the current vehicle velocities, thus colliding. To prevent collision, once vehicles reached boundaries of the *capture set*, vehicle controllers would react through communicating and negotiating through DSRC to agree on a collision-free solution. Control commands were then issued to local actuators to perform brake or throttle operations (no steering was allowed as vehicles were assumed to follow the intersection path), thus avoiding entering the *capture set* and preventing collisions. In a following study [110], the authors revisited the problem of collision avoidance under imperfect information including model uncertainty and communication delay to deal with noisy sensor data and communication instabilities. The proposed formal method was tested with two modified LEXUS IS 250 vehicles at the Toyota Technical Center in Ann Arbor, Michigan, and an on-ramp merge scenario was used for the demonstration.

The formal method used in [109], [110] applies only to two vehicles and the notation of *bad set* and *capture set* are generated globally based on states of the two vehicles. In [111], the authors approached the same problem from a distributed point of view. Vehicles were modeled with a state-space form covering a finite number of sampling instances during which scheduling algorithms were designed to optimize the vehicle control configurations. For collision avoidance, unlike the *bad set* and *capture set* that were based on a global view, each vehicle maintained its individual sets, i.e., the so called *critical set* and *attraction set*. For each vehicle, a *critical set* consisted of all displacements that would potentially lead the vehicle into collisions. If any two vehicles both entered their critical sets at the same time, a collision would occur. Notice that the *bad set* in [110] could be easily constructed by combining *critical sets* of all involving vehicles. On the other hand, an *attraction set* consisted of all configurations that would lead the vehicle unavoidably into its *critical set* in one scheduling step. With those notion, the authors first presented an open-loop centralized optimization algorithm. The algorithm aimed to find optimal vehicle control configurations for each of the sampling instance that could guarantee the safety and maximize a chosen objective such as traffic flow or energy efficiency. In view of the problem complexity, the authors converted the centralized optimization problem into a number of distributed optimization problems associated with each of the vehicles and solved sequentially. Computations were thus distributed to vehicles and each vehicle needed to solve only a local optimization problem. As a computation sequence was involved, a distance based priority was defined, i.e., the vehicle closest to its *attraction set* had the highest priority and should execute the local optimization first. In a following work [112], the authors extended the method with a receding horizon control approach.

E. Vulnerable Road Users

CIM methods have focused on vehicle traffic, while for VRUs at intersections, safety issues such as detection and warning form the majority of research and development. Traditionally, computer vision and infrastructure sensors are major methods for pedestrian detection, see e.g., [113]–[115]. They have been widely used also by industries such as Volvo, BMW, Toyota, Ford, and Nissan. One limitation of those methods is that they rely on a line-of-sight (LOS) detection. To extend the detection area, especially non-line-of-sight (NLOS) areas, methods based on communications e.g., DSRC, 3G, LTE are investigated.

In [116], the authors studied pedestrian safety methods based on cellular communications and Wi-Fi ad hoc networks, and compared their performance. Both methods were shown to be applicable for pedestrian collision avoidance while a hybrid solution was suggested. In [117], [118], a V2P system was proposed based on 3G and wireless local area network (WLAN). The system consisted of cellular phones, car navigation system and a server. Upon approaching an intersection, pedestrians and vehicles reported their statuses to the server through mobile phone and WLAN. The server estimated risks and sent feedbacks to the mobile phones. If high risks were identified, direct communications could be established between pedestrians and vehicles. In [119], communication devices based on ZigBee were developed for pedestrian detection. Pedestrians were assumed to have a transmitter sending information periodically. Four communications boxes were installed at the four corners of a vehicle that were used to locate the pedestrian by comparing the received signal strength. The system was able to detect relative statuses of pedestrians to the vehicle i.e., near, far, approaching and leaving. In [120], the authors formulated the requirements of minimum information exchange distance for V2P communications and studied a Wi-Fi communication-based application, V2ProVu, for VRU protection. In addition to pedestrian, cyclists are also considered. Volvo, POC and Ericsson is developing a cyclist warning system[2] based on Volvo's vehicle cloud. A two-way communication is established between the helmets of cyclists and the connected vehicles. In case of risks, vehicles are alerted through in-vehicle display while cyclists are warned through helmet-amounted light.

DSRC-based V2P safety applications are presented. In [121], based on WAVE and SAE J2735 standards, the authors proposed an intersection pedestrian collision avoidance system, together with messages targeting pedestrians. In [122], the author presented a V2P safety system that were jointly developed by Honda and Qualcomm. The author implemented DSRC stack within a Wi-Fi chipset on a smartphone. Vehicles were equipped with V2V communications that were customized for V2P communications. The system was tested at intersections within residential areas. Similarly, in [123], the author proposed a V2P architecture for pedestrian collision avoidance consisting of DSRC-based applications for both pedestrians and vehicles. DSRC-based V2P equipment are also available by e.g., Arada Systems[3] and Oki Electronic.[4]

V. Projects on Cooperative Intersection Management

Besides numerous research works for CIM, projects dedicated for demonstration and realistic implementations are also conducted worldwide. Up-to-date advanced methods, e.g. sensors, accurate positioning methods, digital maps, V2X communications, have been used for enabling CIM with aims among others to improve traffic flow, to guarantee intersection safety, and to reduce CO2 emissions.

A. The USA Projects

California Partners for Advanced Transportation Technology (PATH)[5] (1986-) is a research and development program focusing on intelligent transportation systems at the University of California, Berkeley. One of the research areas is cooperative intersection collision avoidance for improving intersection safety. V2X communication-based systems are developed that are able to alert drivers at an intersection beforehand with information such as insufficient time left-turn. Besides, PATH has involved many of the national projects on cooperative intersections including Intersection Decision Support (IDS) project, Cooperative Intersection Collision Avoidance Systems (CICAS) program, etc.

Intersection Decision Support (IDS) (2002–2005) [124], [125] was a joint research project sponsored by the states consortium including the Department of Transportation (DOT) of Minnesota, California and Virginia and the Federal Highway Administration (FHWA) in the United States. The project aimed at investigating applications of infrastructure-based and infrastructure-vehicle cooperative systems for improving intersection safety. Three collision types, namely Straight Crossing Path (SCP) collisions, Left-Turn Across Path with Lateral Direction (LTAP-LD) traffic and Left-Turn Across Path with Opposite Direction (LTAP-OD), were considered. SCP was led by Virginia DOT and focused on situations where a driver violated a stop sign or stop signal. LTAP-LD was led by Minnesota DOT and investigated critical situations in rural areas where left-turn traffic merged with major high way traffic. LTAP-OD was led by California DOT in partnership with PATH and investigated urban situations where left-turn traffic was permissive without protected left-turn signal.

Cooperative Intersection Collision Avoidance Systems (CICAS) (2006–2009) was a large cooperative research program involving multiple stakeholders with the aim to address intersection safety by introducing ITS technologies. CICAS focused on critical situations of intersection with the purpose to reduce intersection accidents. Major working areas included CICAS-Violation Warning System (CICAS-V) [126], CICAS-Stop Sign Assist (CICAS-SSA) [127], CICAS-Signalized Left-Turn Assist and Traffic Signal Adaptation(CICAS-SLTA, CICAS-TSA) [128], as well as cost benefits analysis. In CICAS-V, the vehicles estimated risks of signal violation through the traffic light status information received from infrastructure via DSRC, and took precautions in case of high risk. If a dangerous situation already appeared, e.g., red light violation, CICAS-TSA was able to trigger a red light warning for all directions of traffic. CICAS-TSA may also trigger a warning message to infrastructure in the case it detected dangers, so that infrastructure would issue all-red-light warnings. CICAS-SSA installed sensors at intersection and helped drivers to merge into or cross the high-speed road safely.

Connected Vehicle Reference Implementation Architecture (CVRIA)[6] (2011–2014) was a project that aimed to identify key interfaces across the connected vehicle environment thus supporting standardization activities. The project was led by the United States Department of Transportation (USDOT) through the ITS Joint Program Office (JPO). Among all others, two intersection related applications, namely Eco-Approach and Departure at Signalized Intersections, and the Intersection Movement Assist (IMA) were identified. The former was an environmental-related application that aimed to provide advice for the driver to pass traffic lights eco-friendly, e.g., adapt the speed to pass the traffic light on green or decelerate to a stop in the most eco-friendly manner. And the latter was a safety-related application that aimed to reduce the likelihood of crashes at intersections by providing collision warning information.

Connected Vehicle Safety Pilot Program (2011–2013) was a research initiative that involved the USDOT, vehicle manufactures, public agencies and academia. The aim was to test connected vehicle safety applications by realistic demonstrations. The program was conducted by the University of Michigan Transportation Research Institute (UMTRI) at Ann Arbor, Michigan. Within the program, the above-mentioned IMA

[2]https://goo.gl/AeKmfr
[3]http://www.aradasystems.com/
[4]http://www.oki.com/
[5]http://www.path.berkeley.edu/
[6]http://www.iteris.com/cvria/index.html

application was tested. There were 21 signalized intersections equipped with V2I devices that sent out traffic light signal phase and timing information to vehicles. In the case when it was not safe to enter an intersection, the IMA application warned the driver to avoid potential dangerous situations. Results from the program have served as foundations for the new research program Mobility Transformation Center (MTC)[7] at the university of Michigan that aims at a working system of connected and automated vehicles in Ann Arbor by 2021.

B. European Projects

INTERSAFE (2004–2007) [129], [130] was a project under the FP6 PreVENT project aiming to improve the intersection safety. The main purpose was to develop advanced sensor systems and related algorithms for warning the drivers of potential dangerous situations. Two laser-scanners (left and right) in front of the vehicle with a combined scan area of 220° were installed for object detection, tracking and classification. They also assisted the GPS for map building and localization through landmark detection. With a consolidate view of the intersection and information of other vehicles at the intersection, vehicles were able to identify potential conflict and predict passing plans. Risk analysis was introduced to compute risk levels for each of the possible conflict and a HMI module was designed to present the risk level to drivers.

INTERSAFE-2 (2008–2011) [131] was a following project of INTERSAFE and extended the usage of wireless communications for a cooperative intersection system. Besides methods and technologies from INTERSAFE, INTERSAFE-2 deployed infrastructure with V2X communication capabilities. Both independent intersection and cooperative intersection passing were studied. In independent passing, similar to that in INTERSAFE, vehicles relied on their on-board sensors and information fusion for safe passing. In cooperative intersection passing, V2X communications were used to enhance the performance of independent intersection passing. Information collected by sensors was distributed by V2X communications to avoid occlusion, thus improving safety.

Aiming at improving the intersection safety, the results of INTERSAFE and INTERSAFE-2 contributed with sophisticated sensor system, V2X communication architectures for both vehicles and infrastructure, as well as performance demonstration and evaluations. This has provided valuable information for the development CIM methods and C-ITS.

Cybercars (2001–2009) and **Cybercars-2** (2006–2008) aimed at developing vehicles with limited autonomous functionalities that worked at confined zones. The developed cybercars have been used for prototyping and demonstration of a number of cooperative intersection control systems. In [132], the authors prototyped a simple intersection cooperation system with cybercars by coupling the communication-based perception with trajectory planning for safe intersection passing. The prototyping system involves two cybercars with both automatic longitudinal and lateral control. The cybercars were linked through a mesh network over Wi-Fi, where they broadcast their location information periodically. The information was either communicated directly with other cybercars within the communication range or routed through a static intersection communication units. For intersection passing, cybercars planed trajectories by considering all others as obstacles. If two cybercars were too close to each other, one needed to decelerate and let the other to pass.

In [133], the reservation protocol described in [65], [66] was prototyped with cybercars based on collision regions in an X-shaped junction. In [134], the system was further prototyped. Vehicles were allowed to accelerate to the maximum speed before entering the intersection and then pass the intersection with the highest speed. Furthermore, for areas before and after the intersection, adaptive cruise control (ACC) was used for collision avoidance. Also, to minimize reservation requests, only the first vehicle from each lane was allowed to send request. The system was simulated with an eight-shaped circuit.

In [135], an intersection passing was demonstrated with three autonomous vehicles including a cybercar from INRIA (France), a smart fortwo from TNO (Netherlands) and a citroën from IAI (Spain). Wi-Fi was used for vehicular communications based on the architectures developed by the SAFESPOT[8] project. Optimized Link State Routing (OLSR) was used for message routing and information distribution through the vehicle network. Intersection passing followed the right-hand principle where vehicles coming from right had priorities. A vehicle approaching the intersection firstly analyzed the information received to check if the intersection was occupied or if there were vehicles coming from right. If so, it had to wait until the intersection was clear to pass.

COSMO[9] (2011–2013) aimed at demonstrating the energy efficiency by cooperative systems. Cooperative intersection has been tested for public transport in the city of Gothenburg for the Swedish pilot site. COSMO deployed cooperative navigation systems that sent *time-to-green* messages to buses for adjusting the speed and passing the intersection without stops. By reducing the number of stops and making the buses pass intersection more smoothly, energy consumption was reduced, thus emissions. Moreover, comfort for both the drivers and passengers was improved.

KO-PER [136] (2009–2013) project was part of the project initiative Ko-FAS funded by the German Federal Department of Commerce and Technology. Ko-PER developed a cooperative perception system at intersections based on multi-sensor network and wireless communications. The system focused on providing an improved view of the intersection through cooperative perception of vehicles for better decision-making, while intersection passing relied on vehicles themselves. The system deployed sensors and cameras at intersections for monitoring the environments. Similar to INTERSAFE-2, laser-scanners were used for determining and tracking moving objects. Cameras were mounted high above the street level to improve the recognition and tracking results based on the texture information. The information, combined with detailed digital map information, was exchanged among approaching vehicles

[7]http://www.mtc.umich.edu/

[8]http://www.safespot-eu.org/

[9]http://www.cosmo-project.eu/

through 802.11p. This helped the vehicles to build a bird's eye view of the environment with an exhaustive and reliable model of the traffic participants including pedestrians, bicyclists and motorcycles, thus improving safety. The system was deployed and demonstrated at two non-public test intersections and one public intersection in Aschaffenburg, Germany.

Compass4D[10] (2013–2015) focuses on the application of C-ITS for improving road safety and efficiency. Two intersection services, Red Light Violation Warning (RLVW) and Energy Efficient Intersection (EEI), are considered to improve intersection safety and reduce energy consumption. Both the EU ITS-G5 based DSRC and public cellular networks are used in Compass4D. RLVW focuses on red light violation, and can be extended to other situations. The aim is to improve intersection safety by increasing the driver-alertness at signalized intersections through warning messages via V2X communications. EEI aims to improve the energy efficiency at signalized intersections by informing the approaching vehicles with the traffic lights' signal phase and timing information (SPaT). To ensure a pan European deployment, the pilot cities of Compass4D cover major EU countries including Denmark, Germany, Netherlands, France, Spain, Italy and Greece.

GCDC and i-GAME[11] are projects that focus on demonstrating the cooperative driving through challenges between international teams. The Grand Cooperative Driving Challenge (GCDC) (2010–2011) [137] was successfully held in 2011 in Helmond, the Netherlands. Within a total of 9 teams gathered together and during days of intensive working and competition, GCDC demonstrated to public platooning through wireless communications. Following the success and with the aim to integrate state-of-the-art vehicular communications, especially the first release of the EU C-ITS standards, Interoperable GCDC AutoMation Experience (i-GAME) (2014–2016) will again gather teams to showcase their latest work on cooperative driving and bring C-ITS applications a step further to reality. i-GAME takes a multi-vendor approach and aims at testing and demonstrating interoperability of C-ITS implementations from different organizations. Practical scenarios on typical traffic operations are designed to test and demonstrate the effectiveness of C-ITS applications. CIM is considered through the cooperative intersection scenario where a T-shape intersection without traffic light is involved. Incoming traffic from all three directions of the intersection need to negotiate and cooperate with each other to pass the intersection safely, smoothly and environmental friendly. To be more practical, the scenario considers close-to-reality settings where cooperative and non-cooperative vehicles co-exist. Final challenge for i-GAME is planned for the year 2016 at the test site on the A270 highway between Eindhoven and Helmond, in the Netherland.

C. Japan Projects

Driving Safety Support System (DSSS) (1999-) [138] is a danger warning system that has been deployed under Universal Traffic Management Systems (UTMS) in Japan for improving intersection safety. DSSS employs both infrared beacon and DSRC beacon on the infrastructure side. Infrared beacons are broadcast before the intersection and cover a relative small area. Broadcast beacons contain geographical information including road alignment, distance to the intersection, traffic regulation, etc., and approaching vehicles' information including location and lane number. DSRC beacons contain dynamic information detected by roadside sensors such as position and speed of pedestrians, information about other vehicles within the intersection. DSSS targets scenarios including stop sign violation, red light violation, turning accidents, crossing-path accidents, rear-end collision as well as pedestrian collision. The main function is to prevent accidents by warning drivers about potential dangers. Data collected through reception of beacons is processed by vehicles' on-board units for collision risk analysis. Warnings are issued through HMI if collision risks are detected. UTMS/DSSS is part of the ITS development in Japan and has been implemented in joint effort with other projects such as Smartway [139] and Advanced Safety Vehicles (ASV).[12]

VI. Discussion and Research Trends

CIM methods share many fundamental aspects. As mentioned, trajectory planning can be considered as a type of resource reservation where space tiles are allocated consecutively as travel routes. The differences rely on the modeling granularities for optimization. Meanwhile, algorithms for resource allocation and trajectory planning are essential in VTL as virtual light signals need to be planned according to the real time traffic information. Furthermore, though studied separately by literatures, intersection vehicle and VRUs collision avoidance methods are integral components within CIM. Therefore, CIM methods presented in this paper are more complimentary to each other.

On the other hand, CIM methods differ with each other from their control architectures and the distribution of computations, e.g., centralized and distributed. In centralized coordination, computations such as resource grant and trajectory planning rely on the intersection control unit. This has advantages from both the control and communication perspective. The central coordination unit can be deployed with sufficient resources to deal with high computation requirements. Also, centralized CIM only requires communications between infrastructure and road users, where no information needs to be exchanged between road users. However, to install coordination units at each of the intersections may lead to high costs. And as any centralized control systems, significant efforts are needed to guarantee the system reliability and robustness. For distributed CIM, less infrastructure support is needed. Resource reservation and trajectory decision are done locally and computations are distributed among vehicles. This contributes to more robustness as a single vehicle failure doesn't necessary cause a system failure. However, distributed CIM relies on intensive communications between road users for joint decision-making. This poses significant bandwidth requirements for wireless communications.

[10] http://www.compass4d.eu/en/home/home.htm

[11] http://www.gcdc.net/

[12] http://www.nasva.go.jp/mamoru/en/assessment_car/asv.html

CIM methods surveyed in this paper serve a general direction for further development while significant works are needed to relax the assumptions of the CIM methods for practical implementation. Cooperative resource reservation and trajectory planning form major CIM solutions that attract significant research efforts. Meanwhile, as also anticipated by the IEEE[13] that traffic light may become history by the year 2040, VTLs have big potentials to replace the current traffic lights in future traffic with autonomous vehicles. Despite the presented works, many open issues remain to be solved.

Communication performance is one of the critical issues for CIM that faces great challenges in reality. CIM involves safety critical situations that have high requirements on communication capacity, reliability, latency, etc. The current V2X communications based on ITS-G5 have limited capacity because of spectrum allocations. Significant research is needed to optimize resource utilization, such as cross-layer resource optimization in C-ITS. Besides, considering the penetration level of cellular phones, research over cellular communications in vehicular environments forms an interest trend that leads to innovative CIM methods.

Uncertainties need to be considered as an integral part of CIM. Uncertainties may come from control, mechanical, communications, etc. Vehicles may not follow the instructions such as space and time slot reservation, trajectory planning, or VTL signals. For legacy vehicles having human drivers in the loop, human behaviors need to be considered.

VRUs protection is one of the most critical issues in CIM that calls for more research. VRU detection and collision avoidance methods form one important issue while integration of VRUs into the CIM framework forms another challenging issue. Innovative solutions based on smart phones and wearable devices provide with promising solutions that warrants further research and development.

Above all, advanced algorithms form the core research topic for CIM. Regardless of control architecture, e.g., centralized or distributed, algorithms for problems such as optimal resource allocation, optimal trajectory planning, VTL leader negotiation and collision avoidance are critical for safe and efficient decisions. On one hand, those algorithms are required to guarantee traffic safety while improving traffic efficiency. On the other hand, they need to be fast and robust to deal with traffic dynamics. Furthermore, micro vehicle controls are gradually integrated into the optimization framework, e.g., algorithms take care of both macro level effects such as traffic flow, as well as micro level controls, such as acceleration and deceleration. This poses further challenges on the algorithm design that calls for intensive research.

VII. Conclusion and Future Works

Traffic coordination at intersections is one of the most challenging problems within the transport system. The advancements in information and communication technologies, especially the introduction of vehicular communications, have shown great potentials for improving intersection performance. It is anticipated that with the increasing penetration level of vehicular communications, together with vehicle and road automation, cooperative intersection management is promising to provide with efficient methods for coordinating intersection traffic.

This paper focuses on the development of cooperative intersection management methods that are enabled by the fast development of vehicle-to-vehicle and vehicle-to-infrastructure communications, and aims to provide a comprehensive overview of methods for traffic management at intersections. While methods for traffic light optimization are discussed, the focus is on non-signalized intersections, where traffic coordination is done through wireless communications. Cooperative resource reservation methods, both with and without infrastructure support are presented. The methods consider intersection passing as a discrete resource allocation problem and aim to allocate time slots and intersection space to vehicles for safe and efficient intersection passing. Trajectory planning, where intersection passing is considered as a passing sequence optimization problem aiming at maximizing certain utilities with constraints on intersection safety and vehicle maneuvering limits, form another major area of cooperative intersection management. Studies on virtual traffic lights that aim to replace the traffic lights are discussed. For dealing with emergency situations such as mechanical failure, collision avoidance within cooperative intersection management is discussed. Furthermore, considering the importance of vulnerable road users, methods for pedestrian detection and warning are discussed. Finally, major research and demonstration projects from the United States, the EU and Japan on cooperative intersection management are summarized. Discussions on future research topics are also presented.

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Lei Chen received the B.E. and M.E. degrees in communication engineering from Northwestern Polytechnical University, Xi'an, China, in 2004 and 2007, respectively, and the Ph.D. degree in infra-informatics from Linköping University, Linköping, Sweden, in 2013. He is currently a Senior Researcher with the Cooperative Systems Group, Viktoria Swedish ICT, Gothenburg, Sweden. His research interests include mathematical modeling, integer linear optimization, cellular networks, vehicular communications, etc. His current research topics focus on cooperative intelligent transport systems, where he investigates communication technologies (dedicated short-range communication, cellular networks, etc.) and cloud-based services for cooperative and automated transport systems to improve traffic safety, efficiency, and sustainability.

Cristofer Englund received the B.Sc. degree in electrical engineering and the M.Sc. degree in computer science from Halmstad University, Halmstad, Sweden, in 2001 and 2003, respectively, and the Ph.D. degree in electrical engineering from Chalmers University of Technology, Gothenburg, Sweden, in 2007. From 2008 to 2010, he had a research position within industry and was conducting research on 3-D image processing. He is currently a Research Manager with the Cooperative Systems Group, Viktoria Swedish ICT, Gothenburg, Sweden. He is also an Adjunct Senior Lecturer with the School of Information Technology, Halmstad University. He is also the Leader of the Traffic Systems Competence Group, SAFER Vehicle and Traffic Safety Centre, Chalmers University of Technology. His research interests are in random forests, artificial neural networks, kernel methods, pattern recognition, and image processing. The research topics include cooperative intelligent transport systems, traffic coordination, and data mining.