Synchronous Framework Extended for Complex Intersections

Radha Reddy, Luis Almeida, Miguel Gaitan, Pedro M. Santos and Eduardo Tovar

February 22, 2022

Synchronous Framework Extended for Complex Intersections

Radha Reddy[a,b,c], Luis Almeida[a,c,*], Miguel Gaitán[a,b,c], Pedro Santos[a,b,c], Eduardo Tovar[a,b]

[a]CISTER Research Centre, Rua Alfredo Allen, 535, 4200-135 Porto, Portugal
[b]Instituto Superior de Engenharia do Porto (ISEP), R. Dr. António Bernardino de Almeida 431, 4200-135 Porto, Portugal
[c]FEUP, University of Porto, 4200-465 Porto, Portugal

Abstract

Intelligent intersection management systems are an integral part of Smart Cities and have a profound impact in urban traffic management. In a previous work, the authors proposed a specific Intelligent Intersection Management Architecture (IIMA) with the associated Synchronous Intersection Management Protocol (SIMP) for simple single-lane isolated intersections that outperformed other competing protocols in throughput, time loss and polluting emissions. IIMA/SIMP supports both autonomous and human-driven vehicles. This paper extends such work to more complex multi-lane intersections, comparing against traditional and intelligent intersection management approaches. Simulation results achieved with SUMO confirm the advantages of IIMA/SIMP even in complex intersections, improving throughput, average speed, waiting time, trip time loss, and associated fuel consumption.

Keywords: Smart Cities; Intelligent Transportation System; Intersection Management; IIMA; SIMP; Complex Intersections.

1. Introduction

Modern societies are quickly evolving to fully automated transportation relying on Autonomous Vehicles (AVs). However, the penetration of AVs is expected to grow from negligible, today, to 90% share by 2045 Bansal (2017). Until then, AVs must co-exist with Human-driven Vehicles (HVs) in a mixed traffic pattern. To manage the overall traffic, intelligent Intersection Management (IM) approaches stand out in Smart Cities as fundamental components to improve safety, energy and time efficiency, and decrease polluting emissions. Currently, there are IMs tailored to scenarios of HVs-only, AVs-only, and mixed traffic Abdulhai (2003); Younes (2014); Pourmehrab (2019). We have been working with the third case and proposed, recently, the Intelligent Intersection Management Architecture (IIMA) with the Synchronous Intersection Management Protocol (SIMP) for simple single-lane road intersections Reddy (2019) with benefits in user-experience and eco-friendliness. IIMA/SIMP outperformed competing approaches in intersection throughput, travel time loss, fuel consumption and polluting emissions Reddy (2020a,b).

This paper studies the application of IIMA/SIMP to complex multi-lane intersections, comparing its performance against Round-Robin (RR) and Trivial Traffic Light Control (TTLC) as conventional IMs and Intelligent TLC (ITLC) Younes (2014) and Q-learning based TLC (QTLC) Abdulhai (2003) as intelligent IMs. Among these, RR IM grants access to the intersection to vehicles from one inflow road at a time, for a specified green time (e.g., 30s). In turn, TTLC, ITLC, and QTLC generally grant access to vehicles from two opposite lanes at a time.

2. IIMA/SIMP for Complex Intersection

* Corresponding author:
E-mail address: reddy@isep.ipp.pt

.

Figure 1 illustrates the IIMA in a four-way two-lane road intersection, where AVs are presented in yellow color and HVs in white color. In each lane vehicles are serviced in a "First-In-First-Out" fashion and no U-turn is allowed at the intersection. Vehicles share the right-most lane for straight and right-crossing while the center-most lane is dedicated to left-crossing. In the IIMA, road-lanes close to the intersection and the space within the intersection are virtually divided into grid-cells that accommodate a vehicle and some safe distance each. R_i represents the inflow ($i = 1, 3, 5, 7$) and outflow ($i = 2, 4, 6, 8$) road-lanes. In inflow lanes, $R_{i,j}$ stands for the right-most and center-most lanes, for $j = 1$ and $j = 2$, respectively. For outflow lanes, $R_{i,j}$ stands for the left-most and center-most lanes, for $j = 1$ and $j = 2$, respectively. Each road has an associated RSU and two specialized road-sensors (P_1, P_2), that directly communicate with the TLC.

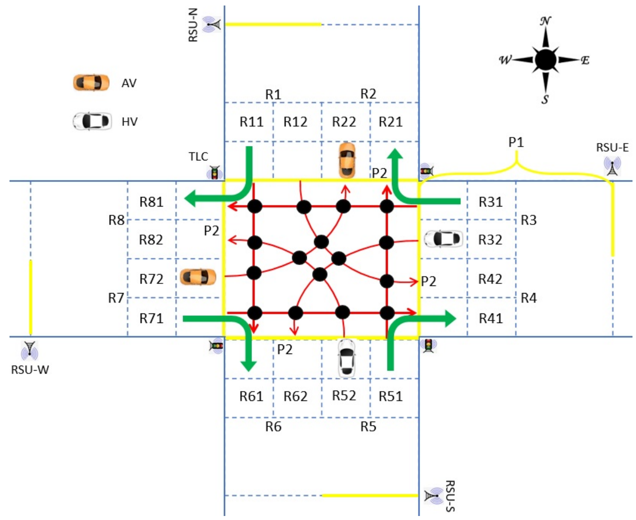
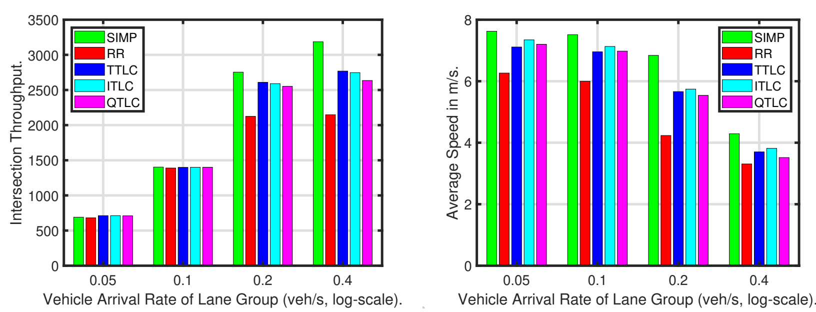


Fig. 1: IIMA for a Four-way Two-lane road Intersection

RSUs behave like brokers supporting the communication between AVs and TLC. Sensors P_1 and P_2 allow identifying the position of vehicles, including the presence and direction of HVs. Once vehicles approach the intersection the TLC will use their directions and consult a **Conflicting Directions Matrix** (CDM) to decide whether they can enter or have to wait. The CDM plays a significant role in SIMP decision-making by providing conflict-free movement of vehicles in cycles. At each cycle multiple vehicles from multiple lanes are allowed to access the intersection if their directions do not conflict, according to the CDM. The black spots in Fig. 1 indicate conflicting directions encoded in the CDM.

3. Simulation Results

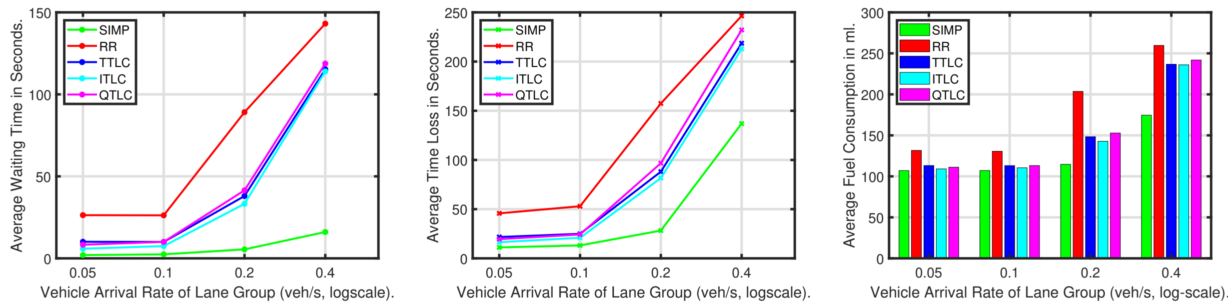
We used SUMO to simulate an intersection like the one in Fig. 1 in a low-speed urban flat-road environment ($30Km/h$ speed limit), and we included all target IM strategies. The traffic is composed of 50% HVs and 50% AVs arriving randomly at the intersection, uniformly distributed among the three possible directions, namely turning right, going straight and turning left. Other simulation parameters are taken from Reddy (2020a). The RR TLC logic sets a green light for $30s$ followed by a yellow light for $4s$ for both inflow lanes at each road at a time and then circulates through all roads. The TTLC, ITLC, and QTLC IM logic parameter values are taken from Björck (2018). Different traffic arrival rates are employed ($0.05veh/s$, $0.1veh/s$, $0.2veh/s$, and $0.4veh/s$). For intersection throughput, a time-based metric, we ran the simulations for $1h$. The other performance indicators are based on the number of vehicles, thus we ran the simulations for 1000 vehicles (AVs and HVs together).



(a) Intersection Throughput (veh/h). (b) Average Speed in m/s.

Fig. 2: Intersection Throughput veh/hour and Average Speed for 1000 Mixed Vehicles.

Figure 2a shows the intersection throughput results. SIMP outperforms its counterparts by serving the highest number of vehicles in the simulation time for all tested traffic densities. TTLC displays the next best performance while the RR strategy exhibits poor performance with the lowest number of vehicles served. The average speed of 1000 vehicles is shown in Fig. 2b, which also indicates an advantage for SIMP against all counterparts and for all tested traffic densities. Here, ITLC shows the next best performance by using vehicle movement information (speed, acceleration, and distance) to adjust the green-light time. Overall SIMP outperforms the competing approaches making use of the CDM to allow multiple vehicles into the intersection from non-conflicting road-lanes.



(a) Average Waiting Time in Seconds. (b) Average Time Loss in Seconds. (c) Average Fuel Consumption in ml.

Fig. 3: Average Waiting Time, Average Travel Time Loss, and Average Fuel Consumption for 1000 Mixed Vehicles.

Figure 3 displays the average waiting time, average travel time loss and average fuel consumption for all the 1000 vehicles in the simulation. The results show the dominance of SIMP against its counterparts, with better performance in all tested traffic densities. For example, with a traffic density of $0.4veh/s$, SIMP managed to reduce over $100s$ of waiting time and travel time loss when compared to TTLC, ITLC and QTLC, consequently reducing fuel consumption, too (Fig. 3c). Concerning fuel consumption, TTLC, ITLC and QTLC exhibit similar behavior with a slight advantage for ITLC. Conversely, RR performs the worst since it allows vehicles from one inflow road at a time, only.

4. Summary

In this work we extended the SIMP protocol to complex multi-lane intersections in urban areas and compared its performance against both conventional and intelligent intersection management approaches available in the literature. We used the SUMO simulation framework and observed a significant advantage of SIMP.

The full paper will contain a complete explanation of the SIMP protocol focusing on building the CDM for this type of intersections. We will also include a sufficient description of the competing intersection management approaches with a discussion of their configuration parameters. Finally, we will include more simulations results, particularly for a speed limit of $50km/h$, together with a discussion on the root causes of SIMP higher performance.

Acknowledgements

This work was partially supported by National Funds through FCT/MCTES (Portuguese Foundation for Science and Technology), within the CISTER Research Unit (UIDB/04234/2020).

References

Abdulhai, B., Pringle, R. and Karakoulas, G.J., 2003. Reinforcement learning for true adaptive traffic signal control. Journal of Transportation Engineering, 129(3), pp.278-285.

Bansal, P. and Kockelman, K.M., 2017. Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies. Transportation Research Part A: Policy and Practice, 95, pp.49-63.

Björck, E. and Omstedt, F., 2018. A comparison of algorithms used in traffic control systems. School of Electrical Engineering and Computer Science, Stockholm, Sweden, pp.1-38.

Pourmehrab, M., Elefteriadou, L., Ranka, S. and Martin-Gasulla, M., 2019. Optimizing signalized intersections performance under conventional and automated vehicles traffic. IEEE Transactions on intelligent transportation systems.

Reddy, R., Almeida, L. and Tovar, E., 2019, December. Work-in-Progress: Synchronous Intersection Management Protocol for Mixed Traffic Flows. In 2019 IEEE Real-Time Systems Symposium (RTSS), pp.576-579.

Reddy, R., Almeida, L., Santos, P.M. and Tovar, E., 2020, September. Comparing the Ecological Footprint of Intersection Management Protocols for Human/Autonomous Scenarios. In 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC), pp.1-6.

Reddy, R., Almeida, L., Santos, P.M., Bouzefrane, S. and Tovar, E., 2020, September. Synchronous Intersection Management to reduce Time Loss. In 23rd EURO Working Group on Transportation Meeting.

Younes, M.B. and Boukerche, A., 2014, September. An intelligent traffic light scheduling algorithm through VANETs. In 39th Annual IEEE Conference on Local Computer Networks Workshops, pp.637-642.