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July 30, 2021

Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2021) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

24th Euro Working Group on Transportation Meeting, EWGT 2021, 8-10 September 2021,
Aveiro, Portugal

Synchronous Framework Extended for Complex Intersections

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Abstract

Current trends towards smart mobility aim at mitigating traffic congestion and providing intelligent and sustainable transportation. Intelligent intersection management systems are an integral part of this trend and profoundly impact urban traffic management. To this purpose, we proposed in prior work a specific Intelligent Intersection Management Architecture (IIMA) for single-lane isolated intersections with an associated Synchronous Intersection Management Protocol (SIMP). The IIMA/SIMP framework targeted autonomous and human-driven vehicles and outperformed competitors in several metrics, notably intersection throughput, time loss, fuel efficiency, and polluting emissions. This paper is the first step to extend such a framework to the more complex scenario of multi-lane intersections, particularly for dedicated left-turn lanes and shared lanes. Using SUMO, we compare IIMA/SIMP performance against competing traditional and intelligent intersection management approaches. Simulation results under varying vehicle arrival rates confirm the advantages of IIMA/SIMP even in complex intersections, improving intersection throughput and reducing average trip time loss.

Keywords: Smart Cities; Smart Mobility; Intersection Management; IIMA; SIMP; Complex Intersections.

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1. Introduction

Smart mobility is one of the thematic areas of smart cities used to improve the Quality-of-Life of city individuals through intelligent transportation (Chen et al., 2016). Intelligent Intersection Management (IIM) is a state-of-the-art solution that targets optimizing resource utilization (e.g., fuel or battery), improve transportation efficiency and user safety, reduce time delays, etc. Nowadays, smart mobility is deeply considering fully automated transportation relying

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on Autonomous Vehicles (AVs). However, AVs are not expected to dominate urban mobility before 2045 (Bansal et al., 2017). Until then, AVs must co-exist with Human-driven Vehicles (HVs) in mixed traffic scenarios.

In general, IIM approaches have been proposed to mitigate traffic congestion under different degrees of AVs/HVs mixed operation (Abdulhai et al., 2003; Younes et al., 2014; Yang et al., 2016; Aoki et al., 2017, 2019). In these cases, the traffic lights control (TLC) decision-making combined information from several heterogeneous sources, including AVs, road-side units (RSU), etc., while leveraging vehicle-to-anything (V2X) communications.

Along this research line, Reddy et al. (2019) proposed an Intelligent Intersection Management Architecture (IIMA) building upon a Synchronous Intersection Management Protocol (SIMP) for simple single-lane road intersections. IIMA/SIMP outperformed competing approaches in intersection throughput, travel time loss, fuel consumption, and polluting emissions (Reddy et al., 2020, 2021). This paper is the first step to extend IIMA/SIMP to complex multi-lane (two lanes) road intersections considering both dedicated left-turn lanes (SIMP-D) and shared lanes (SIMP-S). In the dedicated left-turn lane, the center-most lanes are exclusively dedicated for left-turning vehicles, while the right-most lanes are shared by the straight and right crossing vehicles. In the case of the shared lane, both lanes are shared, meaning that the center-most lane is shared by the straight and left crossing vehicles while the right-most lane is shared by the straight and right crossing vehicles. We then compare them qualitatively and quantitatively against two conventional (pre-timed) intersection management strategies, namely Round-Robin (RR) and Trivial Traffic Light Control (TTLC) (Björck et al., 2018), and two IIM approaches, namely, Intelligent Traffic Light Control (ITLC) (Younes et al., 2014) and Q-learning-based Traffic Light Control (QTLC) (Abdulhai et al., 2003). We simulate these approaches under identical urban traffic conditions using the SUMO simulation framework (Lopez et al. , 2018), and we evaluate their performance in terms of intersection throughput, average time loss, and the average number of stops. The results show that SIMP outperforms all the competing approaches for both types of intersections, except for the number of stops under saturated traffic conditions.

2. Related Work

There is a rich literature tackling complex multi-lane intersections, from conventional pre-timed (Björck et al., 2018; Alekszejenkó et al., 2019) to the intelligent (Abdulhai et al., 2003; Younes et al., 2014; Yang et al., 2016; Zheng et al., 2019), and synchronized approaches (Tlig et al., 2014; Azimi et al., 2015; Aoki et al., 2017, 2019).

The conventional pre-timed approaches switch green phases in a specified order for a maximum allocated time. The RR (Alekszejenkó et al., 2019) and TTLC (Björck et al., 2018) IM mechanisms are the most common conventional approaches. Abdulhai et al. (2003) presents the QTLC mechanism that employs queue-length and elapsed phase time to adjust the green-light timing. The ITLC algorithm was introduced by Younes et al. (2014), using vehicle movement information (queue-length, speed, acceleration, and distance) for traffic signal optimization. We employ RR, TTLC, QTLC, and ITLC IM mechanisms for comparison and further explain them in the coming sections.

Yang et al. (2016) developed an intersection traffic control algorithm (ITCA) for minimizing the total delay of mixed traffic using optimal departure sequence and vehicle position information. The simulation results show that the ITCA is superior to the actuated signal control algorithm that adapts TLC signals based on the traffic information from loop detectors. However, the departure sequence control conflicts with our target of random departure and direction; thus, ITCA is not comparable. Zheng et al. (2019) presented a delay-tolerant IIM for multi-lane intersections to tackle efficiency and deadlock. Simulation results show that this IIM outperforms various back-pressure control mechanisms under low communication delays. However, this mechanism is applicable for AVs only; thus, incomparable to SIMP.

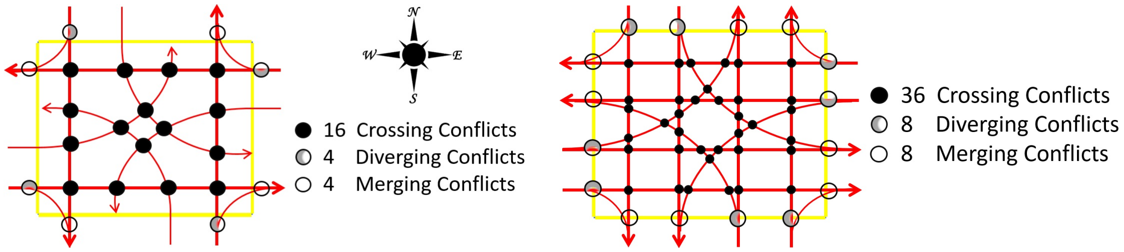
A synchronization-based intersection control mechanism was proposed by Tlig et al. (2014) using local vehicle information at individual intersections that synchronize AVs movements. Therefore, AVs maintain some gaps by reducing their speed. This synchronization significantly reduced total delays and associated fuel consumption compared to the conventional mechanism. Aoki et al. (2017) introduced a configurable synchronous intersection protocol (CSIP) using inter-vehicle distance for AVs management at complex intersections involving GPS errors. CSIP reduced the number of collisions for increased average trip delays than its previous version of the protocol (ballroom intersection protocol, BRIP (Azimi et al., 2015)). In BRIP, AVs synchronize to use the maximum intersection capacity, thus allowing vehicles from all inflow lanes to continue as they arrive. The authors claimed that BRIP improved throughput by 96.24%. Aoki et al. (2019) presented a Distributed Synchronous Intersection Protocol (DSIP), which synchronizes AVs when there are no HVs. The performance of DSIP shows that the trip delay is high for growing AVs penetration rates. In these approaches, the synchronization is among AVs only. Conversely, we tackle seemingly mixed traffic patterns with any ratio of AVs and HVs using sensory data to increase the concurrent traffic management.

3. Signalized Intersection Management Strategies

This section provides the preliminaries of the multi-lane intersections cases we address, namely the dedicated left-turn lane and shared-lane intersections. Then, it details the *synchronous framework*, i.e., the intelligent intersection management architecture (IIMA) and synchronous intersection management protocol (SIMP), applied to such complex multi-lane intersections. This step involves the functional configuration of inflow lanes (i.e., dedicated or shared) and vehicle movements within the intersection (e.g., single or multi left/straight/right-crossing) in horizontal and vertical lanes. Later, we briefly describe the benchmark approaches used for comparison, two conventional IMs (RR and TTLC) and two IIMs (ITLC and QTLC). The RR and TTLC were selected due to their widespread usage. The ITLC was chosen as both the TLC decision-making and order of phases rely on sensory data, similarly to SIMP. The QTLC was chosen because the traffic management at an isolated intersection is perceived as realistic through multi-agent systems coordination.

3.1. Dedicated vs. Shared Left-Turning Lane Intersections

This work considers an isolated four-way two-lane road intersection with a 90° angle between horizontal and vertical ways, and each way contains two inflow and two outflow road lanes. We consider two possible lane assignments, namely dedicated and shared left-turn lanes. We do not consider dedicated right-turn lane, which is more suitable for a one-way to the one-way road turning in high-speed road lanes (Chandler et al., 2013). The dedicated left-turn lane allows vehicles to cross the intersection turning left without blocking the following vehicles. It also aims at reducing potential rear-end collisions among left and straight-crossing vehicles that may happen in shared-lane movements. However, shared lanes are broadly used at current times. Based on the lanes by which vehicles approach the intersection and the vehicles crossing directions, three types of potential conflicts are identified: crossing, diverging (rear-end and sideswipe), and merging conflicts. These conflicts for dedicated and shared left-turn lanes are presented in Fig. 1a and 1b, accordingly. The figure clearly shows the higher complexity of the shared lane case with a higher number of crossing conflicts.



(a) Dedicated left-turn and shared straight/right-crossing. (b) Shared left/straight and straight/right-crossing.

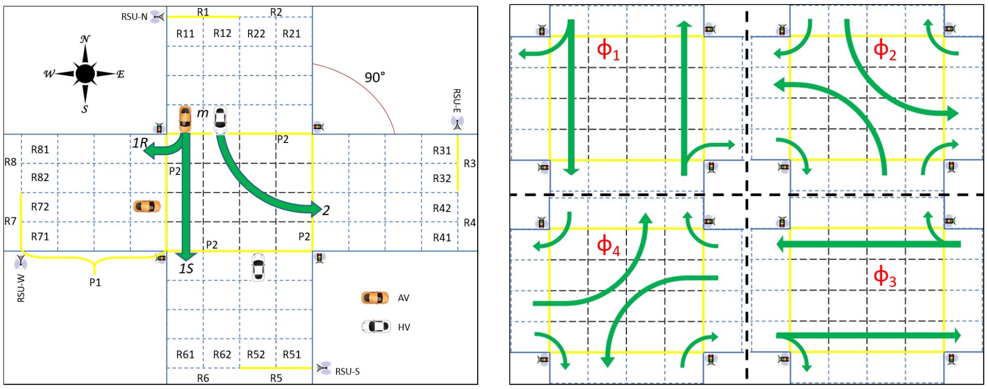
Fig. 1: Potential conflicts of dedicated and shared left-turn lane for a four-way two-lane road intersection.

3.2. Synchronous Framework

The following assumptions are made within IIMA. At the intersection, overtaking and U-turns are not permitted, and in each lane, vehicles are serviced according to First-Come-First-Served (FCFS) policy. AVs are assumed to have the standard components, such as localization, path planning, and autonomous control, including the wireless communication interface and several sensors (Zheng et al., 2019; Aoki et al., 2019). HVs may or may not be equipped with sensors and wireless communication interfaces similar to AVs, but without loss of generality, we consider them non-communicating. The road infrastructure, including TLC, RSUs, and road sensors, is assumed to have wireless communication capabilities. Direct communication among AVs and road infrastructure (TLC and RSUs) provide reliable information exchange. The road-sensors include cameras that allow detecting HVs. AVs access the intersection upon receiving authorization messages from the TLC, while HVs follow the TLC light signals.

Figure 2 represents the IIMA for a dedicated left-turn lane with crossing-conflicts as in Fig. 1a. The IIMA is designed to support mixed traffic, i.e., both HVs (white-color) and AVs (yellow-color). In IIMA, some length of road-lanes approaching the intersection and the intersection space is virtually divided into grid-cells that accommodate a vehicle and target safe distance among consecutive vehicles. R_i represents inflow ($i = 1, 3, 5, 7$) and outflow ($i = 2, 4, 6, 8$) road-lanes. In inflow lanes, R_{ij} stands for the right-most and center-most lanes, for $j = 1$ and $j = 2$, respectively. For outflow lanes, R_{ij} stands for the left-most and center-most lanes, for $j = 1$ and $j = 2$, respectively.

The right-most inflow lane is shared by the right (*m=1R*) and straight-crossing (*m=1S*) vehicles while the center-most inflow lane, in this case, is dedicated for the left-crossing vehicles (*m=2*). We call *m* the direction code.



(a) IIMA for a four-way two-lane road intersection.   (b) CDM-based SIMP control phases.

Fig. 2: Intelligent Intersection Management Architecture (IIMA) along with the Direction Codes (***m***): ***1R/1S***-shared right/straight-crossing and ***2***-dedicated left-crossing; and CDM-based SIMP control phases.

Each road is associated with an RSU that manages two specialized road sensors (P_1 and P_2) that combine induction loop detectors with cameras. The RSUs directly communicate with the TLC recurrently and without significant communication delays. Here, the TLC is assumed to be the primary management entity with the knowledge of intersection traffic within the grid area every time instant *t*. To feed the TLC with accurate information, the RSUs fuse the number of cars and their target directions obtained from P1 with communications from AVs that signal their presence and target direction. Note that HVs (non-communicating vehicles, in fact) will be detected by P1 only. The resulting IIMA can allow/block vehicles to the intersection through a well-defined set of conflict-free vehicle maneuvers. After exiting the intersection, AVs confirm their exit through V2X communication, while P2 detects the exit of HVs.

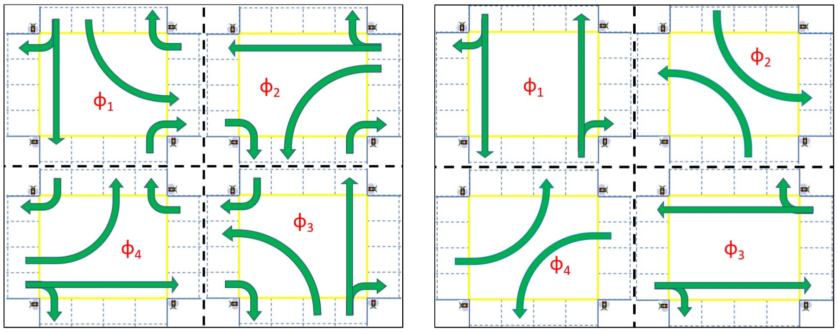
IIMA uses SIMP to process the synchronized movement of vehicles through the intersection in cycles. The end of one cycle triggers the next cycle that enables vehicles' access to non-conflicting directions. In any cycle, SIMP follows the following steps: 1) detecting vehicles at the intersection entrance and determining the total number of vehicles within the access grid area using sensor P1, 2) managing intersection entrance using the *Conflicting Directions Matrix* (CDM), and 3) waiting for vehicles to exit the intersection using sensor P2. Once all vehicles exit the intersection, a new cycle is repeated, going back to step 1.

Table 1: Conflicting Directions Matrix for a 4-way two-lane intersection with dedicated left-crossing (0-no conflict, 1-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			

Table 1 shows the CDM for the dedicated left turn IM strategy (see Fig. 1a). Each matrix position $CDM(D_{ri,mi}; D_{rj,mj})$ represents the conflict state between two vehicles willing to cross the intersection, one arriving from road-lane R_{ri} with direction code mi and the other from road-lane R_{rj} with direction code mj. In the table, 0 indicates a pair of conflict-free directions, and 1 indicates conflicting directions.

The CDM is employed in designing the intersection control phases (ϕ_1, ϕ_2, ϕ_3, ϕ_4) of SIMP protocol presented in Fig. 2b. If no vehicles are detected in a specific phase, the protocol moves immediately to the next phase, allowing vehicles from all lanes in a fluid and fair approach. Note that in each phase, the protocol executed the full 3-steps control cycle referred before.



(a) Round-Robin IM control phases. (b) TTLC, ITLC, and QTLC control phases.

Fig. 3: Control phases of the intersection management protocols used for comparison.

3.3. Round-Robin (RR) Intersection Management

The RR IM strategy is a pre-timed IM system that switches green-phases in a circular order for a fixed allocated time assigned to each road direction in equal amounts (Alekszejenkó et al., 2019). This strategy creates a cycle that we consider to rotate in a clockwise direction. In this paper, the RR IM strategy is improved as usual by permitting non-conflicting right-crossing vehicles from all road lanes. Figure 3a illustrates this RR IM strategy for a dedicated left-turn lane with four TLC phases (ϕ_1, ϕ_2, ϕ_3, ϕ_4) of 30s green time followed by a 4s yellow phase while the other lanes are blocked with red phases.

3.4. Trivial Traffic Light Control Mechanism - TTLC

The TTLC mechanism is also a pre-timed system for a fixed allocated time. In this mechanism, the traffic is controlled by permitting vehicles from two opposite directions, i.e., either from North and South or East and West (Björck et al., 2018). In the four-way two-lane road intersection that we are considering, the center-most lane is dedicated for left-crossing while the right-most lane is shared by the straight and right-crossing vehicles, same as the RR IM strategy. These two lanes are served in sequence for each of the two pairs of opposite directions. This also results in four phases (ϕ_1, ϕ_2, ϕ_3, ϕ_4) that are displayed in Fig. 3b. ϕ_1 and ϕ_3 are assigned with 30s of green time plus 4s of yellow time, while ϕ_2 and ϕ_4 are assigned with 14s of green time plus a similar window of 4s of yellow time. All other lanes are blocked with red phases.

3.5. Intelligent Traffic Light Control Algorithm - ITLC

The ITLC algorithm was presented by Younes et al. (2014). ITLC employs sensory information such as queue length, vehicle speed, and acceleration to determine traffic light phases, order, and length (time) of execution. A lane with a longer queue gets the higher priority. The vehicle speed and distance to the intersection are employed in determining the queue traversal time. The largest traversal time is utilized for allocating green phase timing as long as it is below the fixed maximum green time 60s, followed by a 4s yellow phase while the other lanes are blocked with red phases. The intersection control phases (ϕ_1, ϕ_2, ϕ_3, ϕ_4) of ITLC are the same as in Fig. 3b.

3.6. Q-learning based Traffic Light Control Algorithm - QTLC

The QTLC algorithm was introduced by Abdulhai et al. (2003) for reducing time delays based on multi-agent systems. QTLC utilizes traffic queue-length and elapsed phase time for TLC decision-making, and it decides either to continue with the current phase or to switch to another phase to reduce total vehicle delays. In QTLC, the minimum TLC cycle-length is fixed to 20s, with an arbitrary limit of 10s at the beginning and 10s at the end of the cycle. Like TTLC and ITLC, QTLC has also been implemented for a dedicated left-turn lane that permits vehicles from two opposite directions. The QTLC phases are also the same shown in Fig. 3b, in which each green phase is set between 20s and 60s followed by a 4s yellow time while the other lanes are blocked with red phases.

4. Simulation Setup

We simulate the referred IM strategies under realistic traffic conditions using the SUMO v1.6.0 simulator. We ran it on an Intel i3-4160 CPU, with 4 cores at 3.60Ghz, NVIDIA RTX 2070, 8GB RAM, and 64 bit Ubuntu 18.04.4 LTS OS. The simulated scenario has an intersection joining four 500m long roads. The grid area of IIMA covers 100m of each road next to the intersection. Vehicles are 5m long, and the minimum inter-vehicle distance is 5m. We employed the Krauss and Adaptive Cruise Control car-following models representing HV and AV driving and control mechanisms. We consider two-speed limits typical in urban settings, i.e., 30 and 50km/h, with a maximum acceleration of 2.6m/s^2, a maximum deceleration of -4.5m/s^2, an emergency deceleration of -9m/s^2, a minimum 1s time headway between vehicles and a driving imperfection factor of 0.5, which are common values in similar simulations.

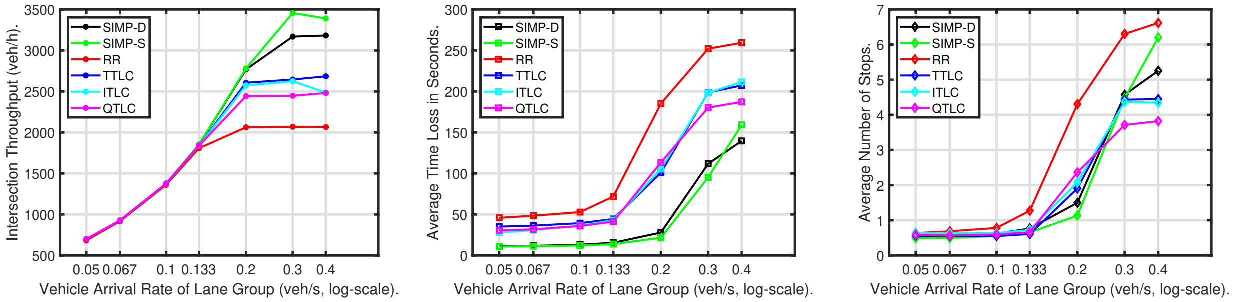
To analyze the IM systems performance, in the simulation scenario, vehicles take a random direction at the intersection, which is uniformly distributed for left, straight, and right crossings. To generate variable traffic intensities, we injected vehicles at the beginning of each road every second with a probability that respects the following average rates: 0.05, 0.067, 0.1, 0.133, 0.2, 0.3, and 0.4veh/s. The vehicles are also randomly chosen with uniform distribution and equal shares as AV or HV, i.e., 50% each.

For intersection throughput, we simulated $1h$ of operation. For the other metrics, we simulated the intersection operation for 1000 vehicles. The simulations ran five times with different random seeds for the same set of parameters in all scenarios. The results are the average of the five runs.

5. Performance Evaluation

We assess the different IM approaches using three metrics, namely intersection throughput, average trip time loss and average number of stops, in all cases for both $30Km/h$ and $50Km/h$. Intersection throughput is defined as the number of vehicles that completed their journey by crossing the intersection in one hour. The trip time loss and number of stops are analyzed for 1000 vehicles. The trip time loss is the delay that vehicles experience due to queuing when approaching the intersection caused by the intersection management, i.e., the time needed for acceleration and deceleration plus the stop time. Besides, the average number of stops (or stop rate) is also a critical intersection performance metric. Xia et al. (2012) refer that vehicles' stop-and-go behavior can cause up to 14% more fuel consumption and emission of air pollutants when compared to constant speed. Finally, for the sake of simplicity, we will occasionally refer to TTLC, ITLC, and QTLC as the xTLC protocols, as well as to SIMP-D and SIMP-S as SIMP protocols.

5.1. 30km/h Results



(a) Intersection throughput (veh/h). (b) Average time loss (s). (c) Average number of stops.

Fig. 4: Intersection throughput, average time loss and average number of stops for 30km/h.

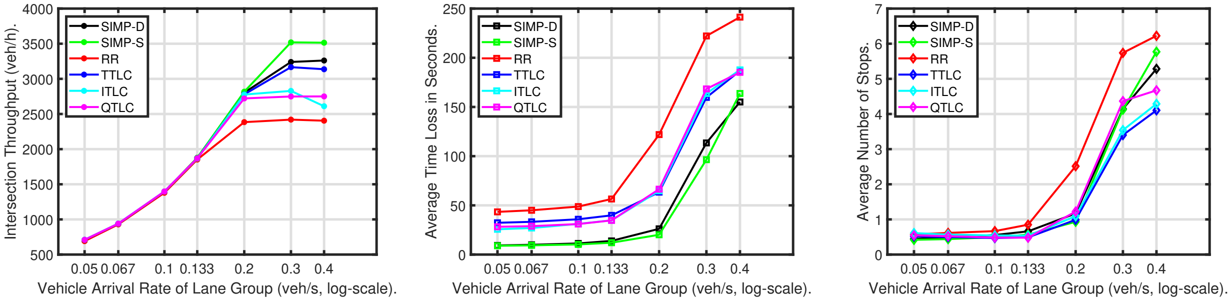
Fig. 4 shows the results of intersection throughput, average time loss, and the average number of stops for 30km/h. Each specific IM policy leads to a different intersection saturation point (Fig. 4a). RR saturates for traffic density near 0.133veh/s, xTLC policies saturate at 0.2veh/s and SIMP ones at 0.3veh/s. SIMP-S presents the highest throughput in all tested scenarios. The reason is that the straight-crossing vehicles share both center-most and right-most lanes, increasing their chances of crossing the intersection. Conversely, SIMP-D accumulates more vehicles in the shared straight/right-crossing lane. The differences in throughput are negligible for low traffic densities (0.1veh/s or lower).

At 0.133veh/s, we start observing a relative degradation of RR, which is the policy that performs the worst. The throughput difference between xTLC and SIMP protocols becomes visible at 0.2veh/s and above.

Fig. 4b and 4c show the average time loss and stop ratio results for 30km/h, respectively. The average time loss shows a clear separation between the performance of RR (the worst), the xTLC protocols (intermediate), and the SIMP approaches (the best). Within each group, the differences are negligible below the saturation point, increasing slightly for highly saturated scenarios (0.3veh/s or more). For the average number of stops, the results are similar for all protocols in non-saturated conditions. Upon saturation, we observe a relative increase in the number of stops, first by RR and then by xTLC protocols with respect to SIMP protocols. Curiously, the situation flips for strongly saturated scenarios (0.4veh/s), with the number of stops increasing significantly for the SIMP protocols. We believe this is due to SIMP allowing one vehicle from each non-conflicting lane at a time, only leading to 1 stop per-protocol cycle. SIMP-S also becomes worse than SIMP-D (more stops), possibly caused by fewer conflicts in the CDM of SIMP-D.

5.2. 50*km/h* Results

We also compared IM protocols for a speed limit of 50km/h. Fig. 5 shows the results we obtained. Overall, these results are very similar to those achieved with a speed limit of 30km/h. In general, there is an expected slight increase in throughput and a small decrease in both average time loss and the number of stops for all protocols. However, the relative superiority of SIMP protocols is slightly lower with the higher speed limit. This behavior is also expected since SIMP handles vehicles one by one, thus breaking sequences of vehicles, while all other protocols take advantage of such sequences, and the higher the speed, the higher the advantage.



(a) Intersection throughput (veh/h). (b) Average time loss (s). (c) Average number of stops.

Fig. 5: Intersection throughput, average speed and average number of stops for 50km/h.

5.3. Summary

The experiments showed that SIMP, in both versions, outperforms all other IM protocols, with a higher saturation level leading to a higher throughput under high traffic density. All protocols exhibit similar throughput for low traffic densities, as expected since there is little vehicle accumulation. Conversely, the average time loss is always lower for SIMP than for all others, even for low traffic densities. This is due to the phases with a minimum duration that the other protocols use. The average number of stops is also similar for all protocols under low traffic density. Increasing traffic density reveals an advantage for SIMP initially, but the situation flips for high saturation levels, with SIMP protocols exhibiting a higher number of stops than the xTLC protocols. Moreover, SIMP does not take advantage of higher speeds, while all other protocols do. Thus, the superiority of SIMP reduces when the speed limit is increased. The results also show that the extra complexity of SIMP-S, i.e., allowing a shared left/straight-crossing lane, does not bring clear benefits with respect to a dedicated left-crossing lane when the three crossing directions are uniformly distributed. Finally, we experimented with the shared left-turning lane with TTLC, ITLC, and QTLC policies, which were the configurations proposed by their authors and frequently found in existing intersections. The results were similar with a slight increase in intersection throughput and travel time loss, but with a significant increase in the number of stops because of the cars turning left, yielding to let the cars crossing straight from the opposite road pass first. We consider this approach less safe than a dedicated left-turn lane because it relies on the vehicles to avoid collisions.

6. Conclusion

This paper addressed multi-lane intersections in urban areas and assessed the recently proposed IIMA/SIMP intelligent management performance in such context. We considered two intersection configurations, namely dedicated and shared left-turn lanes. We implemented SIMP in both configurations together with four other IM approaches for comparison, namely two conventional (RR and TTLC) and two intelligent ones (ITLC and QTLC). We simulated all the IM strategies in the SUMO simulation framework for a range of realistic traffic arrival rates and speed limits for urban areas. The results for intersection throughput, average trip time loss, and the average number of stops show a clear superiority of SIMP in all scenarios and metrics, with the exception of the number of stops at intense saturation conditions. Finally, we did not observe a significant difference between dedicated and shared left-turn lanes.

In the future, we plan to adapt the IIMA/SIMP for different types of vehicles, e.g., light to medium and heavy-duty vehicles, and we will also analyze grids of intersections.

Acknowledgements

This work was partially supported by national funds from FCT/MCTES (Portuguese Foundation for Science and Technology), through the CISTER Research Unit (UIDB/04234/2020), and by the European Social Fund (ESF) and the Regional Operational Programme (ROP) Norte 2020, through PhD grant 2020.06685.BD.

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