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Synchronous Intersection Management Protocol for Mixed Traffic Flows

RTSS 2019 originally postponed from December 2019 (Hong-Kong) to February 2020 (York, UK) was cancelled.

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CISTER-TR-191005

2020/02/18

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Abstract

Urban traffic management (UTM) is responsible forplanning and controlling traffic on road infrastructures, includinglane closures, full freeway closures, and pedestrian access. Anessential element in UTM is the Intersection Management (IM)that deals with traffic lights (real or virtual) signaling and isvulnerable to traffic congestion and accidents. In this paper,we propose an intelligent intersection management architecturealong with the synchronous intersection management protocol(SIMP). Simulation results show the advantages of SIMP-M(a version of SIMP) over the well known TraCI IM protocol,in terms of both worst-case and average vehicle speed passingthrough one intersection.

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Work-In-Progress: Synchronous Intersection Management Protocol for Mixed Traffic Flows

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***Abstract*—Urban traffic management (UTM) is responsible for planning and controlling traffic on road infrastructures, including lane closures, full freeway closures, and pedestrian access. An essential element in UTM is the Intersection Management (IM) that deals with traffic control and is vulnerable to traffic congestion and accidents. In this paper, we propose an intelligent intersection management architecture along with the synchronous intersection management protocol (SIMP) instantiated in two versions. Simulation results show the advantages of SIMP-M (one of the versions) over the well known TraCI_TLS IM protocol, in terms of both worst-case and average vehicle speed passing through one intersection.**

***Index Terms*—Smart Cities, Autonomous Vehicles, Intelligent Transportation System, and Intersection Management.**

I. Introduction

The United Nations (UN), 2018 report on urbanization, forecasts that by 2050, the urban population will represent 68% of the worldwide population. In such a scenario of high urban density, Urban traffic management (UTM) is one of the key challenges to provide transportation guaranteeing users' safety. On the other hand, the emergence of autonomous vehicles (AVs) creates the opportunity to use Information and Communication Technologies (ICT) to improve traffic throughput while keeping traffic safe, i.e., the Intelligent Transportation System (ITS). The ITS carries out traffic management through the coordination and cooperation of AVs, smart road infrastructures, including wireless sensor networks. An essential element in ITS-based traffic management is the Intersection Management (IM) that deals with traffic lights (real or virtual) signaling to avoid traffic congestion and accidents while improving throughput. Examples of IM include the ballroom intersection protocol [1] and the configurable synchronous intersection protocol [2]. However, these approaches are for AVs, only. As experts and scientists anticipate, the transition towards an AVs-only scenario will be long and not before 2045 [3]. Therefore, there is a need to support mixed traffic-flow scenarios, i.e., AVs and Human-driven Vehicles (HVs) coexisting together. To tackle this mixed traffic-type scenario, we propose the Synchronous Intersection Management Protocol (SIMP), on top of the grid-based Intelligent Intersection Management Architecture (IIMA) introduced in [4]. In this paper, we present early simulation results based on SUMO/OMNeT++, including two versions of SIMP, namely SIMP-1 and SIMP-M, and a well-known IM called TraCI_TLS[1] in a single cross-intersection scenario. The simulation results show that our grid-based IIMA and associated SIMP-M protocol performs better with mixed-vehicle traffic in terms of worst-case and average vehicle speed.

This work was partially supported by National Funds through FCT/MCTES (Portuguese Foundation for Science and Technology), within the CISTER Research Unit (UID/CEC/04234).

II. Related Work

Existing intelligent intersection management approaches can be classified into two categories: fully AVs and mixed AVs/HVs. One example is the Ballroom Intersection Protocol (BRIP) [1], proposed for AVs synchronous flow, that ensures vehicles access the intersection at disjoint instants. Another one is the Configurable Synchronous Intersection Protocol (CSIP) [2], an extension to BRIP for handling GPS location errors. Another well-known example is the Traffic Control Interface (TraCI) Traffic Light Control System (TLS) based on the Krauss car-following model (CFM) to control the runtime behavior of vehicles. However, these protocols were not designed to handle scenarios with mixed AVs and HVs coexisting on the roads.

Curiously, we find less literature addressing mixed AVs/HVs scenarios. Qian et al. introduced HVs as priority vehicles, stopping AVs until HVs leave the intersection [5]. In the Hybrid-Autonomous IM protocol [6], the AVs sensing capabilities were used to detect HVs, but the AVs were prevented from accessing the intersection for $3.5s$ to detect HVs. The IM in [7] uses pre-sorting and pre-signaling for mixed AVs/HVs scenarios. These approaches impose strong differentiation between AVs and HVs with penalties in throughput and travel time.

In our approach, we integrate AVs and HVs smoothly, in synchronous intersection management, and we will use an AVs-only approach adapted for hybrid traffic, namely TraCI_TLS, as the baseline for comparison.

III. Intelligent Architecture

This section introduces the intelligent intersection management architecture for supporting mixed AVs and HVs, including the system model and assumptions.

[1] https://sumo.dlr.de/docs/Tutorials/TraCI4Traffic_Lights.html

A. Assumptions

The design of IIMA and the SIMP protocol considered several assumptions. Firstly, all vehicles follow the First-In-First-Out (FIFO) policy, meaning there are no overtakes. For the AVs, we considered standard assumptions as described in [2]. For the HVs, we also considered they have all the sensing capabilities of AVs. However, while AVs explicitly communicate with the intersection infrastructure to signal arrival and desired direction, HVs are detected by the infrastructure in their arrival, desired direction and departure. The infrastructure communicates with the AVs directly with explicit messages, e.g., to grant access to the intersection, while HVs are granted access using traffic light signals.

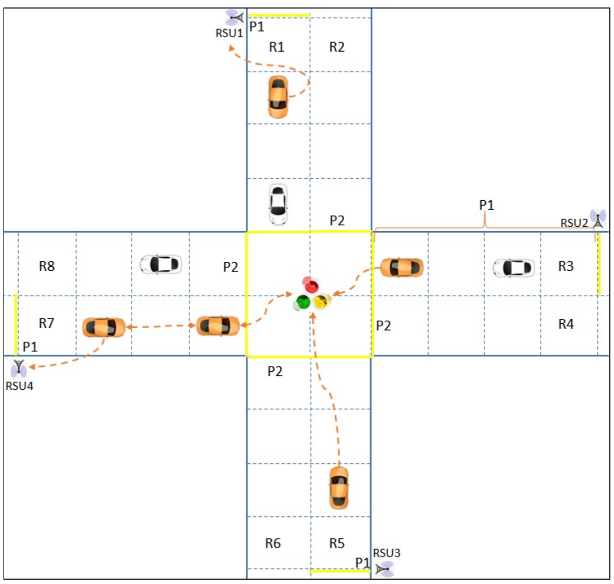

Fig. 1. Grid-based Intelligent Intersection Management Architecture (IIMA). AVs are represented in yellow while HVs are represented in white.

B. Architecture

We consider a four-way single lane intersection. The intersection and incoming lanes (within a certain length) are divided into equal-sized cells (Fig. 1). Each cell can accommodate a vehicle plus some gap between consecutive vehicles for safety reasons (we call this the grid-based IIMA). We use labels R1, R3, R5, R7 to represent the incoming road lanes and R2, R4, R6, and R8 to represent the outgoing road lanes. The intersection is equipped with a Traffic Lights Controller (TLC) that runs on a Road-Side Unit (RSU) and executes the SIMP protocol, allowing or blocking vehicles access to the intersection. Sensor P1 (e.g., induction loop sensor plus camera) identifies vehicle arrivals to the incoming lane grid area and recognizes vehicles desired direction and presence at the entrance of the intersection. Sensor P2 is placed at the exit of the intersection in each outgoing lane to detect vehicle departures (Fig.1). One RSU per incoming lane connects the sensors in the respective lanes (incoming and outgoing) and handles communication with the AVs (V2I communications). All RSUs involved in the intersection communicate among them to achieve intersection management.

IV. SIMP

This section introduces the Synchronous Intersection Management Protocol, starting with the notations and then the detection of HVs and the conflicts matrix for crossing directions.

A. Notations

The following notations are used in the scope of SIMP.

- Road lane index $r = 1, .., n_l$ (number of lanes $n_l = 8$).
- R_r is the road lane with index r
- Direction index $m = 1, 2, 3$ (right, straight, left).
- $D_{r,m}$ is the arrival from lane R_r with direction m.
- S is the maximum length of the vehicles.
- d_s is the inter-vehicle safety distance.
- $d = S + d_s$ is the length of the road cells.
- (d, d) is the size of the squared cells in the intersection.
- **c(t)** is the number of pending arrival messages from different AVs to the TLC at time t, in all incoming lanes.
- **n(t)** is the number of vehicles detected by the sensor $P1$ at time t, in all incoming lanes.

B. HVs Detection

Consider **n(t)** $= (n_{R1,t}, n_{R3,t}, n_{R5,t}, n_{R7,t})$ the number of vehicles detected by sensor $P1$ on road lanes R1, R3, R5, R7 at time t. Let the number of pending arrival messages at the TLC by AVs at time t be **c(t)** $= (c_{R1,t}, c_{R3,t}, c_{R5,t}, c_{R7,t})$. Therefore, at time t, the expression **n(t) - c(t)** computes the total number of HVs on the incoming road lanes.

C. Direction Conflicts Matrix

Figure 2(a) shows the road lanes and the directions that can be taken in the intersection, namely right, straight, and left. The sub-figures b), c), and d) show the occupancy of intersection cells when taking the referred direction. On the basis of these directions and the condition that any cell cannot be used by more than a vehicle at any time, we derived a direction conflicts matrix shown in Table I, where, 0 represents a conflict-free direction, and 1 indicates a conflicting direction, between two vehicles at the entrance of the intersection in any two distinct incoming lanes. The empty positions represent impossible situations due to the FIFO arrival of cars in each lane. For example, line 2 in the Table I represents the conflicts with direction $D_{1,2}$ (a vehicle arriving from lane R_1 and going straight $m = 2$). This direction has no conflict with another vehicle arriving from lane R_3 and turning right ($m = 1$), or arriving from lane R_5 and turning right ($m = 1$) or going straight ($m = 2$). Vehicles arriving from any lane (R_3, R_5, R_7) with other directions will cause a conflict. In case the desired direction of and HV is not safely recognized, the system will assume the direction imposing the strongest conflicts, i.e., $m = 3$. The resulting authorizations to enter the intersection are then communicated both with the traffic lights (for the HVs) and by means of explicit communication (for the AVs).

Two SIMP variants have been devised: SIMP-1 and SIMP-M:

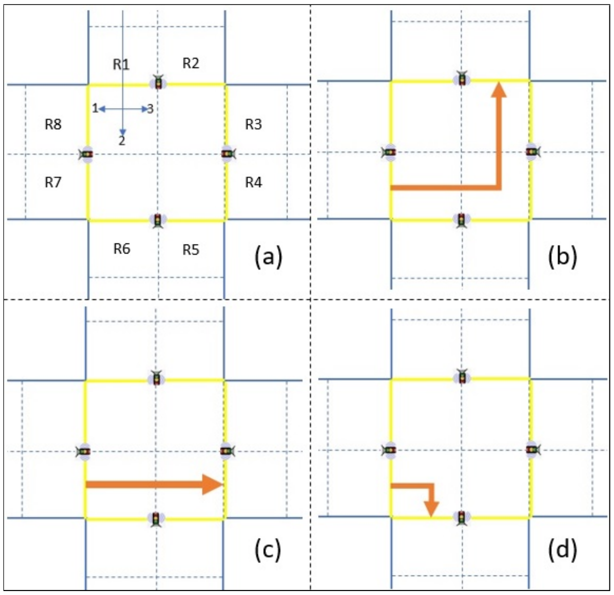

Fig. 2. (a) Direction codes (1-right, 2-straight, 3-left), (b) Left Crossing, (c) Straight Crossing, and (d) Right Crossing

TABLE I
DIRECTION CONFLICTS MATRIX FOR A 4-WAY SINGLE-LANE INTERSECTION (0-NO CONFLICT, 1-CONFLICT).

$D_{r.m}$		$D_{1.m}$			$D_{3.m}$			$D_{5.m}$			$D_{7.m}$		
	m	1	2	3	1	2	3	1	2	3	1	2	3
$D_{1.m}$	1				0	1	1	0	0	1	0	0	0
	2				**0**	**1**	**1**	**0**	**0**	**1**	**1**	**1**	**1**
	3				0	1	1	1	1	1	1	1	1
$D_{3.m}$	1	0	0	0				0	1	1	0	0	1
	2	1	1	1				0	1	1	0	0	1
	3	1	1	1				0	1	1	1	1	1
$D_{5.m}$	1	0	0	1	0	0	0				0	1	1
	2	0	0	1	1	1	1				0	1	1
	3	1	1	1	1	1	1				0	1	1
$D_{7.m}$	1	0	1	1	0	0	1	0	0	0			
	2	0	1	1	0	0	1	1	1	1			
	3	0	1	1	1	1	1	1	1	1			

- SIMP-1 - the intersection accepts only one vehicle at any time (conservative approach). A vehicle is admitted if the intersection is free. If not, it is blocked until the previous vehicle exits the intersection. Once a lane is served, the controller checks the next lane in a round-robin fashion.
- SIMP-M - the intersection checks all incoming lanes simultaneously and admits all vehicles in non-conflicting directions based on the direction conflict matrix. As soon as all vehicles exit the intersection, another admission round can take place.

V. SIMULATION RESULTS

From the International Transport Forum analysis, most of the International Road Traffic and Accident Database (IRTAD) countries have a default speed limit for urban residential areas of 30km/h[2]. For analyzing the performance of our IIMA and associated SIMP protocol, we use this value of 30km/h as the maximum allowed speed (or correspondingly 8.33m/s). We have analyzed both the variations of SIMP: SIMP-1 and SIMP-M using SUMO simulator [8], and compared the achieved results with TraCI_TLS the default IM protocol in SUMO.

We employed Krauss CFM for HVs and Intelligent Driver Model (IDM) CFM for AVs in simulating mixed traffic-flow [9]. The Krauss CFM has an additional parameter σ, usually set to 0.5 that represents the driver imperfection in making decisions. The IDM has two additional parameters, δ – an acceleration exponent usually set to 4, and τ – drivers desired (minimum) time headway generally set to $1.5s$.

We then carried out three experiments. Experiment A induces heavy traffic, with cars being injected in the system at the average rate of 1 per 10s, according to Uniform distribution. Experiment B injects moderate traffic, at the average rate of 1 car every $20s$. Then, experiment C induces a scenario with light traffic, injecting 1 car every $30s$. The individual average speed (IAS) is analyzed as the performance indicator, and it is computed dividing the total length of the route end-to-end by the travel duration time. This time includes any waiting time at the intersection, and thus, it is a performance indicator of the intersection management approach. Table II shows the SUMO simulation parameters and their values.

TABLE II
PARAMETERS USED IN THE SIMULATIONS

Parameters	**Values**
Intersection Management Models	TraCI_TLS, SIMP-1 and SIMP-M.
Road Network Area	1000 X 1000 m^2.
Intersection Area	20 X 20 m^2.
Intersection Type and Logic	Centralized TLC with Fixed Logic.
Simulation Time	600 Seconds.
Probability of vehicle insertion	Uniform, Random between (0,1).
Traffic Generation – Experiments	A - 1/10, B - 1/20, and C - 1/30.
Vehicle Types and Size (5 meters)	HVs – Krauss CFM, and AVs – IDM CFM
Min. Gap - d_s	5 meters
Acceleration	0.8 m/s^2
Deceleration	4.5 m/s^2
Maximum Speed	30kmph, i.e., 8.33333 m/s

Figures 3, 4 and 5 show the histograms of the IAS with a resolution of 1.5 m/s. The maximum, average and minimum (worst-case) IAS values are shown in Table III.

Experiment A (Fig.3) shows that TraCI_TLS, under heavy traffic, has bi-modal behavior, with many vehicles with either low (1 to 2.5 m/s) or high (7 to 8 m/s) IAS. This indicates that several cars are blocked at the intersection while other cars are being granted fast access. This behavior is expected since TraCI_TLS has a leader-follower dependency, allowing two consecutive cars from the same lane to cross the intersection at once, which reduces the blocking time for the follower car at the expense of increasing it for the others. For SIMP-1, the majority of the vehicles exhibit low speed (1 to 2.5 m/s), thus long blocking in the intersection, with progressively fewer vehicles exhibiting higher speeds. This is also expected due to the restriction of allowing only 1 car at a time in the intersection. On the contrary, SIMP-M has most vehicles with medium speeds (2.5 to 7m/s), showing a more balanced

[2]1. https://www.itf-oecd.org/sites/default/files/docs/speed-crash-risk.pdf

TABLE III
Comparisons among the average speed results for experiments A, B, and C.

	Average Speed m/s.								
	Experiment A			Experiment B			Experiment C		
	TraCI_TLS	SIMP-1	SIMP-M	TraCI_TLS	SIMP-1	SIMP-M	TraCI_TLS	SIMP-1	SIMP-M
Min.	1.77	1.24	2.36	4.49	3.61	**5.11**	4.47	5.36	**6.23**
Max.	7.99	7.44	7.79	7.93	7.85	**7.97**	7.93	7.73	**7.97**
Avg.	4.81	2.99	4.61	6.75	6.17	**6.88**	6.81	6.69	**7.08**

behavior. Overall, TraCI_TLS has the highest average IAS in this scenario, though a rather low minimum (worst-case) value, while SIMP-M has close average IAS but better worst-case behavior.

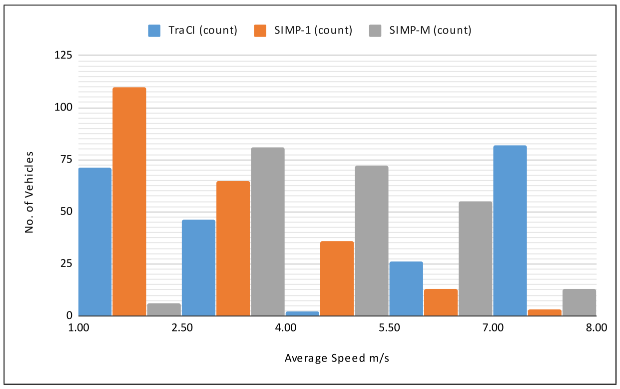

Fig. 3. Histogram of Individual Average Speeds for Experiment A.

Reducing traffic intensity, scenarios B (Fig.4) and C (Fig.5), SIMP-M shows the best results, both for average IAS as well as minimum IAS (worst-case). Particularly in the light load scenario (C), even the conservative SIMP-1 protocol has minimum IAS (worst-case blocking) better than that of TraCI_TLS. This indicates that SIMP-1 round-robin rotation in the intersection access is more effective in reducing blocking.

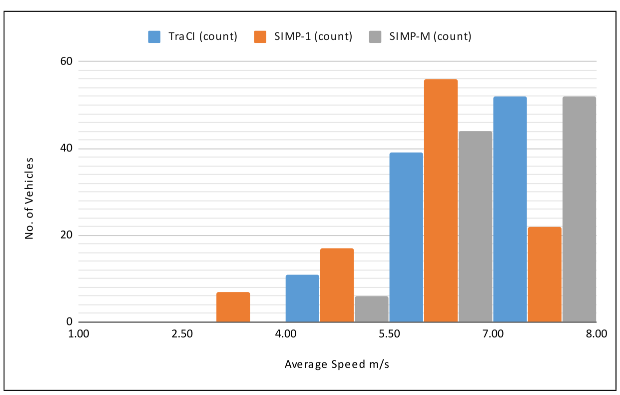

Fig. 4. Average Speed for Experiment B.

In summary, SIMP-M shows the best average performance in medium and low traffic scenarios and the best worst-case performance in all scenarios. SIMP-1, in turn, is very conservative leading to poor performance, except the worst-case under light traffic, in which case it overtakes TraCI_TLS.

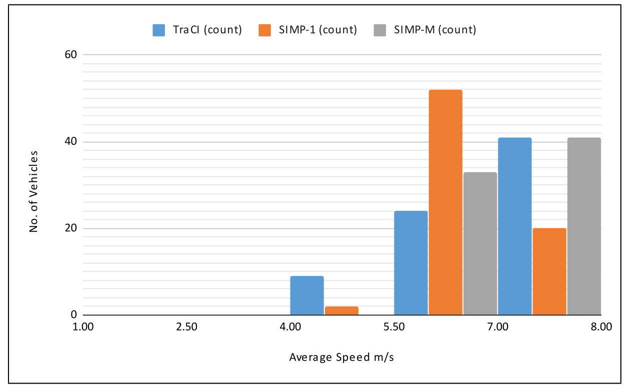

Fig. 5. Average Speed for Experiment C.

VI. Conclusions

In this paper, we proposed a new synchronous intersection management protocol, SIMP, that allows cars to enter the intersection in cycles triggered by the end of the previous cycle, and which handles both AVs and HVs smoothly. We analyzed its performance in terms of Individual Average Speed of the vehicles, which revealed to be better than that of a contending well-known protocol, TraCI_TLS. In the future, we will formalize the protocol to prove desired properties, and we will implement the required V2X communications and analyze their impact in the intersection operation.

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