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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.

Sustainability Analysis of Complex Multi-Lane Intelligent Signalized Intersections

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Abstract
Multi-lane road intersections are complex intersections with multiple-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 and associated fuel wastage. In this work, we carry out a sustainability analysis of three state-of-the-art IIMs quantitatively for mixed autonomous and human-driven vehicles. Simulation results achieved with SUMO show that the synchronous framework outperforms all the counterparts with the lowest average waiting time and average fuel consumption.

Author Keywords. Intelligent transportation systems, intelligent intersection management, urban traffic management.

1. Overview

Intersections are fundamental elements of urban traffic management (UTM) and are identified as bottlenecks. Intelligent intersection management (IIM) approaches significantly reduce traffic congestion and associated fuel wastage. In this context, we consider complex multi-lane road intersections with several inflows and outflows some of which can use dedicated and shared lanes. In particular, we look at a typical four-way two-lane road intersection considering a dedicated lane for turning left and a shared lane to turn right and straight crossing. We do not consider a dedicated right-turning since it is suggested for a one-way road to a one-way road or for high-speed road lanes, only (Chandler et al., 2013). Figure 1 illustrates such intersection, with the dedicated and shared lanes also indicating all possible outflow lanes coming from all possible inflow lanes, highlighting the diverging, crossing, and merging conflicts. The crossing conflicts, as explained further on, are used by one of the IIM protocols that we analyze to decide the admission of vehicles into the intersection.

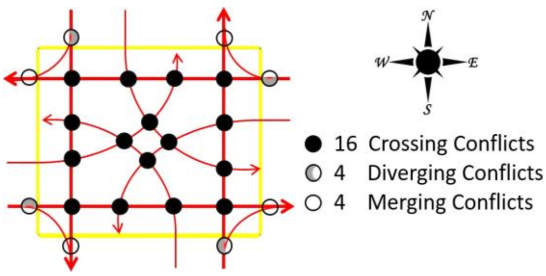


Figure 1: Potential conflicts among all possible crossings in the considered type of intersection.

2. Intelligent Intersection Management Strategies

This paper compares three state-of-the-art IIM policies in terms of sustainability when applied to complex multi-lane road intersections with two inflow and two outflow lanes per road. By sustainability we refer the determination of the respective saturation points in traffic throughput. One of these IIM policies is the synchronous intersection management protocol (SIMP), which was originally presented in (Reddy et al. 2021). The other two are the intelligent traffic light control (ITLC) policy (Younes et al. 2014) and the Q-learning-based traffic light control (QTLC) policy (Abdulhai et al. 2003), all applied to the same intersection as shown in Figure 1.

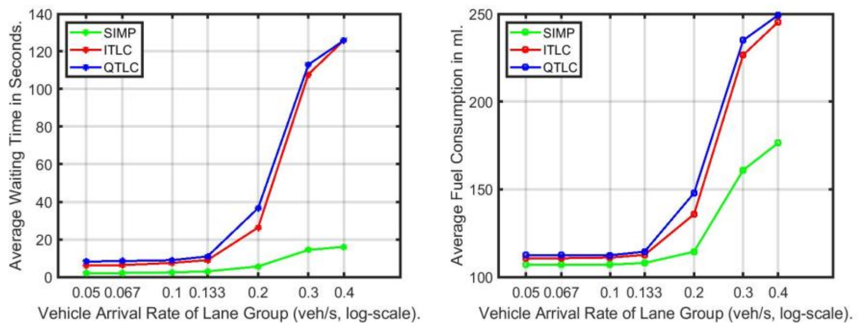
SIMP was initially proposed within an intelligent intersection management architecture (IIMA) to provide smoother vehicles behavior considering a mix of both human-driven vehicles (HVs) and autonomous vehicles (AVs) at an isolated simple single-lane road intersection (Reddy et al., 2019). IIMA uses roadside units (RSUs) equipped with multiple sensors, e.g., magnetic loops and cameras, to detect HVs presence and intersection crossing direction. An RSU is employed at each road for information collection and communication with the traffic lights controller (TLC). The SIMP protocol is implemented in the TLC unit. 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 within the intersection 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 outcome of TLC decision-making is sent to AVs as data messages and to non-communicating HVs using physical traffic light signals, only. IIMA/SIMP was initially extended for multi-lane intersections in (Reddy et al., 2021).

The Intelligent Traffic Light Controlling (ITLC) policy was proposed to reduce waiting time by increasing traffic fluidity. Similarly, to SIMP, 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 lane with the longest queue gets the highest priority in the allocation of green phases. The vehicle speed and distance to the intersection are employed to determine the queue's traversal time, and the largest traversal time is utilized for allocating green phase timing up to a limit of 60s, followed by a 3s yellow phase. The ITLC was implemented on the same four-way two-lane intersection as SIMP.

The Q-learning-based traffic light control (QTLC) policy was introduced for reducing time delays based on multi-agent systems. QTLC utilizes queue-length and elapsed phase time for TLC decision-making, which decides whether to continue with the current phase or switch to another phase at a penalty for 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 the other two protocols, QTLC was also implemented on the same four-way two-lane intersection.

3. Performance Evaluation

We used the SUMO v1.6.0 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 50% HVs and 50% AVs of identical dimensions arriving randomly at the intersection. 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.



a) Average Waiting Time in Seconds. **b)** Average Fuel Consumption in ml.

Figure 2: Comparison of waiting time and fuel consumption averaged for 1000 mixed vehicles.

The average waiting time results presented in Figure 2a show the dominance of the synchronous approach (SIMP) against the other two approaches, exhibiting the lowest average waiting time values. Notably, this behavior is observed up to saturation conditions, i.e., around 0.4veh/s. At this arrival rate, SIMP managed to reduce 100s of waiting time when compared to ITLC and QTLC. Likewise, average fuel consumption results shown in Figure 2b also exhibit a clear advantage of using the synchronous framework, with the lowest values when compared to the counterparts, i.e., around less 70ml for the total route at 0.4veh/s. This results from the smoother velocity pattern induced by the synchronous behavior of mixed vehicles at the intersection, at the expense of more complex sensing mechanisms to handle non-communicating HVs.

4. Summary

This work compared the average waiting time and associated average fuel consumption of three state-of-the-art IIM approaches for an isolated multi-lane road intersection under mixed traffic conditions. Simulation results with SUMO show the advantages of employing a synchronous protocol against common approaches based on sequential phases. In the future, we will analyze the applicability of these IIM policies for mixed traffic with respect to vehicle size, e.g., a mixture of light-duty vehicles and heavy-duty transportation trucks.

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