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Radha Reddy

Luís Almeida

Miguel Gutiérrez Gaitán

Pedro Miguel Santos

Eduardo Tovar

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Radha Reddy, Luís Almeida, Miguel Gutiérrez Gaitán, Pedro Miguel Santos, Eduardo Tovar

CISTER Research Centre

Rua Dr. António Bernardino de Almeida, 431

4200-072 Porto

Portugal

Tel.: +351.22.8340509, Fax: +351.22.8321159

E-mail: reddy@isep.ipp.pt, lda@fe.up.pt, mjggt@isep.ipp.pt, pss@isep.ipp.pt, emt@isep.ipp.pt

https://www.cister-labs.pt

Abstract

In urban road transportation, intersections are traffic bottlenecks with increased waiting delays and associated adverse effects. A recently proposed intelligent intersection management (IIM) approach, the Synchronous Intersection Management Protocol (SIMP), synchronizes the vehicles access to simple single-lane isolated intersections, outperforming competing approaches in various performance metrics. In this paper, we apply SIMP to multi-lane intersections, increasing significantly the applicability of the protocol while dealing with the additional complexity emerging from the multiple crossing conflicts. Using the SUMO simulator, we compare the performance of SIMP with two conventional (Round-Robin - RR and Trivial Traffic Light Control - TTLC) and two IIM approaches (Intelligent Traffic Light Control - ITLC and Q-learning based Traffic Light Control - QTLC) under continuous and interrupted upstream traffic flows scenarios in urban settings. The results using a maximum speed of 30km/h confirm the superiority of SIMP, improving traffic throughput (~14.4%) and reducing travel delays (~64.4%) and associated fuel consumption (~25.5%) when compared to the best of the other approaches.

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RESEARCH ARTICLE

Synchronous Management of Mixed Traffic at Signalized Intersections Toward Sustainable Road Transportation

RADHA REDDY[1,2,3], **(Graduate Student Member, IEEE),**
LUIS ALMEIDA[1,3], **(Senior Member, IEEE), MIGUEL GUTIERREZ GAITÁN**[1,4], **(Member, IEEE),**
PEDRO M. SANTOS[1,2,3], **AND EDUARDO TOVAR**[1,2], **(Member, IEEE)**
[1]CISTER Research Centre, 4200-135 Porto, Portugal
[2]Instituto Superior de Engenharia do Porto (ISEP), 4200-135 Porto, Portugal
[3]Faculdade de Engenharia da Universidade do Porto (FEUP), 4200-465 Porto, Portugal
[4]Centro de Transporte y Logística (CTL), Universidad Andres Bello, Santiago 8370146, Chile

Corresponding author: Radha Reddy (reddy@isep.ipp.pt)

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ABSTRACT In urban road transportation, intersections are traffic bottlenecks with increased waiting delays and associated adverse effects. A recently proposed intelligent intersection management (IIM) approach, the Synchronous Intersection Management Protocol (SIMP), synchronizes the vehicles access to simple single-lane isolated intersections, outperforming competing approaches in various performance metrics. In this paper, we apply SIMP to multi-lane intersections, increasing significantly the applicability of the protocol while dealing with the additional complexity emerging from the multiple crossing conflicts. Using the SUMO simulator, we compare the performance of SIMP with two conventional (Round-Robin - RR and Trivial Traffic Light Control - TTLC) and two IIM approaches (Intelligent Traffic Light Control - ITLC and Q-learning based Traffic Light Control - QTLC) under continuous and interrupted upstream traffic flows scenarios in urban settings. The results using a maximum speed of 30 km/h confirm the superiority of SIMP, improving traffic throughput (up to 14.4%) and reducing travel delays (up to 64.4%) and associated fuel consumption (up to 25.5%) when compared to the best of the other approaches.

INDEX TERMS Sustainable road transportation, intelligent transportation system, intelligent intersection management, synchronous intersection management, traffic throughput, travel time loss, fuel efficiency.

I. INTRODUCTION

Urban traffic management (UTM) is one of the worst-hit transportation domains in terms of sustainability due to the growing number of automobile users and policies that favor individual passenger cars [13]. With forecasts of about 68% of the worldwide citizens living in urban regions by 2050 [10], we can expect the UTM challenges to aggravate in the upcoming decades. A promising solution for sustainable road transportation (SRT) is adopting advanced vehicular technologies, such as connected vehicles (CVs), autonomous vehicles (AVs), and electric vehicles (EVs), towards smart mobility [9]. These support SRT in multiple dimensions, maximizing accessibility via improved throughput (economic dimension), energy efficiency through reduced fuel consumption and associated emissions (economic and environmental dimensions), and reduced travel time loss through efficient intersection operation (economic dimension) while providing safety, particularly reduction of collisions (economic and social dimensions) [20]. To achieve these benefits,

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intersection management (IM) can play a crucial role as part of UTM due to the crossing conflicts, access waiting times, and associated fuel wastage, including the emission of air pollutants.

Intelligent IM aims to optimize resource consumption (e.g., fuel or electricity), improving travel time efficiency and user safety, among other benefits. Some of these IM systems target the minimization of traffic congestion by leveraging the new opportunities for vehicle control offered by AVs and considering different degrees of penetration of AVs in mixed operation with human-driven vehicles (HVs) [3], [4], [6], [15], [33], [34]. For this purpose, traffic light control (TLC) combines the information from various heterogeneous data sources, comprising AVs and roadside units (RSUs), thus typically leveraging vehicle-to-everything (V2X) communication.

In this research direction, [28] proposed an Intelligent Intersection Management Architecture (IIMA) and associated Synchronous Intersection Management Protocol (SIMP) for the operation of simple single-lane isolated intersections in urban areas. Their approach is TLC-based, not relying on specific AV features, such as remote control for inter-vehicle coordination and synchronization. All vehicles, either AV or HV, are considered fully independent. IIMA/SIMP outperformed contesting approaches w.r.t. intersection throughput, travel delays (average and worst-case), energy efficiency, and emission of air pollutants [29], [30], [31]. However, the applicability and potential benefits of IIMA/SIMP were not verified for more complex intersections, which remained an open problem.

This paper takes such a step and puts forward the following novel contributions:

- Extension of the synchronous SIMP from simple single-lane to complex multi-lane road intersections, particularly with the typical configuration of two inflow and two outflow lanes, considering both Dedicated (SIMP-D) and Shared (SIMP-S) left-turn lanes.
- Comparison of SIMP-D and SIMP-S qualitatively and quantitatively against two conventional IM approaches (pre-timed control), namely Round-Robin (RR) and Trivial Traffic Light Control (TTLC) [7], and two intelligent strategies, namely Intelligent Traffic Light Control (ITLC) [41] and Q-learning based Traffic Light Control (QTLC) [1]. To the best of our knowledge, these mechanisms represent the state-of-the-art in TLC-based management for independent vehicles,[1] and use compatible models.

These contributions significantly open the scope of applicability of the proposed synchronous framework. We conjecture that multi-lane intersections are more common than single-lane ones, supporting the relevance of our contributions.

[1] Without compromising the vehicle independence assumption, we allow vehicles to adopt car-following technologies such as Adaptive Cruise Control.

The comparison study simulated the referred IM approaches under uniform urban traffic settings using SUMO [21], and we collected throughput, travel time loss, and fuel consumption metrics under time-invariant and time-varying traffic patterns. The results confirm the higher performance of SIMP, even in complex intersections, outperforming the competing approaches in all tested cases. These results place SIMP in a privileged position to achieve SRT.

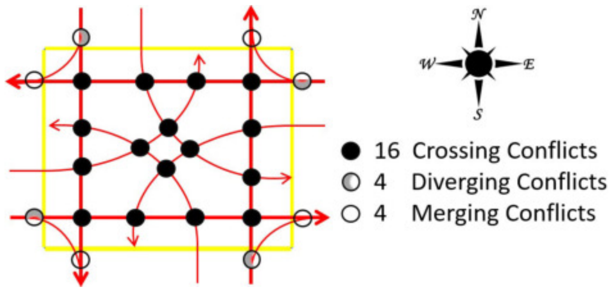
This paper is organized as follows: We review the relevant related works in Section II. Section III describes the complex multi-lane signalized intersections. Section IV describes the synchronous framework, and Section V outlines the other IM protocols used for comparison. Section VI presents the car-following models representing HVs and AVs, the fuel consumption model, associated parameter settings, and the simulation scenarios. The performance of the synchronous framework against other comparing IM approaches is presented in section VII. Limitations of this work are presented in section VIII. Final remarks are drawn in Section IX.

II. RELATED WORK

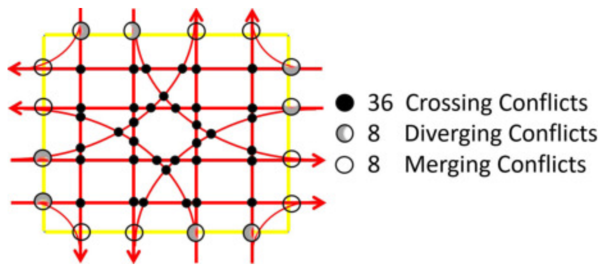
Conventional pre-timed intersection management (IM) approaches were introduced initially for managing arbitrary traffic at intersections. These IM strategies control green periods in a pre-defined sequence for a predetermined time but can be configured to support different allocated times for different periods of the day. RR IM approach [2] and TTLC [7] strategies are the most frequent strategies of this kind. They can also be tuned for specific time-invariant traffic patterns, using optimization approaches to set the cycle length and green phase duration accordingly, e.g., [12] and [27]. As typical in TLC-based approaches, they are also agnostic to the type of traffic, AV or HV, providing extra versatility and ease of deployment. However, these approaches are inefficient under time-varying traffic arrival patterns since their service does not adjust to the dynamic fluctuations of the vehicles' arrivals.

To tackle the aforementioned limitation, a wealth of solutions is reported in the literature concerning the so-called *intelligent* approaches, or IIM. Some approaches use the CVs information (position, speed, length, etc.) for TLC optimization [38] to improve the user throughput [24] or minimize delays [35] and for identifying the non-CVs presence [19]. The management of heterogeneous CVs is studied comprehensively in [14]. Though our work can use CV technologies for added robustness, we do not rely on them, accommodating the cases in which they are not present.

Other approaches use different operating mechanisms, including TLC signal timing optimization [1], [41], generally combined with AVs trajectory optimization [11], [15], [26], [32], [33], [40] or with AVs longitudinal control [5], [25], [27], [34]. Some approaches optimize traffic signal timing matching the traffic demand using reinforcement learning [18] and adaptive fuzzy-logic [22]. Other approaches reduce the need for the TLC by synchronizing



(a) Dedicated left-turn movement with shared straight/right movements.



(b) Shared left/straight movements with straight/right movements.

FIGURE 1. Conflicting points for dedicated and shared left-crossing lanes in a two-lane four-way road intersection operation.

AVs trajectories to minimize contention at the intersection [3], [4], [6], [36]. Most of these approaches leverage the potential of controlling AVs remotely, which opens new possibilities for inter-vehicle coordination and synchronization and significant safety and security challenges beyond the already important autonomy challenge. Since we also want to support HVs, we do not consider these approaches further in this work.

Two exceptions among the works referred to above are ITLC - Intelligent Traffic Lights Control [41] and QTLC - Q-learning based Traffic Lights Control [1]. Both policies are TLC-based, as their names say, being agnostic to the type of vehicles that cross the intersection, either AV or HV. They differ in the way they adapt to the current traffic pattern. Both consider, in each lane, the queue length and the position and speed of vehicles. However, ITLC is more reactive and adapts each cycle according to the queue and vehicle dynamics in the preceding cycle. QTLC uses Q-learning to set the green phase duration in each lane according to queue length observations in the respective lane, tracking the long-term average vehicle arrival rate.

Both ITLC and QTLC are compatible with IIMA/SIMP model (TLC-based) in the same way as RR and TTLC. We believe these represent the state-of-the-art in this class of protocols. Therefore, we will use them for comparison and provide further details in the next section.

III. COMPLEX SIGNALIZED INTERSECTIONS

This section introduces the complex multi-lane intersections that we will use in this work, namely isolated four-way road intersections with two inflow and two outflow road lanes per roadway. Without loss of generality, we consider equal roads organized vertically and horizontally. Several lane assignments to the directions of the vehicles can be considered. We analyze two specific assignments in which the right-most lane is always shared for right-turns and straight-crossing, while the inner-most lane (left lane) can be assigned only for left-turns or shared for left-turns and straight-crossing [8].

When using the dedicated left lane, the left-turning cars do not block the following vehicles in the same lane. In the shared left lane case, we may always have situations where the vehicle at the intersection entrance is not given access. In contrast, the following vehicle in that lane, going in a different direction, could have gotten access. A consequence of this blocking is that it also increases the chances of rear-end collisions between the vehicles in this lane. However, shared lanes tend to increase throughput for straight-crossing vehicles. Thus, both configurations are often used in practice.

Analyzing the movements of the vehicles through the intersection, we can identify three types of potential conflicts: merging, diverging (sideswipe and rear-end), and crossing. These conflicts are shown in Fig. 1a and 1b for dedicated and shared left lanes, respectively. It is visible in the figures that the shared left lane case has a higher complexity, with more conflicts of all kinds, particularly crossing ones.

IV. SYNCHRONOUS MANAGEMENT FRAMEWORK

Our synchronous framework includes the IIMA architecture and the SIMP protocol. It is synchronous in the sense that vehicles are admitted to the intersection one by one in synchronous rounds. We make the following assumptions in the intersection and the inflow lanes: U-turns and overtaking are not allowed, and vehicles are served following a First-In-First-Out (FIFO) policy. We also consider AVs to be featured with several sensors and specific services, namely localization, path planning, autonomous control, and wireless communication via, e.g., 5G or IEEE 802.11p (for detailed information, see [4] and [42]). Although HVs can also be featured with sensors and wireless communication similarly to AVs, we take a conservative approach and consider them non-communicating.

We consider the road infrastructure to include RSUs, entities capable of communicating wirelessly with the vehicles (can be 5G- and/or IEEE 802.11p-capable), a TLC (hosted locally, e.g., in an edge computing node), and road sensors (e.g., induction and camera sensors). All these entities are connected via a wired medium assumed to have no losses and no latency. The AVs can communicate directly with the road infrastructure (RSUs and TLC) to announce their presence and desired crossing direction. The road sensors compensate for the non-communicability of HVs, detecting them and their desired crossing directions. The TLC issues the authorization to enter the intersection using wireless communication for AVs and light signals for HVs. For robustness, both means are used simultaneously, though.

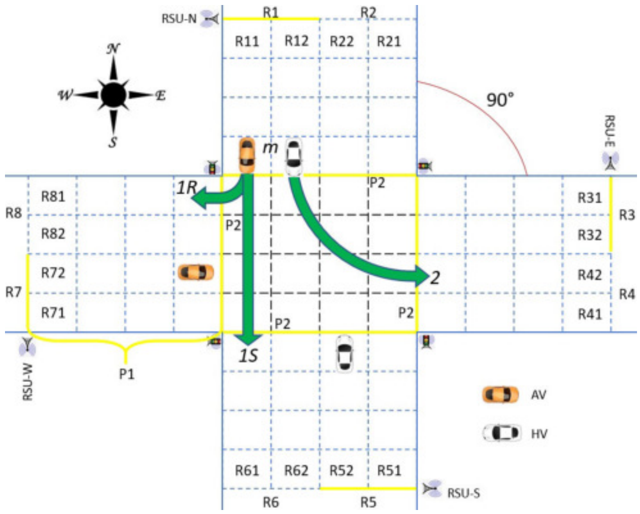


FIGURE 2. **The direction codes (*m*) used in the Intelligent Intersection Management Architecture (*m*): *1R*-right-crossing; *1S*-straight-crossing; and *2*-dedicated left-turn movement.**

Figure 2 shows an intersection with a dedicated left lane and the referred IIMA. The figure highlights the three possible crossing directions, identified with three different codes assigned to a direction variable m. As shown, $m = 1R$ refers to turning right, $m = 1S$ means crossing straight, and $m = 2$ identifies a left turn. Other features of IIMA include the support for mixed traffic of both AVs and HVs (shown in the figure with different colors). Moreover, some lengths of the lanes towards the intersection and the area within the intersection are partitioned into virtual cells, each corresponding to one vehicle and an extra inter-vehicle distance for safety.

The roads are represented in two directions, inflow and outflow. Road i is referred as R_i where odd indexes $(i = 1, 3, 5, 7)$ stand for inflow lanes and even indexes $(i = 2, 4, 6, 8)$ for outflow lanes. We further separate the two lanes in each road using index j; thus, R_{ij} stands for road i lane j. This index assumes two values, $j = 1$ and $j = 2$, to refer to the side (right) and center-most (left) lanes, respectively.

Every road in the intersection is featured with an RSU with two specific sensors (P_1 and P_2) that combine cameras and induction loop detectors. Note that for dedicated left-crossing lanes the cameras are not required, but only the induction loop detectors to find the vehicle presence at the intersection entrance. The TLC carries out the intersection management and tracks the roads and intersection area state using communication with the road RSUs. The RSUs inform the TLC periodically of the number and position of vehicles in each inflow lane, particularly their presence at the entrance of the intersection area and the direction they wish to take. This information is obtained using the P1 sensor and possibly using communications with AVs, too. The IIMA allows or blocks vehicles into the intersection in cycles that take at most one vehicle from each lane. The decision is based on the *Conflicting Directions Matrix* (CDM) that encodes the crossing conflicts to ensure that all vehicles allowed into the intersection in one cycle follow conflict-free paths. Each RSU uses its P2 sensor to detect the departure of vehicles from the intersection on the corresponding road. For AVs, this information may also be obtained via communication.

The SIMP protocol synchronously manages the cars' movement inside the intersection in cycles. Each cycle starts with detecting vehicles at the intersection entrance from all lanes and their desired crossing directions (P1 sensors). Then, there is a decision on which vehicles on all the lanes can enter the intersection using the CDM. Finally, detecting vehicles exiting the intersection on all roads (P2 sensors) allows ending the cycle and restarting a new one.

The CDM for the case of a dedicated left-turn lane intersection is shown in Table 1 and reflects the conflicts in Fig. 1. The position $CDM(D_{ri,mi}; D_{rj,mj})$ in the matrix encodes whether the paths followed by two vehicles attempting to cross the intersection have a crossing conflict or not. One vehicle arrives from lane R_{ri} with crossing direction mi while the other arrives from lane R_{rj} with crossing direction mj. The values 0 and 1 encode the absence or presence of a crossing conflict, respectively.

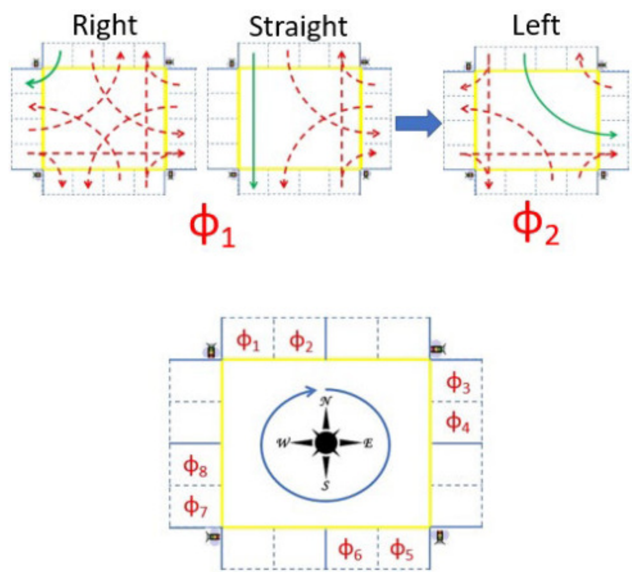


FIGURE 3. **Control phases of SIMP.**

To arbitrate between vehicles trying to access the intersection from different lanes simultaneously, SIMP checks one lane at a time in a circular fashion. If a vehicle is present in that lane, it is admitted to the intersection with the vehicles at the entrance of the intersection in other lanes that have no conflicts with it and among them. For instance, starting from the North as in Fig. 3 (bottom), SIMP checks the right lane (phase ϕ_1) and then the left lane (phase ϕ_2), followed by the right and left lanes of East (phases ϕ_3 and ϕ_4), South (phases ϕ_5 and ϕ_6) and West roads (phases ϕ_7 and ϕ_8). In Fig. 3 (top), we also presented the remaining conflict-free directions (dashed red lines) when permitting right, straight, and left crossing vehicles (solid green lines) during ϕ_1 and ϕ_2 phases. Similarly, in each phase, SIMP allows the vehicle of the checked lane and one vehicle of each other lane with no

TABLE 1. Conflicting directions matrix of a four-way two-lane road intersection assigned with a dedicated left lane (1-conflict, 0-no conflict).

$CDM(D_{ri,mi}; D_{rj,mj})$			$D_{rj,mj}$											
	r		R_{11}		R_{12}	R_{31}		R_{32}	R_{51}		R_{52}	R_{71}		R_{72}
		m	1R	1S	2	1R	1S	2	1R	1S	2	1R	1S	2
$D_{ri.mi}$	R_{11}	$1R$				0	1	0	0	0	0	0	0	0
		$1S$				0	1	0	0	0	1	1	1	1
	R_{12}	2				0	1	1	0	1	0	0	0	1
	R_{31}	$1R$	0	0	0				0	1	0	0	0	0
		$1S$	1	1	1				0	1	0	0	0	1
	R_{32}	2	0	0	1				0	1	1	0	1	0
	R_{51}	$1R$	0	0	0	0	0	0				0	1	0
		$1S$	0	0	1	1	1	1				0	1	0
	R_{52}	2	0	1	0	0	0	1				0	1	1
	R_{71}	$1R$	0	1	0	0	0	0	0	0	0			
		$1S$	0	1	1	0	0	1	1	1	1			
	R_{72}	2	0	1	1	0	1	0	0	0	1			

conflicts. When all admitted vehicles exit the intersection, i.e., at the end of a cycle, SIMP checks the next lane to start a new cycle. If no vehicle is found in the lane, SIMP immediately checks the next one. Thus, crossing cycles are triggered fairly and fluidly whenever there are vehicles at the entrance of the intersection. In summary, SIMP assigns slots on-demand to individual vehicles, unlike all other protocols that handle groups of vehicles at once. A sample video of SIMP working at a dedicated left-turn lane intersection can be seen in the YouTube link.[2]

Finally, note that this framework can be equally applied to other types of intersections as long as the CDM is properly configured.

V. OTHER IM PROTOCOLS USED FOR COMPARISON

This section presents the IM strategies used for benchmarking against our synchronous framework (SIMP), namely RR, TTLC, ITLC, and QTLC. These protocols are grouped into three categories according to the way they select green phase time: reactive (SIMP), fixed (RR and TTLC), and adaptive (ITLC and QTLC). As an initial note, the original TTLC, ITLC, and QTLC protocols handled the left-turning traffic together with the straight-crossing ones leaving the responsibility to vehicles to avoid collisions. For consistency with SIMP and RR, we modified these protocols to handle this traffic separately, in dedicated phases, thus in a collision-free manner. For this reason, all these four protocols consider only dedicated left lanes.

Regarding configuring the timings of the protocol phases, we generally used those suggested by the proposers of each protocol. In the case of RR, we studied which timings would improve performance, and we used the best configuration [30]. In TTLC, ITLC, and QTLC we carried out a small change of the left-turn timing that we observed to improve performance, too.

A. ROUND-ROBIN (RR) INTERSECTION OPERATION

The RR IM mechanism, also called the uniform signal control, is a pre-configured system consisting of green phases for a predetermined time allocated to each road direction and that operates in a circular order [2]. In this IM strategy, we consider that the cycle rotates clockwise. This paper improves the RR IM approach by authorizing vehicles' right-turn movements from conflict-free road lanes. The RR IM mechanism for a dedicated left-crossing movement has four phases ϕ_1, ϕ_2, ϕ_3, and ϕ_4 as illustrated in Fig. 4b. In each phase, the green time is set to 30s, followed by 4s of yellow time, as done in [30]. A sample video of the RR working at a dedicated left-turn lane intersection can be seen in the YouTube link.[3]

B. TRIVIAL TRAFFIC LIGHT CONTROL SYSTEM - TTLC

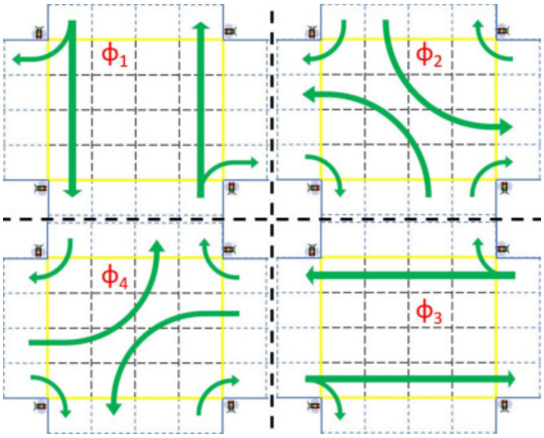
The TTLC strategy is also a pre-configured IM mechanism. This strategy controls traffic by authorizing vehicles from opposing directions at the same time, instead, thus alternating between North-South and East-West [7]. This operation can also be represented by four circular phases (ϕ_1, ϕ_2, ϕ_3, ϕ_4) as shown in Fig. 4a. ϕ_1 and ϕ_3 are set with $30s$ of green time and $4s$ of yellow time, while ϕ_2 and ϕ_4 are set with $15s$ of green time also followed by $4s$ of yellow time. These values are those used in [7] except for the duration of ϕ_2 and ϕ_4 that was increased from $12s$ to $15s$ to cope with a higher flow rate of left-turning vehicles.

C. INTELLIGENT TRAFFIC LIGHT CONTROL PROTOCOL - ITLC

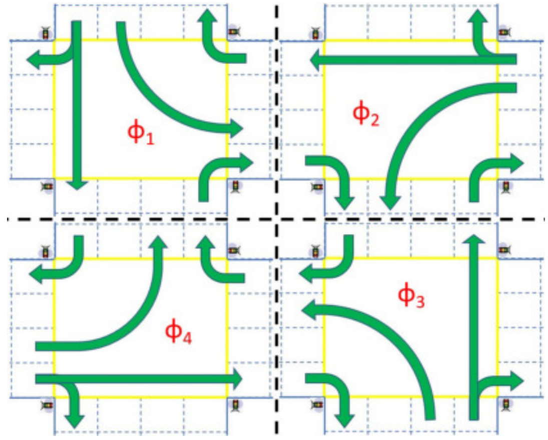
Younes and Boukerche presented the ITLC algorithm [41]. The ITLC mechanism uses the information from roadside sensors, namely queue length in vehicles, vehicle speed, and associated acceleration, to determine the green time applied to the respective lane. This adaptation is made per cycle, thus making the protocol highly reactive. Nevertheless, given that two opposite lanes are served at a time, the green time used is always the maximum of those two lanes. This time for the S/R lane is bounded between 5 and $60s$, and for lane L, it is fixed to $15s$, again, both cases are followed by $4s$ of yellow time, while the vehicles from adjacent inflow lanes are stopped. Similar

[2]https://youtu.be/ut5MfFqHawY

[3]https://youtu.be/eoSdmoAMOkw



(a) TTLC, ITLC, and QTLC control phases.



(b) Round-Robin IM control phases.

FIGURE 4. Control phases of the IM protocols used for comparison.

to TTLC, ITLC also follows four phases (ϕ_1, ϕ_2, ϕ_3, ϕ_4) in cycles, as shown in Fig. 4a.

D. Q-LEARNING BASED TRAFFIC LIGHT CONTROL - QTLC

The QTLC protocol was presented in [1] for minimizing travel delays by relying on multi-agent systems. QTLC employs vehicle queue length and phase duration to inform TLC decisions. It either chooses to continue with the present phase or change to the next phase to minimize travel delays. This adaptation, done by means of Q-learning, targets tracking long-term average traffic arrival rates, thus being slower than with ITLC. QTLC has also been implemented for a dedicated left lane intersection permitting traffic from opposing road directions, similar to TTLC and ITLC. The QTLC control phases are also similar to TTLC, and ITLC, as in Fig. 4a. Nonetheless, the green time of phases ϕ_1 and ϕ_3 is adjusted between 20s and 60s accompanied by 4s yellow time as suggested in [1]. The duration of phases ϕ_2 and ϕ_4 is kept equal to 15s green time followed by 4s of yellow time. Note that, similarly to ITLC, there is a coupling between opposite lanes and the green time applied to each in each cycle is the maximum of their individual values.

E. SUMMARY OF IM PROTOCOLS PROPERTIES

Table 2 presents the main properties of the IM approaches that we use for benchmarking. Concerning road infrastructure, it is required by some protocols (SIMP, ITLC, and QTLC), while other protocols work on plain roads, i.e., without infrastructure (RR and TTLC). Regarding left lane configurations, SIMP provides both dedicated and shared left lanes. Although all other protocols could also support the shared left lane configuration, we omitted it from this study for consistency with their proposals that considered dedicated left lanes, only.

For the TLC cycle decision-making, we can identify three different cases. While SIMP presents a reactive approach that responds to the presence of individual vehicles in the different lanes, RR and TTLC present a fixed cycle independent from the traffic patterns. ITLC and QTLC present an adaptive behavior that changes the cycle according to the current traffic intensity in the different lanes. This behavior is also reflected in the cycle length. SIMP presents the shortest cycle length for handling a single vehicle per lane. Conversely, all other protocols present cycle lengths that can grow considerably due to the use of a time slot. We indicate the maximum green time of both S/R and L lanes with variable cycle lengths.

The main objective pushing the development of the protocols was either to increase the fluidity of the traffic (SIMP), to simply manage the traffic to avoid collisions (RR and TTLC) or to reduce average delays (QTLC). ITLC aims at both increasing fluidity and reducing average delays.

VI. SIMULATION SETUP

This section describes the main models used in our simulations as implemented by the SUMO simulator, namely the car-following models (CFM) used for the driving control of AVs and HVs, the fuel consumption estimation model, and the simulation scenarios, along with their parameter settings.

A. CAR-FOLLOWING MODELS

The motion of each vehicle is determined by a CFM that generates a trajectory according to a specified path. The paths used in the simulation are shown in Fig. 1.

The CFM also determines the vehicle behavior when following another one. In our work, we considered the Krauss CFM to control HVs [17] and Adaptive Cruise Control (ACC) CFM control AVs [23], [39].

The Krauss CFM aims at letting cars drive as fast as possible while maintaining a safe distance. In this model, every vehicle can have two types of motion: free and interactive. In free motion, the vehicle velocity v is bounded by its maximum velocity v_{max} ($v \leq v_{max}$). In interactive motion, the vehicle (follower) interacts with the vehicle ahead (leader) to adjust its velocity to avoid collisions. In this situation, the follower vehicle velocity v_f is bounded by a safe velocity v_{safe}

TABLE 2. Main properties of the IM approaches under comparison.

IM	Road Infrastructure	Left lane	TLC	Green time (s) (S/R & L)	Objective
SIMP	Y	D/S	R	2.5 & 3s	Fluidity
RR	N	D	F	30 & 30s	Manage
TTLC	N	D	F	30 & 15s	Manage
ITLC	Y	D	A	[5 60] & 15s	Fluidity & Delays
QTLC	Y	D	A	[20 60] & 15s	Delays

Notes. D-dedicated, S-shared, R-reactive, A-adaptive, F-Fixed, Y-yes, N-no.

calculated for every time step using Eq 1:

$$v_{safe}(t) = v_l(t) + \frac{g(t) - v_l(t)\tau}{\frac{v_l(t)+v_f(t)}{2b} + \tau} \tag{1}$$

where, t is the time step, $v_l(t)$ is the velocity of the leader at time t, $v_f(t)$ is the velocity of the follower at time t, $g(t)$ represents the gap between vehicles in t, τ is the driver reaction time (default $1s$), and b is the deceleration function.

The ACC CFM is a vehicle longitudinal control system in which a vehicle adapts its speed (via brake and throttle actions) in a pre-selected time gap (default $1s$) whenever it detects a vehicle ahead using its sensors.

The distance and speed errors of a vehicle were used to model the acceleration in Eq 2:

$$a_k = k_1(X_{k-1} - X_k - t_{hw}v_k) + k_2(v_{k-1} - v_k) \tag{2}$$

where a_k, X_k, and v_k indicate the acceleration, position, and velocity of k^{th} vehicle, respectively; X_{k-1} and v_{k-1} are the position and velocity of preceding vehicle, t_{hw} is the selected time-gap; and k_1 and k_2 are the gains from both the position and speed errors [23], [39].

B. FUEL CONSUMPTION

In the SUMO simulator, fuel consumption is quantifiable based on the Handbook on Emission Factors for Road Transport (HBEFA3.1[4]). According to HBEFA and European Emissions Standard IV, the emission class PC_G_EU4 characterizes a passenger car (e.g., AVs and HVs) with gasoline fuel. Following HBEFA3.1, the total fuel utilization C for every vehicle trajectory is estimated using Eq 3.

$$C = \int_{t_i}^{t_j} Q(t)dt. \tag{3}$$

where t_i and t_j indicate the starting and the ending time instants while $Q(t)$ represents the fuel flow. Here, the fuel flow over time t is estimated using the velocity $v(t)$ and acceleration $a(t)$, i.e., $Q(t) = Q(v(t), a(t))$ [37].

C. PARAMETER SETTINGS

We simulate the discussed IM policies under practicable traffic settings employing the traffic simulator SUMO v1.6.0. The simulated scenarios have an intersection connecting four roadways of equal length (500 m), and the IIMAs grid area covers 100 m of each road starting from the intersection. The intersection space is set to 20 m^2, thus the maximum distance that vehicles travel to complete their journey is 1020 m. Both HVs and AVs are 5 m long, and the minimum safety distance among consecutive vehicles is 5 m. As described above, we employed the Krauss CFM for HV and ACC CFM for AV for vehicle driving and control mechanisms.

TABLE 3. Parameters used in the simulations.

Parameters	Values
Road Network Area	1020 X 1020 m^2.
Vehicle Length	5 *meters*.
Safety Distance	5 *meters*.
Vehicle Insertion Process	Random and Uniform between (0,1).
Vehicle Types	HVs (Krauss CFM), AVs (ACC CFM).
AVs rate	50%.
Acceleration	2.6 m/s^2.
Deceleration	4.5 m/s^2.
Emergency Braking	-9 m/s^2.
Minimum Time Headway	$1s$
HV Drivers Imperfection	0.5
Maximum Speed	30 km/h, i.e., 8.33 m/s.

We tested 30 km/h maximum speed with acceleration (2.6 m/s^2), deceleration (-4.5 m/s^2), and emergency deceleration (-9 m/s^2) respecting the low-speed urban mobility.[5] We have employed the SUMO default values for HVs and AVs representing car-following model-specific parameters, such as the minimum time headway (the time/space distance between a car's front bumper to the preceding car's back bumper), set at $1s$, and the driver imperfection parameter, set at 0.5. The summary of simulation parameters and assigned values are shown in Table 3.

We injected vehicle flows per road with average arrival rates from 0.05 to 0.4 veh/s covering non-saturated to saturated traffic conditions and using approximately regular points in a logarithmic scale. The vehicle traffic is also randomly dispersed across lanes with uniform distribution and balanced portions of AVs and HVs, i.e., 50% each. For assessing the intersection throughput, simulations were run for $1h$ of intersection operation; 1000 vehicles are considered for other metrics. In all scenarios, simulations were run five times over a range of random seeds for the same parameter values, and hence the results represent the average of those five simulation runs.

To reduce possible bias on the IM systems performance, in both scenarios, caused by the asymmetric distribution of directions in intersection crossing, we make vehicles take a random direction distributed uniformly for left, straight, and right crossings, i.e., 1/3 for each crossing direction. In the case

[4]https://www.hbefa.net/e/index.html

[5]https://sumo.dlr.de/docs/Vehicle_Type_Parameter_Defaults.html

of SIMP-S, the vehicles doing a straight crossing are evenly distributed to each lane, i.e., 1/6 to each.

Two traffic generation scenarios are defined to compare the performance of the IM approaches:

- Scenario-1: Continuous upstream traffic - the traffic is continuously injected in four inflow directions, randomly, with the specified average rates, following a time-invariant approach;
- Scenario-2: Interrupted upstream traffic - to represent real-world road intersections, the traffic is interrupted for every 250s in a circular fashion starting from the North. This creates a time-varying pattern in each lane.

The interrupted upstream traffic scenario provides insights into the adaptivity of these IM approaches to sustained variations in traffic patterns, either caused by road blockage, e.g., due to accidents or changes in road usage. To avoid inserting a bias on the performance of a single lane, we apply a 250s traffic interruption to all lanes, one at a time, in a cyclic fashion, starting from North and rotating clockwise. The duration of the traffic interruption corresponds to the longest time required by a stream of vehicles to exit the network under ITLC and QTLC in their worst cases. This is the highest value of all protocols. These protocols also couple every pair of opposing lanes by forcing the same green time in both every cycle. This needs to be taken into account when analyzing the results. For completeness, we also checked a few cases of simultaneous traffic blocking on opposite lanes, but we considered these to be less realistic, and thus we did not expand them. For saturated traffic conditions, the interruption periods may not be visible due to the presence of queued vehicles in all lanes.

VII. PERFORMANCE EVALUATION

We study the performance of various IM policies relying on three performance metrics: intersection throughput, average travel time loss, and average fuel consumption, with a speed limit of 30 km/h representing low-speed urban settings. Intersection throughput is determined as the number of cars that concluded their trip by crossing the intersection in an hour. The travel time loss is the delay cars suffer due to lining up on the approaching lane of the intersection attributed to the intersection operation, i.e., the time required for acceleration and deceleration and the stop time. As mentioned above, the total fuel consumption can be estimated by knowing the vehicle's velocity and acceleration from origin to destination. Here, we analyze the average fuel consumption of 1000 mixed vehicles. Finally, we will occasionally refer to SIMP-D and SIMP-S as SIMP protocols and to TTLC, ITLC, and QTLC as the xTLC protocols for the sake of simplicity.

A. INTERSECTION THROUGHPUT

Fig. 5 shows the intersection throughput results of two simulation scenarios with a maximum speed of 30 km/h, where the X-axis is the vehicle arrival rate in veh/s at each road on a log scale, including all three directions and both types of vehicles, as referred before. Throughput results show that each IM strategy results in a different saturation point in these tested scenarios. For instance, RR and xTLC protocols saturate at approximately 0.2 veh/s, and SIMP protocols at approximately 0.3 veh/s. Notably, SIMP-S exhibits the highest saturation throughput values in both scenarios as the straight-crossing vehicles are distributed by both inflow road lanes, enhancing their crossing opportunities in the intersection. Contrarily, SIMP-D piles up more straight/right-crossing cars on the right-most lane, reaching saturation faster and showing lower saturation throughput. RR achieves the lowest saturation throughput being the worst-performing IM approach. The differences in throughput results are minor for arrival rates of 0.133 veh/s and below. These differences become evident at 0.2 veh/s and above.

The interruption in upstream traffic influences the throughput results. Note that the vehicle arrival rates apply to periods of vehicle injection only, without accounting for the interruptions. However, due to the interruptions, there are less injected vehicles overall in scenario-2. This can be observed in Fig. 5, with lower throughput results for scenario-2 than for scenario-1 for traffic arrival rates until 0.2 veh/s, when saturation starts to occur. Upon saturation, each IM exhibits different behavior.

RR and TTLC are agnostic to changes in traffic inflow, thus, when the saturation level is sufficient to mask the traffic interruptions with queuing, they offer the same saturation throughput in both scenarios, namely a little more than 2000 veh/h for RR and a little less than 2500 veh/h for TTLC.

ITLC and QTLC have to be analyzed per scenario. In scenario-1, ITLC provides longer green times on average, resulting in a slightly improved saturation throughput. In turn, QTLC converges to green times that are close to those used in TTLC, leading to similar saturation throughput. However, as saturation increases, all xTLC protocols converge to the same saturation throughput near 2500 veh/h.

In scenario-2, ITLC shows an unexpected degradation. This is caused by the coupling of the green times of both opposing lanes being served in each phase. Thus, ITLC is unable to adapt to the interruption in a single lane, and it will continue offering long green times for less vehicles, thus effectively reducing throughput. Conversely, QTLC tracks long-term average arrival rates, being influenced by a time window that captures the interruptions in both opposite lanes. This allows it to effectively adjust the green times to the actual arrival rates, thus improving throughput.

Finally, as expected, SIMP protocols show the highest saturation throughput since they explore parallelism in crossing the intersection per vehicle. They are also reactive at the vehicle resolution, thus accommodating instantaneously any change in arrival patterns. As discussed before, SIMP-D

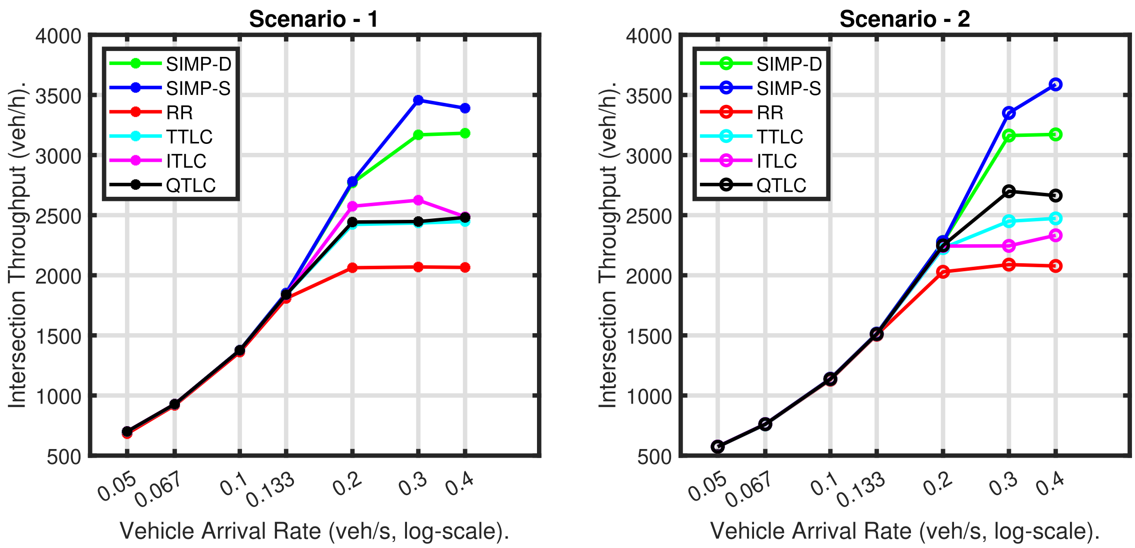


FIGURE 5. Intersection throughput (no. of vehicles) of continuous (scenario-1) and interrupted (scenario-2) upstream traffic flows for 30 km/h maximum speed.

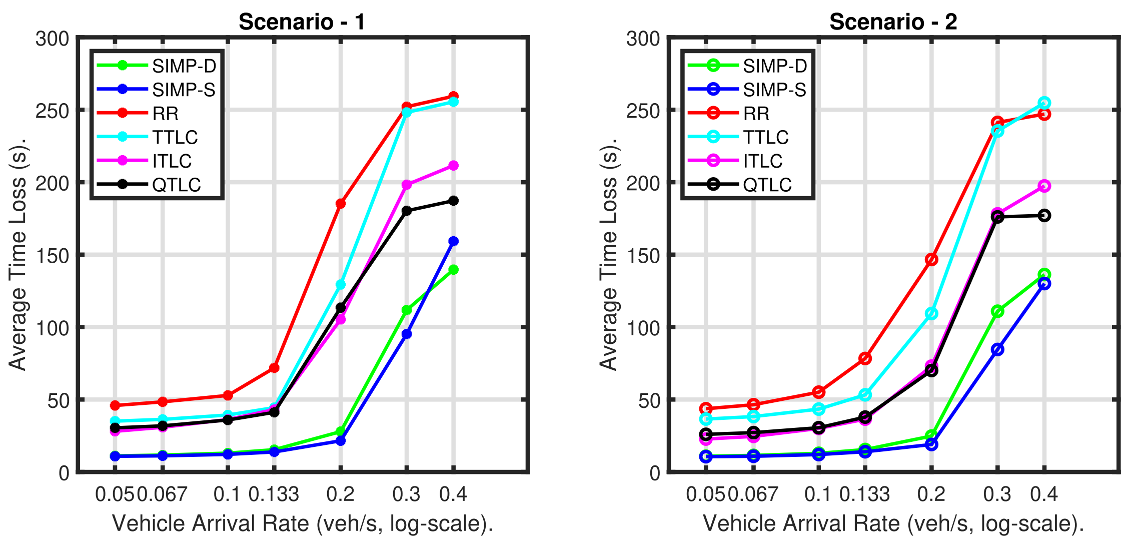


FIGURE 6. Average travel time loss (s) of 1000 vehicles for Scenario-1 and Scenario-2 at 30 km/h maximum speed.

saturates faster due to the accumulation of traffic on the right lanes, reaching approximately 3200veh/h in both scenarios. SIMP-S goes beyond, reaching around 3500veh/h. The difference between the two scenarios in SIMP-S is still being analyzed, whether it is an artifact of the simulation conditions or a fundamental aspect of the protocol. In any case, SIMP-S is clearly the protocol that achieves the highest sustained throughput, saturating with almost twice the saturation throughput of RR.

B. TRAVEL TIME LOSS

The average travel time loss results for both scenarios for 30 km/h maximum speed are presented in Fig. 6. The X-axis shows the vehicle arrival rate in veh/s on each road, while the Y-axis shows the average travel time loss (s) of 1000 vehicles. RR and TTLC show the highest time losses, with a small disadvantage for RR. In these protocols, the time loss is similar in both scenarios, with a slight decrease in scenario-2. This is caused by traffic interruptions leading to queue size reductions in the respective lanes. Thus, the vehicles that arrive after the interruptions suffer smaller time losses.

ITLC and QTLC show very similar behavior between them and lower time loss than the previous two protocols. The only visible difference is under strong saturation, as we have already seen that ITLC becomes less effective than QTLC. These protocols show the largest reduction from scenario-1 to scenario-2, given their adaptive features that increase the green times and serve more vehicles per cycle. However, this is non-trivial as longer green times also increase the cycle time, but this effect seems to be less impactful.

Again, the SIMP protocols offer the lowest time loss, which also maintains almost similar behavior between

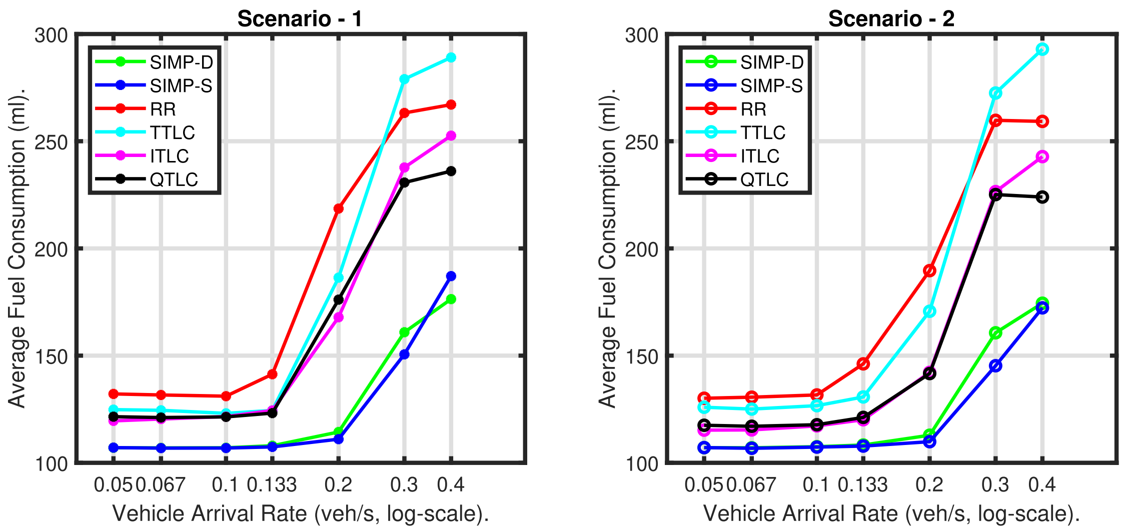


FIGURE 7. Average fuel consumption (ml) of 1000 vehicles for Scenario-1 and Scenario-2 at 30 km/h maximum speed.

scenarios. There is a small difference for SIMP-D, which shows a slightly higher time loss in scenario-1 under strong saturation. This is due to the accumulation of traffic in two directions in the right lanes (right and straight crossings).

C. FUEL EFFICIENCY

Fig. 7 illustrates the average fuel consumption results of the same experiments as mentioned earlier. The first observation is that fuel consumption behavior correlates with the corresponding behavior of travel time loss in each scenario. This is expected since the higher the time lost, the longer the engines work with slow movements or even idling, and more fuel is consumed. Thus, similar comments apply. There is just one particular note concerning TTLC, in which fuel consumption increases significantly for strong saturation traffic, surpassing RR. This is due to a higher number of start-stop queue maneuvers that TTLC allows per cycle.

D. SUMMARY

The experiments with both continuous (time-invariant) and interrupted (time-varying) upstream traffic scenarios explored the performance of IMs at an isolated intersection w.r.t. throughput, travel time loss, and associated fuel efficiency. These are relevant metrics for sustainable road transportation. In general terms, with time-invariant balanced traffic patterns (scenario-1), the protocols can be classified into three groups according to their performance. RR is alone as the worst-performing protocol. Then, the xTLC protocols show an intermediate performance, with a slight advantage of QTLC under strong saturation and a general disadvantage of TTLC. Then, SIMP protocols exhibit a similar performance but are significantly better than the other protocols.

Under time-varying traffic patterns (scenario-2), the capacity of the protocols to adapt dynamically impacts the performance. This is visible for both ITLC and QTLC, generally improving their metrics when the traffic has interruptions. The only exception is throughput, in which ITLC actually degrades its performance, as explained before. In general, the rigidity of TTLC makes it depart from the xTLC group and exhibit a performance that now approaches and even falls behind that of RR in terms of fuel consumption. SIMP protocols exhibit their inherent reactivity capability and maintain the best performance across all scenarios, metrics, and traffic intensities. We hypothesize these benefits emerge from the synchronous movement of vehicles upon their arrival at the intersection one by one, which may lead to an emerging behavior of a slowly moving queue with fewer starts/stops.

Finally, we also experimented with the original configurations of TTLC, ITLC, and QTLC with the shared left lanes handled as presented by their authors. These allow left and straight-crossing vehicles from opposing lanes to enter the intersection simultaneously and conflicts are avoided by the vehicles. The simulation results are comparable, plus a minimal increase in intersection throughput, travel delays, and fuel consumption because the left-turning vehicles yield to let the vehicles through movement from the opposing roads cross first. This kind of operation is less safe than the dedicated left-turn movement due to its dependency on cars to prevent collisions. We also experimented with a speed limit of 50 km/h, having reached similar results, despite a slightly lower relative advantage of SIMP concerning the other protocols.

VIII. LIMITATIONS

This work extends the synchronous framework (IIMA/SIMP) initially proposed for simple single-lane intersections to complex multi-lane intersections. Nevertheless, the efforts to implement the considered IM approaches through simulation development and analysis of their results have some limitations. As aforementioned, all AVs and HVs use similar car-following models, ACC and Krauss, respectively. However, several manufacturers implement different control algorithms and drivers may exhibit variable driving patterns, and this volatility is not considered in this work. Moreover, despite the large extent of the simulations, the random traffic generation process may still cause some level of bias in the results. However, given the smoothness of the patterns in the results, we believe these are small enough to be neglected. Finally, the results are limited to the defined scenarios, directions, traffic patterns, and specific intersection layouts. However, we believe that using a uniform distribution of directions upon arriving at the intersection captures the intrinsic properties of the IMs. Similarly, using two types of traffic generation, namely time-invariant and time-varying, captures the adaptation capabilities of the IIMs, and finally, the intersection layouts used are prevalent in practice. Therefore, we believe the results are significant.

IX. CONCLUSION

This paper addresses intersection management protocols for low-speed urban areas that handle AVs and HVs indistinctly. In particular, the paper considered the recent IIMA/SIMP framework and proposed its extension to multi-lane complex intersections with two inflow/outflow lanes frequently found in urban settings. Two intersection operations are considered, particularly the dedicated left-turn movement and shared left-turn movement intersections. We implemented both SIMP-D and SIMP-S and four other IM mechanisms for comparing two traditional ones (TTLC and RR) and two IIM ones (ITLC and QTLC). These represent the state-of-the-art IMs that are agnostic to the type of vehicle, either AV or HV. All IM strategies are simulated using the SUMO framework for various practicable vehicle arrival rates in low-speed urban settings, i.e., 30 km/h maximum speed, with time-invariant and time-varying traffic patterns. We collected three metrics to quantify the performance of the IM protocols, namely throughput, travel time loss, and fuel consumption. SIMP shows that a synchronous approach can outperform existing strategies in all metrics and scenarios, confirming the benefits already observed in simple single-lane intersections, and revealing a high potential to improve sustainability in urban road systems. Moreover, the application of SIMP to complex intersections can easily be adapted to other types of urban intersections, such as T-type, hybrid lane configurations, and multi-legged.

In future research work, we target to adapt the synchronous framework for various-sized vehicles, i.e., short-haul to long-haul vehicles, and for grids of intersections.

DISCLOSURE STATEMENT

The authors notify that there is no potential conflict of interest.

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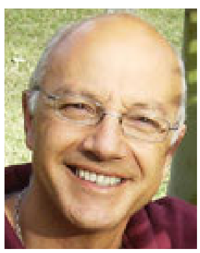
RADHA REDDY (Graduate Student Member, IEEE) received the B.Sc. and M.Sc. degrees in computer science from Sri Venkateswara University, in 2007 and 2009, respectively, and the M.Tech. degree in computer science and engineering from JNTU-Anantapur, Andhra Pradesh, India, in 2014. He is currently pursuing the Ph.D. degree with FEUP, University of Porto, Porto, Portugal.

He was with the FCT Fellowship, in 2021. Since October 2013, he has been an External Collaborator with the CEDRIC Laboratories, CNAM-Paris, France. He is currently a Research Fellow with the CISTER Research Center (ISEP). He has two years of teaching experience in educational institutions in India. Before the CISTER Research Center, he was involved in full-time research with COPELABS-Lisbon and Inria-Paris. His research interests include intelligent transportation systems (ITS), wireless sensor networks (WSN), cyber-physical systems (CPS), cloud and information security, self-organized systems, and the coordination and co-operation of heterogeneous networked systems.



LUIS ALMEIDA (Senior Member, IEEE) received the Graduate degree from the University of Aveiro, Portugal. He is currently an Associate Professor with the Electrical and Computer Engineering Department, University of Porto, Portugal, where he coordinates the Distributed and Real-Time Embedded Systems Laboratory (DaRTES). He is also the Vice Director of the CISTER Research Center on Real-Time and Embedded Computing Systems, the Past Chair of TCRTS—the IEEE Technical Committee on Real-Time Systems (Chair), in 2020 and 2021, and the Chair of EMSIG—the EDAA Special Interest Group on Embedded Systems. He is the Editor-in-Chief of the *Journal of Real-Time Systems* (Springer) and an Associate Editor of the *Journal of Systems Architecture* (Elsevier) and the *SAGE International Journal on Advanced Robotic Systems*. He was the Program and General Chair of the IEEE Real-Time Systems Symposium, in 2011 and 2012, respectively, the Local Co-Chair, in 2016, and the General Co-Chair of CPSweek, in 2018. He was also a Trustee of the RoboCup Federation, from 2008 to 2016, and the Vice President, from 2011 to 2013. His research interests include real-time communications for distributed industrial/embedded systems, for teams of cooperating agents and sensor networks.

MIGUEL GUTIERREZ GAITÁN (Member, IEEE) received the B.S. degree in electronics engineering from the Pontifical Catholic University of Valparaso (PUCV), Chile, the M.S. degree in telecommunications engineering from the Polytechnic University of Turin (PoliTo), Italy, and the Ph.D. degree in electrical and computer engineering from the University of Porto, Portugal.

Since 2023, he has been the Chairman of the IEEE ComSoc Chile Chapter and a Research Associate with the Research Centre in Real-Time and Embedded Computing Systems (CISTER), Porto, Portugal. He is currently an Assistant Professor with the Faculty of Engineering, Andrs Bello University (UNAB), Santiago, Chile. He has coauthored more than 25 peer-reviewed publications in relevant journals and conferences including, IEEE Sensors Journal, IEEE Embedded Systems Letters, IEEE WF-IoT, IEEE RTSS, IEEE VTC, and IEEE GLOBECOM. Among other honors and awards, he received the ''Best Paper Award'' at the RAGE Workshop at DAC 2022 and the ''Best Work-in-Progress Paper Award'' at IEEE WFCS 2021. His research interests include wireless networking, real-time communication, and the IoT.

PEDRO M. SANTOS received the B.Sc. and M.Sc. degrees in electrical and computer engineering from the University of Porto, Portugal, in 2009, and the joint Ph.D. degree in electrical and computer engineering from the University of Porto and Instituto de Telecomunicações (Portuguese Research and Development Institution), in 2017. He is currently an Assistant Researcher with the CISTER Research Unit, Porto, Portugal, and as an invited Assistant Lecturer with the University of Porto. He has been a P.I. for international projects, notably Eureka ITEA3 ''MIRAI'' and Carnegie Mellon University-Portugal Program ''FLOYD.'' He was a postdoctoral and Ph.D. student researcher in numerous Portuguese (P2020), European (FP7), and international projects (CMU-Portugal Program). He has published and a Reviewer for a number of forums on communications and networking (IEEE Transactions on Wireless Communications, VNC, and VTC) and served or serves as a TPC Member for IEEE VNC, WCFS, and EAI Future5V. He was a Visitor to Carnegie Mellon University for three months. His research interests include wireless propagation, 5G/6G, vehicular networking, and the Internet of Things for smart cities.

EDUARDO TOVAR (Member, IEEE) received the Licentiate, M.Sc., and Ph.D. degrees in electrical and computer engineering from the University of Porto, Porto, Portugal, in 1990, 1995, and 1999, respectively. Currently, he is a Professor with the Computer Engineering Department, School of Engineering (ISEP), Polytechnic Institute of Porto (P.Porto), where he is also engaged in research on real-time distributed systems, WSN, multiprocessor systems, CPS, and industrial communication systems. He heads the CISTER Research Laboratories. He was the Vice Chair of ACM SIGBED (2015–2019) and a member of the Executive Committee of the IEEE TC-RTS. Since 1991, he has ben authored or coauthored more than 300 scientific papers in the areas of RTES, CPS, and WSN. He has been consistently participating in top-rated scientific events as the Program Chair (e.g., ECRTS—2005, RTCSA—2010 and 2016, RTAS—2013, and ICCPS—2016). He has been the General Chair/Co-Chair of various scientific events, including the IEEE/ACM CPS Week—2018.