Sustainability Analysis of Complex Multi-Lane Intelligent Signalized Intersections

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Abstract

Multi-lane road intersections are complex intersections with multi-inflow/outflow lanes that are either dedicated or shared. Intelligent intersection management (IIM) strategies play a vital role in sustainable transportation by mitigating traffic congestion and reducing waiting times, fuel wastage, and associated emissions. In this work, we carry out the sustainability analysis of four state-of-the-art IIMs quantitatively and qualitatively for mixed autonomous and human-driven vehicles. The SUMO simulation results show that the synchronous framework outperforms all the counterparts with the lowest average waiting time and average fuel consumption.

Author Keywords. Complex Signalized Intersections, Intelligent Decision-Making, Environmental Sustainability.

1. Overview

Multi-lane road intersections with several inflows and outflows are considered complex intersections due to several dedicated and shared inflow/outflow and crossing lanes. For example, in a four-way two-lane road intersection, the two possible lane assignments are dedicated left/right turn lanes and shared lanes. The dedicated right-turning is only suggested for a one-way road to a one-way road at high-speed road lanes (Chandler et al., 2013). Therefore, the dedicated left-turn lane and shared lanes for a four-way two-lane road intersection are analyzed. Figure 1 illustrates both dedicated left-turn and shared lanes intersection with their diverging, crossing, and merging conflicts. Note that the crossing conflicts of the shared-lanes intersection are more than twice that of the dedicated left-crossing one.

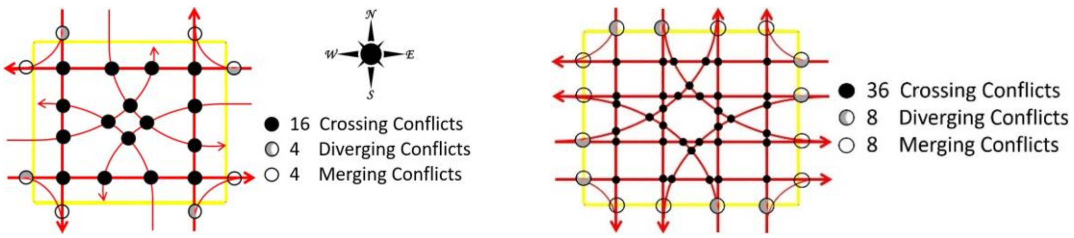

Figure 1: Four-way Two-lane Road Intersection Crossing Lanes; **a).** Dedicated left-turn lane and **b).** Shared lanes and Associated Conflicts (Crossing, Diverging, and Merging).

Nevertheless, with the introduction of connected and autonomous vehicles (AVs) into the traffic streams, there is a need for novel IIM strategies that consider AVs and human-driven vehicles (HVs). Because the driving behavior of AVs must synchronize with HVs behavior in mixed traffic. This is the focus of the present work.

2. Intelligent Signalized Intersection Management Strategies

This paper compares four state-of-the-art IIM's sustainability for complex multi-lane road intersections with two inflows and two outflows. Two of these IIM's are the *synchronous intersection management protocol* (SIMP) for the dedicated left-turn lane, a.k.a. SIMP-D, and shared lanes, a.k.a. SIMP-S (Reddy et al. 2021). The other two are the *intelligent traffic light control* (ITLC) algorithm (Younes et al. 2014) and the *Q-learning-based traffic light control* (QTLC) mechanism (Abdulhai et al. 2003), indicating the dedicated left-turn lane. All these approaches were implemented, representing original configurations presented by their authors.

The SIMP was initially proposed along with the intelligent intersection management architecture (IIMA) to provide smoother driving behavior among HVs and AVs at an isolated simple single-lane road intersection (Reddy et al., 2019). In IIMA, various sensors (roadside and camera sensors) are employed for detecting HVs at different locations around the intersection. A roadside unit (RSU) is employed at each road for information dissemination. A traffic light control (TLC) unit is responsible for data analytics and green light scheduling based on the information from various sensors. The outcome of TLC decision-making is sent to AVs as messages, while HVs follow physical TLC signals only. SIMP is crucial in TLC decision-making, identifying HVs among AVs and allocating green phases based on vehicles' desired direction and conflict-free crossing within the intersection. IIMA/SIMP was extended for multi-lane intersections (Reddy et al., 2021) for dedicated left-turn lanes (SIMP-D) and shared lanes (SIMP-S).

The Intelligent Traffic Light Controlling (ITLC) algorithm was proposed to reduce waiting time by increasing traffic fluidity. ITLC employs sensory information for determining traffic light phases, order, and length (time) of execution using the information of individual traffic flows, such as queue length, vehicle speed, and acceleration. The road lane of a larger queue length gets the higher priority in the allocation of green phases. The vehicle speed and distance to the intersection are employed in determining the queue’s traversal time, and the largest traversal time is utilized for allocating green phase timing as long as it is below the 60s, the fixed maximum green time followed by a 3s yellow phase. The ITLC was implemented on a four-way two-lane intersection with a dedicated left-turn lane.

The Q-learning-based traffic light control (QTLC) algorithm was introduced for reducing time delays based on multi-agent systems. QTLC utilizes traffic queue-length and elapsed phase time for TLC decision-making, and outcomes are either continuing with the current phase or switching to another phase to penalize 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, accompanied by a 4s yellow phase while the other lanes are blocked with red phases. Like ITLC, the QTLC has also been implemented for a dedicated left-turn lane intersection.

3. Performance Evaluation

We used the SUMO simulator to implement and simulate IM strategies targeting an isolated intersection in a low-speed urban flat-road environment with a 30Km/h speed limit. The traffic is composed of 50% HVs and 50% AVs of identical dimensions arriving randomly at the intersection, uniformly distributed among the three possible directions, namely turning right, going straight, and turning left. The rest of the relevant simulation parameter values are taken from (Reddy et al., 2021). In this work, different traffic arrival rates are used (0.05veh/s, 0.067veh/s, 0.1veh/s, 0.133veh/s, 0.2veh/s, 0.3veh/s, and 0.4veh/s). Moreover, the performance is evaluated in terms of average waiting time and associated average fuel consumption for 1000 mixed vehicles. The results are shown in Figure 2. Note that each data point is an average of five simulation runs with different random seeds.

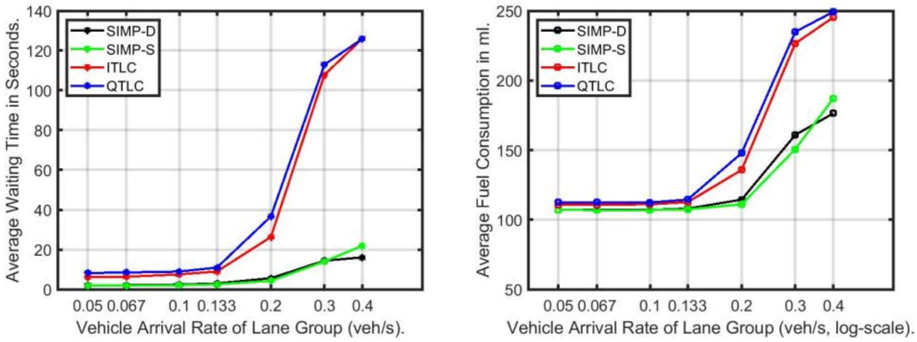

Figure 2: a). Average Waiting Time (s) and **b).** Average Fuel Consumption (ml.) for 30Km/h Speed limit.

The average waiting time results presented in Figure 2a show the dominance of the synchronous framework (both SIMP-D and SIMP-S) against the benchmark approaches with the lowest average waiting time values. Notably, both SIMP-D and SIMP-S show similar results for low traffic intensities, and at the system saturation conditions, i.e., 0.4veh/s, SIMP-D surpasses SIMP-S. Overall, SIMP managed to reduce 100s of waiting time at 0.4veh/s when compared to ITLC and QTLC. Likewise, average fuel consumption results (Figure 2b) also show the advantages of using the synchronous framework with the lowest values than the counterparts (70ml at 0.4veh/s). This resulted from the smoother pattern induced by the synchronous behavior of mixed vehicles at the intersection.

4. Summary

This work compared the average waiting time, and associated average fuel consumption of four state-of-the-art IIM approaches for isolated multi-lane road intersections under mixed traffic conditions. The SUMO simulation results show the advantages of employing synchronous protocol against the counterparts. We observed that the SIMP-D outperforms the benchmark approaches at the system saturation settings. In the future, we will analyze the applicability of these IIM's for mixed traffic w.r.t. vehicle size.

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.

Chandler, B.E., Myers, M., et al. 2013. Signalized Intersections Informational Guide (No. FHWA-SA-13-027). United States. Federal Highway Administration. Office of Safety.

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., Gaitan, M., Santos, P.M. and Tovar, E., 2021. Synchronous Framework Extended for Complex Intersections. Accepted in 24th EURO Working Group on Transportation Meeting (EWGT2021).

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.

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