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Autonomous Intersection Management: A Short Review

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***Abstract*—Connected Autonomous Vehicles (CAVs) are the near future mode of transportation. Thus, it is necessary to adapt current traffic infrastructure and processes to manage such vehicles in terms of safety, speed and impact on the environment. One of the most challenging traffic infrastructures for CAVs are intersections. Therefore, a hot topic in this field is the research of novel strategies and protocols which can be used with even today available technology to manage the crossing of CAVs through intersections. In this paper, we review the literature related to the Autonomous Intersection Management strategies, protocols and simulation tools to identify open issues for future research.**

***Keywords*— Autonomous Intersection Management, Connected Vehicle Environment, Intelligent Transportation Systems, Self-driving Vehicles**

I. Introduction

The Society of Automotive Engineers (SAE) J3016 standard [1] defines six levels of driving automation, from SAE Level 0 (no automation) to SAE Level 5 (full vehicle autonomy). According to the same standard, top 11 global automakers [2] predict significant number of cars with some self-driving capabilities (Level 3) on the road by the early 2020's (mostly on motorways), almost fully self-driving (Level 4) and even the fully Autonomous Vehicles (AVs) (Level 5) within a decade (urban driving included). Main two problems for the technology of AVs to be ready for consumers in the predicted time-frame are legal regulation (out of the scope of this paper) and the needed infrastructure.

Since driving in urban environments with various participants (pedestrians, bikers, human driving vehicles - HDVs, etc.) and complex traffic infrastructure (intersections, traffic lights, signs, etc.) is most compelling for AVs, a lot of research is done over the past decade in this area. The research is related to how to upgrade traffic infrastructure to support autonomous driving and create strategies and protocols which can use onboard technology and connected vehicle environments (CVEs) including Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication to manage AVs driving through urban environments in safely, timely and economically manner. One of the major challenges, which has to be addressed, is the transitional period with partially CVE in which traffic infrastructure has to be able to manage [3] human-driven and various levels of self-driving vehicles at once.

We have organized the paper as follows. The second section describes the most popular intersection traffic management strategies in the last decade. Criteria which has to be met for a good Autonomous Intersection Management (AIM) system is described in the third section. The fourth section presents Connected Autonomous Vehicles (CAVs) models and simulators, and fifth section describes some of the models and strategies proposed in recent years for managing autonomous intersections. Conclusion and final thoughts end the paper.

II. Intersection Traffic Management strategies

Since intersections are one of the most complex, unsafe and inefficient part of the traffic infrastructure, most of the research regarding CAVs has been done in developing intersection traffic management strategies and systems. Various big international research projects were defined and executed in tackling this area. The INTERSAFE-2 is an EU project which aimed to develop and demonstrate a Cooperative Intersection Safety System (CISS) that is able to significantly reduce injury and fatal accidents at intersections. Vehicles equipped with communication technology and onboard sensor systems cooperate with the roadside infrastructure in order to achieve a comprehensive system that contributes to the public policy "Vision Zero" (VZ) [4] which aims to reduce fatalities and serious injuries in road traffic accidents to zero by year 2020, as well as to significantly improve the efficiency in traffic flow and thus reduce fuel consumption in urban areas.

CyberCars-2 was an FP6 project based on the FP5 projects CyberCars and CyberMove whose goal was development and evaluation of the Cybernetic Transport System (CTS). CTS is a network of driverless, fully automated urban vehicles (CyberCars) and a traffic management system which controls the network flow. Since CyberCars prototype vehicles were designed for low demanding traffic conditions and did not have the capability to communicate with each other, CyberCars2 project was started to empower these vehicles with V2V and V2I communication for the CTS to enable higher traffic flows and improved network efficiency.

IntelliDrive, a U.S. Department of Transportation (US DOT) project, is a platform of various technologies and applications for providing connectivity between vehicles (V2V), vehicles and infrastructure (V2I) and also with consumer devices using wireless communications. The main project goals were (i) improved safety using V2V and V2I communication, (ii) improved mobility by capturing and managing real-time data and (iii) developing dynamic mobility applications and improving

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impact on the environment using Applications for the Environment: Real-Time Information Systems (AERIS). Based on IntelliDrive inputs from V2V and V2I communication (infrastructure status data, vehicle status data, weather data, transaction data, location data, etc.) various applications can provide actionable information like real-time travel information or safety alerts and warnings, and are able to adjust phase and timing of traffic lights on intersections to meet real-time conditions, etc.

AIM is a protocol for coordination of vehicles movement through the intersections without using traffic lights or signs. An ideal AIM protocol must satisfy seven properties [5]: (i) fully distributed and autonomous control by the vehicles; (ii) simple communication; (iii) non-expensive vehicle sensors; (iv) standardized communication protocol; (v) deployability; (vi) safety; and (vii) efficiency. Traffic signals and stop signs are very inefficient in terms of large delays and intersections can only manage a limited traffic capacity. A lot of various control methods were proposed for more efficient intersections, like Multi-agent intersection control [6], [7], Auction [8] and Platoon based control [9], Buffer coordination method [10], etc. Majority of these control methods are based on CVE (V2V and V2I communication) in which the vehicles have to negotiate a right to safely and without stopping cross the intersection. Recently a lot of concerns have been raised regarding the security of V2V and V2I communication and exchanged data. Therefore, authors in [11] propose a Blockchain technology and smart contracts as a possible solution for addressing security issues.

III. Autonomous Intersection Management Systems Criteria

When developing AIM systems, a set of criteria have to be set in place for evaluating the developed system. In [12], authors discuss five pairs of conflicting evaluation criteria which have to be balanced to achieve a good AIM system.

The first pair of conflicting criteria is robustness and efficiency. Robust AIM system is designed with safety margins related to the vehicles state and ensures that vehicles can avoid mutual collisions regardless of unexpected events causing emergency or other sudden maneuvers. On the other hand, efficiency is better when safety margins are lower and efficient systems do not tolerate unexpected events very well. A very robust AIM system is not efficient and vice versa.

The second pair of conflicting criteria is deliberative and reactive planning. When planning the trajectories for each vehicle crossing the intersection, some strategies use future states of the system (deliberative planning), and others past and present states (reactive planning) of the system. Deliberative planning of trajectories cannot react to unexpected events while reactive planning can cause short-sighted actions and potential deadlocks.

The third pair of conflicting criteria is centralized and distributed AIM system. Centralized AIM system, according to the policy used, commands the vehicles on how to cross the intersection. It is efficient and information consistent system, but not so feasible in practice since the decision-making process is moved from the vehicles. In distributed AIM system, in most cases, all participants mutually communicate and the decision-making process is always done by the vehicle itself. Although very scalable, distributed AIM system must have a very reliable communication protocol to achieve and ensure communication consistency.

The fourth pair, cooperative and egoistic criteria, are mostly applied to multi-agent AIM systems in which two classes of agents, vehicles and intersection manager, have different goals. While intersection manager aims at the most efficient and safe intersection, vehicles aim to cross the intersection in the fastest possible way while ensuring comfort and fuel economy.

The last fifth pair of criteria is related to homogeneous and heterogeneous vehicles. In theory, an assumption is made that all vehicles are the same or homogeneous. But, in reality, that is not the case. A wide variety of vehicles exists with different properties like self-driving or human-driven, size, weight, priority level, performance, etc. which makes them heterogeneous.

IV. Connected and Autonomous Vehicles Simulation

Several studies related to CAVs present pieces of evidence of safety and capacity improvements of roads [13–16]. However, there are few studies dedicated to the evaluation of CAVs influence on traffic stream and Level of Service (LoS) through various traffic simulators (VISSIM, AIMSUM, SUMO). A major difficulty for these studies lies in the fact that CAVs simulation requires different driver behaviors models [17], compared to existent human drivers models (Wiedemann model, intelligent driver model, Gipps model). CAVs models must include connection between vehicles and other agents of traffic flow [18], and new headway [19], [20], overtaking [21–24] and platooning formation rules [25–27].

In order to conduct experiments on this subject, it will be necessary to use a microscopic traffic simulator that has implemented alternative car-followings models for the CAVs, or use software that allows such implementation. For commercial software AIMSUN, an external driver was implemented resulting in good estimates of the impacts that CAVs could have on motorway capacity. However, the car-following rules and algorithm parameters are the property of Nissan Motor Company [28]. For commercial software VISSIM, another external driver was built, this time using the well-known Intelligent Driver Model (IDM) car-following rules for CAVs, resulting in an increase of the capacity and lane-changing new behaviors [29]. Using the open-source software SUMO with modifications in the original source code and the addition of an external package [30], authors studied autonomous vehicles platooning formation and the influence of communication delays in this case [26].

Regardless of the car-following model or the microscopic simulator used, studies for traffic evaluation are established on scenarios based on penetration rates of vehicles of interest, for example, heavy-vehicles [31], [32] or nowadays AVs [28],

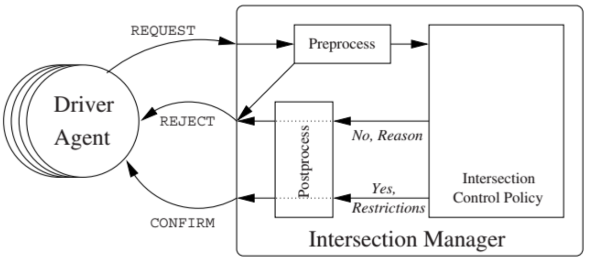

Figure 1. Space-time block reservation process [6]

[29]. Thus, experiments using microscopic simulators need three necessary steps: (i) Establish external driver modules with appropriate car-following rules; (ii) Create scenarios with different penetration rates of vehicles of interest; and (iii) Collect data with sensors in order to evaluate characteristics of the traffic flow.

Since CAVs interact with other vehicles and traffic agents, studies demand comprehension about traffic control and management [33]. AIM is a new intersection control policy, made to incorporate CAVs [34] which reservations of CAVs are prioritized by arriving time using First-Come-First-Serve (FCFS) rules. More details about AIM could be found on section V. It is relevant to mention that priority rules can be assigned to emergency situations [35] and AIM can be more efficient compared to regular traffic light control interfaces, under certain circumstances [36], [37].

V. Autonomous Intersection Management Control Methods

In this section, we will review several existing methods proposed for managing autonomous intersections.

A. Agent and Multiple-Agent based AIM

Dynamically changing environments and geographical distribution of transportation systems are the main reasons agent-based approaches can be used as AIM method. The complex transportation system can be broken down to smaller segments named multiple agents which interact with each other to achieve the desired goal. Due to their autonomy, collaboration, and reactivity, agents can operate without human intervention which enables implementation of automated traffic control and management systems like AIM. Distributed subsystems of a larger system collaborate with each other in real-time according to actual traffic conditions to perform traffic control and management. In term of AIM system, vehicles and intersection are treated as autonomous agents in a multiple agent system.

Dresner and Stone in [6] proposed a reservation-based multi-agent intersection control protocol for coordination of the movement of AVs through intersections more efficiently than through traffic light and sign operated intersections. They introduce computer programs called Driver Agents (DA) which control the vehicles and arbiter agent called an Intersection Manager (IM) which is placed at each intersection. The DA attempts to reserve space-time block in the intersection by sending a request to IM prior entering the intersection. The IM can accept or decline the request according to an intersection control policy (Fig. 1).

The request includes various parameters from DA: position, time and velocity of arrival, heading, vehicle characteristics like size, acceleration/deceleration capabilities, sensor range, etc. The IM sends received parameters to the intersection control policy which decides if DA can cross the intersection safely. If the crossing can be done safely, IM sends the message to DA about accepting the request and which restrictions have to be observed for crossing the intersection safely. If the request is rejected, IM notifies DA which may not cross the intersection without a reservation. In addition to confirming or rejecting the request, the IM may respond with a counter-offer. The intersection control policy is based on “First Come, First Served (FCFS)” rule and it works by running an internal simulation of the trajectory of the vehicle across the intersection using received parameters of DA. The intersection is divided by n x n tiles (n is the granularity of the policy) and if the policy determines that at any given moment DA occupies the tile already reserved by another DA, the policy rejects the request (Fig. 2). Otherwise, the tiles are reserved for the time they are needed by DA.

The main problem of FCFS policy is that it is not efficient with HDVs. Therefore, authors proposed FCFS-Light policy [6] which is compatible with human drivers, but they discovered that average delay time of all vehicles significantly increases under this policy if there is more than 5-10 percent of HDVs in the traffic.

Since AIM is designed for fully AVs, the challenge is how to control intersections in the transition period from HDVs to AVs. Au, Zhang and Stone in [5] proposed a new intersection control system called Semi-Autonomous Intersection Management (SemiAIM). It can accommodate both fully AVs and semi-autonomous vehicles (SAVs) with limited self-driving automation. As mentioned before, FCFS-Light AIM protocol prohibits HDVs from entering intersections during red signal phases. SemiAIM sets out to overcome these issues by allowing SAVs, vehicles with limited autonomous driving and wireless communication capabilities, to use the AIM reservation system to enter an intersection during red signal phases. While these vehicles are not fully autonomous, they are able to follow a limited number of predictable trajectories at intersections more precisely than human drivers. This ability allows them to utilize the proposed constraint-based reservation system to make reservations in the same manner as fully AVs and enter an intersection at red signals. In the recent work [7], Sharon and Stone extended they research on managing HDVs and proposed a protocol called Hybrid Autonomous Intersection Management (H-AIM) which manages crossing of mixed autonomous and HDVs through an intersection.

FCFS AIM protocol was also improved by the management scheme proposed in [8] which differentiate trip priorities of incoming vehicles at an intersection. It is called a decentralized auction-based AIM scheme in which each driver has a so-

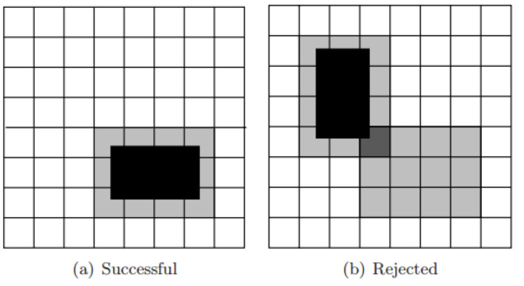

Figure 2. The internal simulation of a granularity-8 FCFS policy [6]

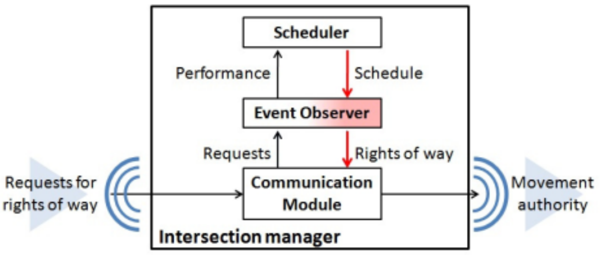

Figure 3. Architecture of Petri Net model of AIM [40]

called "wallet agent" which bids in the name of the driver/vehicle for the right to pass the intersection faster than others.

B. Ant Colony System for AIM

Previously described AIM protocols deal with the incoming vehicles one at the time in order to make a schedule for crossing the intersection. They present a combinational optimization problem which has to be solved in real time and with raising the number of lanes it quickly becomes an exponential problem. In [38], authors have proposed a heuristic approach based on the Ant Colony System (ACS) algorithm, one of the best variant of Ant Colony Optimization (ACO) method, for solving the problem with large numbers of vehicles and lanes. The principle of the algorithm is to find an approximate solution for evacuating incoming vehicles for each sequence of arrival in real time using artificial ants which find the solution by exchanging information via pheromone deposited on graph edges. The original AIM problem is in the essence the same as the Traveling Salesman Problem (TSP) where vehicles become cities and the shortest route which visits all the cities only once present a sequence of vehicles with minimal exit time through an intersection.

C. Intersection Management using iCACC

iCACC is a tool proposed in [39] for optimizing the crossing of autonomous vehicles through intersections using Cooperative Adaptive Cruise Control (CACC) systems in order to minimize intersection delays and avoid collisions. The success of the proposed tool was measured and confirmed by two evaluation variables, average delay and average fuel consumption which yielded savings in 91 and 82 percent respectively relative to conventional traffic light control. System inputs are physical characteristics, entry speed and acceleration of all vehicles, weather condition which affects the road (wet or dry) and characteristics of an intersection. Intersection Zone (IZ) is divided into three segments, Zone 1, Zone 2 and Intersection Box (IB). In Zone 1, all the vehicles should accelerate to maximum speed and maintain it until Zone 2 starts. End of Zone 1 is called Anchor Point and in this point, all the vehicles should travel at maximum speed. The optimization is done in Zone 2, if conflicting vehicles exist, by deceleration or acceleration of vehicles and optimizing the arrival time at the second anchor the point (end of Zone 2 and beginning of the Intersection box). At that point, all the vehicles should have maximum speed and can cross through Intersection Box safely. Vehicle Dynamics Model is used to simulate acceleration maneuver and to predict speed profiles of vehicles after the Zone 2 arrival time optimization. Fuel consumption is simulated using Virginia Tech Comprehensive Powerbased Fuel Model (VT-CPFM) which was compared to vehicle trajectory data.

D. Petri Net Model of AIM

For simple AIM simulation authors in [40] use P-timed Petri net model for defining a centralized protocol which manages the vehicles crossing the intersection without collisions and Dioid Algebra as a mathematical tool for the linear description of a Petri net variant called Timed Event Graph (TEG). Instead of vehicles, robots are used in the simulation. The main part of the protocol is named "Event Observer" which controls how rights-of-way are distributed across all the robots entering the intersection. Other parts of the intersection manager are Communication Module and Scheduler (Fig. 3).

E. Platoon-based AIM system

A platoon is a group of several vehicles driving one behind the other, and maintaining mutual distance and speed according to the leading vehicle which controls speed and direction for the whole platoon. For successful platooning, all the vehicles in platoon must communicate with each other. Authors in [9] propose a scenario in which vehicles entering intersections as a platoon can improve any AIM scheduling policy and reduce V2I communication traffic since the platoon leader negotiates right of the way in behalf of all the vehicles in the platoon. Simulating the scenario on a single 4-way intersection with intersection manager acting as a stop sign, using Platoon-based Delay Minimization (PDM) function, the average delay per vehicle was reduced by 50 percent, but the variance in delay times was increased. To address this problem, authors have proposed Platoon-based Variance Minimization (PVM) function which reduced the average delay by 40 percent and variance by 50 percent. In [41], authors extended they work by introducing a reservation-based policy for creating optimal schedules for platoons of vehicles crossing the intersection in terms of minimizing delay and variance for increased intersection throughput and decreased fuel consumption.

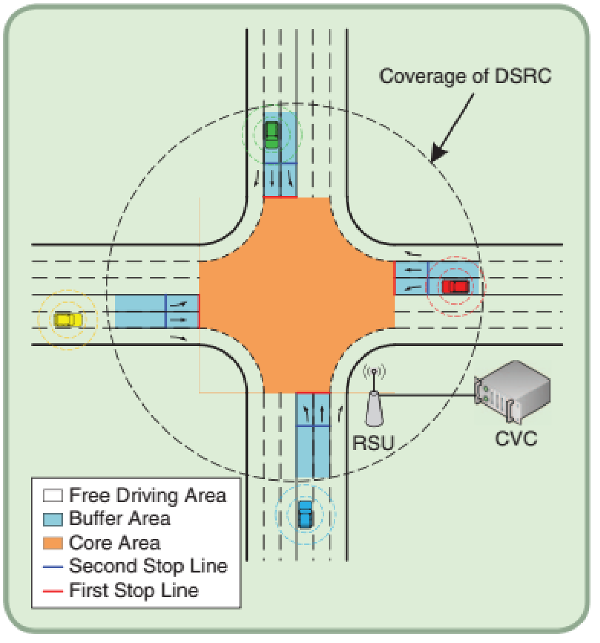

Figure 4. Buffer Coordination Method intersection layout [10]

F. Buffer Coordination Method for AIM

Some previously mentioned AIM strategies and control methods passively observe incoming vehicles to an intersection and predict the trajectories in terms of time-space slot reservation instead of adjusting the trajectories during vehicle approach to the intersection. Thus, authors in [10] proposed a novel coordinated intersection control method which uses buffer-assignment mechanism for coordination of autonomous vehicles crossing the intersection without collisions and traffic jams. Intersection manager called Connected Vehicle Center (CVC) sets a specific crossing span and sends it to the autonomous vehicle which has to follow it to make a safe crossing. The intersection is divided into three main areas (Fig. 4): (i) free driving area in which vehicles move without coordination or are operated by humans, (ii) buffer area in which AV‘s connect to CVC for time-space adjustment before entering in the (iii) third area called core area and to finally cross the intersection. There are also two stop lines in place with actual (first line) and virtual (second line) traffic lights operated by CVC for controlling HDV and/or AV in the cases of assignment failures. The performance of the buffer method was evaluated on an actual traffic network and simulations showed improvement in efficiency and sustainability of autonomous intersections.

G. Robust Intersection Management for Connected Autonomous Vehicles

Robust Intersection Management (RIM) for CAVs [42] is a space-time method which is focused on minimizing differences between real and model parameters by which velocity of respected AV is calculated and possible external influence which can occur when a vehicle is approaching the intersection. The

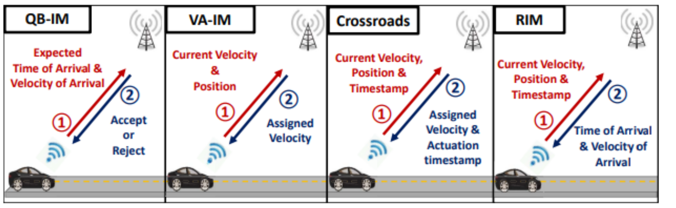

Figure 5. Main AIM strategies and RIM [42]

RIM method calculates Time of Arrival (TOA) and Velocity of Arrival (VOA) for incoming CAVs. CAV must follow optimal trajectory which can fulfill TOA while driving at VOA for safe intersection crossing. The robustness of the method is in fact that CAV positions itself on optimal trajectory according to TOA and VOA which compensates model mismatch and external influence (Fig. 5).

VI. Conclusion

One of the main issues in researching and developing new methods and protocols for AIM lies in the fact that they cannot be tested and verified in real traffic conditions since CAVs are not yet available. All presented work in this paper is validated only by simulating traffic conditions, vehicles (autonomous and human-driven) and intersections so results depend on the accuracy of models and data used in simulations. Another challenge is the transit period from all human-driven vehicles to all autonomous vehicles on the road. In that period hybrid strategies, protocols and infrastructure have to be used to manage mixed types of vehicles. Also, there is a concern regarding compatibility, reliability, security and data integrity in V2V and V2I communication. All reviewed strategies and protocols in this paper rely on connected vehicle environment where at least one mode of communication, V2V or V2I, is used for managing CAVs through intersections. And last, decision-making and planning policies or behavior implemented in CAVs will play a major role in researching and developing new strategies for AIM. Nevertheless, results obtained by presented work are promising and represent a good foundation for future research and development when CAVs become a reality.

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