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Poster

Work-in-Progress: Exploring the Composition of Synchronous Intelligent Intersections

Radha Reddy
Luís Almeida
Pedro Miguel Santos
Eduardo Tovar

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Radha Reddy, Luís Almeida, 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, pss@isep.ipp.pt, emt@isep.ipp.pt

https://www.cister-labs.pt

Abstract

Private vehicles are expected to continue representing a large share of the urban traffic requiring intelligent management to provide safe and efficient urban mobility. In this context, it is imperative to mitigate traffic congestion and associated travel delays to improve the quality of life of urban dwellers. This paper explores the global performance of grid networks of independent intersections using different intersection management protocols. We particularly aim to compare the performance achieved when using the intelligent intersection management architecture (IIMA) that relies on the synchronous intersection management protocol (SIMP), against two conventional (Round-robin - RR and trivial traffic light control - TTLC) and two adaptive (Max-pressure control algorithm - MCA and Websters traffic light control - WTLC) intersection management approaches. We consider four-way two-lane intersections with two crossing configurations, namely dedicated and shared left lane, on a 2×2 grid network of intersections. Simulation results with SUMO show that composing intersections with synchronous management considerably improves the network throughput and reduces travel delays.

Work-in-Progress: Exploring the Composition of Synchronous Intelligent Intersections

Radha Reddy
CISTER Research Center
ISEP, FEUP, Porto, Portugal
reddy@isep.ipp.pt

Luis Almeida
CISTER Research Center
FEUP, Porto, Portugal
lda@fe.up.pt

Pedro Santos
CISTER Research Center
ISEP, FEUP, Porto, Portugal
pss@isep.ipp.pt

Eduardo Tovar
CISTER Research Center
ISEP, Porto, Portugal
emt@isep.ipp.pt

***Abstract*—Private vehicles are expected to continue representing a large share of the urban traffic requiring intelligent management to provide safe and efficient urban mobility. In this context, it is imperative to mitigate traffic congestion and associated travel delays to improve the quality of life of urban dwellers. This paper explores the global performance of grid networks of independent intersections using different intersection management protocols. We particularly aim to compare the performance achieved when using the intelligent intersection management architecture (IIMA) that relies on the synchronous intersection management protocol (SIMP), against two conventional (Round-robin - RR and trivial traffic light control - TTLC) and two adaptive (Max-pressure control algorithm - MCA and Websters traffic light control - WTLC) intersection management approaches. We consider four-way two-lane intersections with two crossing configurations, namely dedicated and shared left lane, on a 2×2 grid network of intersections. Simulation results with SUMO show that composing intersections with synchronous management considerably improves the network throughput and reduces travel delays.**

***Index Terms*—Smart urban mobility, intelligent intersection management, traffic lights control, synchronous traffic management.**

I. Introduction

Urban transportation must be safe and efficient as it highly influences the quality of life of urban dwellers. The research on post-pandemic (COVID-19) traffic patterns shows an increase in private vehicles over other transportation means, emphasizing the role of traffic management for sustainable urban mobility [1].

In the last decade, numerous intersection management (IM) approaches were designed, such as the max-pressure control algorithm (MCA) [2], hourly green time splitting [4], fixed cycle traffic light algorithm [3], multi-agent systems (MAS), and reinforcement learning [5]–[7]. Their goal is to optimize traffic signals at individual intersections, possibly providing cooperation & coordination among several intersections, to reduce network traffic congestion and associated delays and improve throughput. However, they typically operate in a circular slot-based fashion, which intrinsically imposes extra delays caused by the traffic lights control cycle. To provide traffic fluidity at isolated intersections supporting both mixed human-driven vehicles (HVs) and autonomous vehicles (AVs), we proposed the intelligent intersection management architecture (IIMA) and associated synchronous intersection management protocol (SIMP) [8], [10]. This synchronous framework revealed improved performance in throughput, time delays, and emissions at individual intersections [8]–[10].

This work-in-progress paper shows the initial steps to study global performance when composing independent intersections in grid networks. We use a 2×2 grid network of four-way two-lane intersections and inject dynamic patterns of mixed HVs and AVs. We also consider two intersection crossing configurations: dedicated and shared left lane. Then we use the SUMO simulation framework [12] to compare the global throughput and delays when using different IM protocols, namely the synchronous SIMP, pre-timed conventional protocols (Round-Robin - RR and Trivial Traffic Light Control - TTLC) and adaptive (MCA and Websters) approaches [2], [10], [11]. The results suggest that the SIMP-based synchronous framework is superior to its counterparts in grids of independent intersections.

II. Related Work

In recent decades, urban traffic management has received significant attention. For instance, Varaiya P. [2] introduced the fixed-time MCA to stabilize the network traffic without requiring knowledge of the traffic demand, just controlling adjacent lanes' traffic movement at individual intersections.

Boon and Leeuwaarden [3] presented a network algorithm that decomposes networks of intersections into isolated intersections that are managed based on the fixed cycle traffic light model.

Terraza et al [4] proposed an hourly green split mechanism for minimizing delays at individual intersections towards the network level optimization hour-by-hour to track varying traffic inflows.

Liu et al [5] introduced a multi-agent Q-learning IM approach to optimize the trajectories of vehicles. The algorithm calculates optimal control actions by considering the local and neighboring intersection traffic information. Torabi et al [6] developed the Distributed Agent-based traffic LIghts (DALI) based on the Traffic Signal Timing system (TST) for highly dynamic and congested traffic conditions. In DALI, the traffic light agents

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directly communicate with neighboring agents to collaborate by sharing incoming traffic flow information.

Jiang et al [7] presented an accumulated exponentially weighted waiting time-based adaptive traffic signal control to calculate the road priorities and then applied the distributed multi-agent reinforcement learning (DMARL) with a graph decomposition approach. The decomposition divides a network-level traffic control problem into sub-problems based on the average residual capacities.

Overall, some of these works propose collaborating intersections, some rely on global information, some support AVs only, and generally use cyclic slot-based intersection management. However, communication among intersections is not always supported, global information is frequently unavailable and hybrid AV/HV traffic will likely persist for a significant time. Thus, we target compositions of independent intersections particularly assessing fluid synchronous AV/HV traffic management, which is still an open research line, comparing against cyclic slot-based approaches.

III. Composing Intersections

A. Grid Network of Intersections

Without loss of generality, we consider $M \times M$ grid networks of four-way intersections deployed regularly on a squared area of size $D \times D$. In such a configuration, the distance between neighboring intersections is regular and given by $l = D/(M+1)$. Fig. 1 shows the case of $M = 2$, where the set of intersections is $\mathcal{I} = \{I_0, I_1, I_2, I_3\}$. Note that each intersection has an associated manager (IM) that implements TLC policies for serving the inflow traffic.

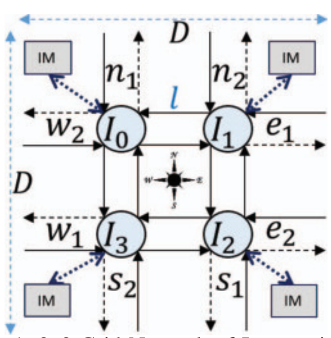

Fig. 1: 2x2 Grid Network of Intersections.

We can view the grid network as a non-directed acyclic graph in which the nodes are the intersections, and the edges are the associated roads. The edge degree is the number of lanes of each road in each direction (inflow and outflow). In four-way two-lane intersections, as we are considering, the edge degree is two, meaning we have two inflow and two outflow lanes per road (edge). Among the inflow lanes, we consider the rightmost lane to convey traffic that turns right and goes straight. Conversely, for the innermost (left) lane, we consider two cases: it is dedicated only to left-crossing traffic or is shared between left and straight-crossing traffic. We refer to these cases as dedicated and shared left lanes, respectively. These configurations were chosen because they are widespread in urban settings.

For simplicity, we use the four cardinal directions (n,s,e,w) to refer to the grid network sides. In this regular model, each network side has M roads connecting the outside world to M intersections, e.g., with $M = 2$ (Fig. 1) n_1 and n_2 connect to I_0 and I_1, respectively. We call these the outer edges, which are of particular relevance to this work, since they are the points of traffic injection (inflow lanes) and traffic egress (outflow lanes). With $M = 2$ (Fig. 1) the set of outer edges is $\mathcal{O} = \{w_2, n_1, n_2, e_1, e_2, s_1, s_2, w_1\}$.

B. Synchronous Framework

Here we briefly recall the main features of the synchronous framework that is the focus of this study and which was proposed before for isolated intersections [8], [10]. It uses the IIMA architecture and the associated SIMP protocol. The IIMA combines communication capabilities to interact with communication-enabled vehicles, mostly AVs, with enhanced sensors, e.g., induction loop detectors and cameras, to interact with non-communicating vehicles, mostly HVs. Either by communicating or by using the sensors, IIMA allows the detection of vehicles in each inflow lane and their target crossing direction, as well as vehicles exiting from the intersection. In terms of operation, at each moment, SIMP checks the vehicles at the entrance of the intersection and their directions and grants crossing permission to those that follow non-conflicting directions, one vehicle from each inflow lane at a time. Once all admitted vehicles exit the intersection, a new cycle begins.

A fundamental component of IIMA/SIMP is the *conflicting directions matrix* (CDM), which SIMP uses to decide which vehicles at the intersection entrance can be admitted in each cycle. The CDM contains all possible conflicts in crossing directions to ensure safe crossings. Fig. 2 shows the conflicts between all crossing directions for the two intersection configurations we are considering, namely dedicated and shared left lanes, exhibiting the higher complexity of the latter configuration.

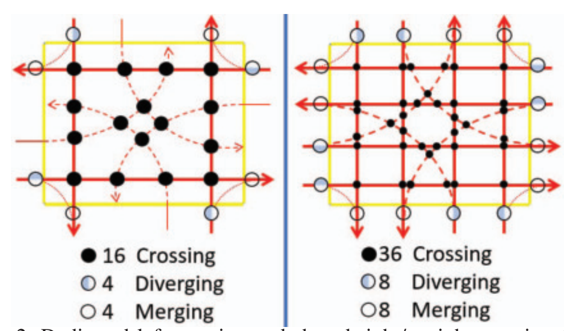

Fig. 2: Dedicated left-crossing and shared right/straight crossing (left) and shared left/straight and right/straight crossing (right) intersections of a four-legged intersection with two inflow and two outflow lanes.

C. Comparing Protocols

In order to assess the performance of grid networks composed of independent intersections using IIMA/SIMP, we use a set of comparable IM protocols that can be deployed equally independently in similar grids and configurations. Namely, we use two traditional (RR and TTLC) [10] and two adaptive (MCA [2] and WTLC [11]) IM approaches.

The conventional approaches operate under fixed time cycles and are unaware of intersection and inflow traffic status. RR serves both inflow lanes of each road in a dedicated time slot (green phase) that rotates clockwise. TTLC also serves traffic in fixed green phases but pairs of opposite non-conflicting lanes at a time. Concerning the adaptive approaches, MCA uses adjacent lanes' traffic flow to service vehicles for a fixed green phase, too, but in an acyclic manner. WTLC operates cyclically but adapts the green time between specified minimum and maximum values based on the inflow traffic volume. All these approaches have a short yellow phase that follows their respective green phases.

IV. GLOBAL PERFORMANCE ASSESSMENT

We report early experimental results of the global performance of grids of independent intersections, namely throughput and time loss, when using IIMA/SIMP and the other IM protocols.

A. Simulation Setup

The experiments were carried out running the SUMO v1.14.1 [12] simulator on a computer featured with an Intel Core i3-4160 CPU @ 3.6Ghz, an NVIDIA RTX 2070 graphics processor, 8GB RAM, and 64-bit Ubuntu 18.04.4 LTS OS.

The simulated physical scenario corresponds to a 2×2 grid network with $l = 500m$ and intersection space $20m$ ($D = 1540m$). The distances covered within the intersections vary between $5m$ and $60m$ for right/straight/left-crossing and for 1, 2, and 3 crossed intersections. The vehicle length and safety distance between consecutive vehicles are set to $5m$. We have employed the SUMO default values for HVs and AVs, e.g., $1s$ minimum time headway, 0.5 driver's imperfection for HVs (and 0 for AVs). The maximum speed of all vehicles is set to $30km/h$ representing an urban environment, a maximum acceleration of $2.6m/s^2$, a maximum deceleration of $-4.5m/s^2$, and an emergency deceleration of $-9m/s^2$.

Concerning the IM protocols, RR and MCA use a fixed green phase of $30s$, while TTLC uses two green phases, $30s$ and $15s$ for right/straight and left (or left/straight) crossings, respectively. WTLC varies the green phase time between $11s$ and $44s$. The yellow phase is $4s$ long. Thus, the cycle time is $136s$ for RR, $106s$ for TTLC, and between $60s$ and $180s$ for WTLC. The cycle length of SIMP is considered to be a maximum of $11s$ under saturated traffic. Note that all these values are the ones suggested in the papers where the protocols were proposed.

Finally, we implement the dedicated and shared left lane configurations for all protocols, being identified as $*-D$ and $*-S$, respectively, where $*$ stands for any of the IM protocols.

B. Traffic Patterns

The traffic is injected randomly in all inflow lanes of the outer edges following a Poisson distribution. We execute the simulation in a single long run corresponding to $5h$ of simulated time. After each hour the average arrival rate at each outer edge is changed to the next value in the following set ($0.025veh/s$, $0.05veh/s$, $0.067veh/s$, $0.1veh/s$, and $0.133veh/s$). These values cover low to medium and close to saturated traffic conditions. We do not use higher arrival rates to avoid traffic spill-back in the inner edges of the grid. The switch between different arrival rates occurs only after all the vehicles generated with the previous rate exit the grid. Moreover, the injected cars can be HVs or AVs with equal probability.

When a vehicle is injected, its path is statically defined at that moment, picked randomly and uniformly among the $4*M-1$ possible destinations (assuming U-turns are forbidden and considering preset routes). For $M = 2$, Fig. 3 shows the traffic routes for the seven destinations reachable from w_2 (left) and from n_1 (right). We follow the same procedure for all the outer edges of all intersections, rotating the patterns as needed. The pattern on the left applies to all $*_2$ outer edges, while that on the right applies to all $*_1$ outer edges ($*$ stands here for any cardinal direction). Since we generate patterns from all four cardinal directions to all respective destinations with similar stochastic properties, all edges have a similar and time-invariant stochastic traffic load for the $1h$ that lasts each arrival rate value.

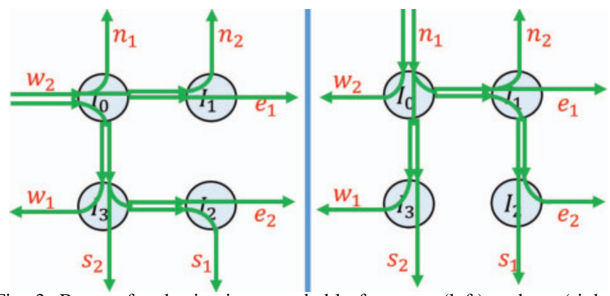

Fig. 3: Routes for destinations reachable from w_2 (left) and n_1 (right).

The maximum distance vehicles travel from injection to destination is $1020m$, $1550m$, and $2060m$ When the path crosses one, two, and three intersections, respectively.

Altogether our experiment injected a total of 10817 vehicles in the set of outer edges, of which 1608, 6196, and 3013 crossed one, two, and three intersections, respectively.

C. Network Throughput

We define network throughput as the number of vehicles that complete their journey in $1h$, considering the constant long-term traffic arrival rate. Fig. 4 shows the network throughput of the 2×2 grid using all the referred IM protocols for both dedicated (left) and shared (right) left lanes.

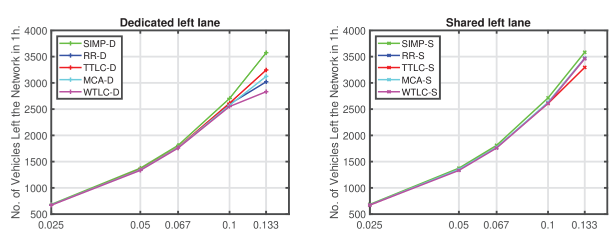

Fig. 4: Grid network throughput (veh/h) for dedicated (left) and shared (right) left lane.

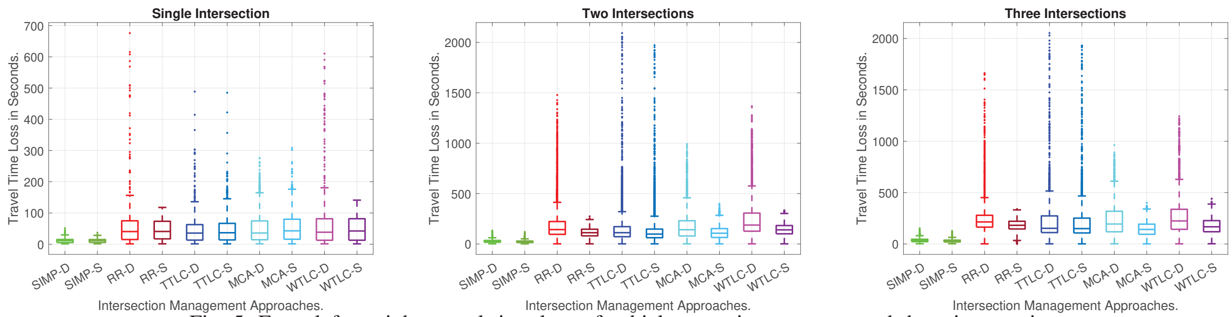

Fig. 5: From left to right, travel time loss of vehicles crossing one, two and three intersections.

All IM approaches saturate above $0.1veh/s$ (see the slight inflection of the respective lines), except SIMP-S (which was observed to be at $0.2veh/s$). SIMP shows dominance over the other IM protocols for both intersection configurations, particularly at higher traffic intensities near/at saturation. For low traffic intensity, the global throughput is very similar for all IM protocols.

Between the two configurations, the shared left lane shows a higher traffic saturation point (thus higher throughput), resulting in two lanes serving the traffic going straight at each intersection. For the dedicated left lane configuration, the differences between the IM protocols at a traffic arrival rate of $0.133veh/s$ (saturated traffic) are already significant. At this arrival rate, the global throughput of SIMP-D is $\sim 300veh/h$ ($\sim 10\%$) higher than that of TTLC-D, the second best performing protocol with dedicated left lanes. With SIMP-S, the difference to the second performing protocol with shared left lanes, RR-S, is smaller, $\sim 100veh/h$ ($\sim 3\%$).

D. Travel Time Loss

The travel time loss represents the additional traveling time caused by the presence of intersections, including stopped delay, approaching delay, time-in-queue delay, and intersection control delay. Fig. 5 shows the travel time loss results of the vehicles grouped by the number of intersections in their path. Naturally, the more intersections are crossed, the more waiting can occur, leading to higher travel time losses. In all three cases, the plots show consistently that the time losses with SIMP, in both left lane configurations, are a small fraction of the time losses incurred by the other IM protocols. When crossing one intersection, in both left lane configurations (D and S) SIMP time loss median is $11.57s$, while the following best is TTLC with $37s$ (~ 3 times more). With two intersections and dedicated left lanes, SIMP-D time loss median is $25.7s$ while the next best protocol is TTLC-D with $112s$ (~ 4 times higher). With shared left lanes, SIMP-S time loss median is $22.1s$ while the next best is TTLC-S with $98.2s$ median (and a similar ratio). When crossing three intersections, SIMP-D time loss median is $33.3s$ while the second best is TTLC-D with a median of $152.4s$ (~ 5 times more). Similarly, SIMP-S time loss median is $29.6s$ while the next best is WTLC-S with a median of $141.5s$, i.e., a similar ratio.

V. Conclusion and Work in Progress

This paper presented an early study of the global performance of grid networks of independent intersections, particularly using a synchronous framework compared against other standard IM protocols. Using a grid network and random traffic covering all possible destinations favors the observation of intrinsic properties of the studied protocols. In a 2×2 grid network, we observed a clear dominance of the synchronous IIMA/SIMP, particularly concerning the reduction of travel time loss.

We are currently starting an analytical performance study of grid networks of independent intersections, the accuracy/precision of which will be assessed by comparing with observed experimental results. We also plan to study each IM protocol's configuration parameters to maximize performance. Finally, we will also study how the performance of the synchronous IIMA/SIMP framework compares against networks of cooperating intersections.

References

[1] Das, S., Boruah, A., Banerjee, A., Raoniar, R., Nama, S. and Maurya, A.K., 2021. Impact of COVID-19: A radical modal shift from public to private transport mode. Transport Policy, 109, pp.1-11.

[2] Varaiya, P., 2013. Max pressure control of a network of signalized intersections. Transportation Research Part C: Emerging Technologies, 36, pp.177-195.

[3] Boon, M.A. and van Leeuwaarden, J.S., 2018. Networks of fixed-cycle intersections. Transportation Research Part B: Methodological, 117, pp.254-271.

[4] Terraza, M., Zhang, J. and Li, Z., 2021. Intersection Signal Timing Optimisation for an Urban Street Network to Minimise Traffic Delays. Promet-Traffic & Transportation, 33(4), pp.579-592.

[5] Liu, Y., Liu, L. and Chen, W.P., 2017. Intelligent traffic light control using distributed multi-agent Q learning. In 20th IEEE International Conference on Intelligent Transportation Systems, pp.1-8.

[6] Torabi, B., Wenkstern, R.Z. and Saylor, R., 2020. A collaborative agent-based traffic signal system for highly dynamic traffic conditions. Autonomous Agents and Multi-Agent Systems, 34(1), pp.1-24.

[7] Jiang, S., Huang, Y., Jafari, M. and Jalayer, M., 2021. A Distributed Multi-Agent Reinforcement Learning With Graph Decomposition Approach for Large-Scale Adaptive Traffic Signal Control. In IEEE Transactions on Intelligent Transportation Systems, pp.1-13.

[8] Reddy, R., Almeida, L. and Tovar, E., 2019. Work-in-Progress: Synchronous Intersection Management Protocol for Mixed Traffic Flows. In 40th IEEE Real-Time Systems Symposium, pp.576-579.

[9] Reddy, R., Almeida, L., Santos, P.M., Bouzefrane, S. and Tovar, E., 2021. Synchronous Intersection Management to reduce Time Loss. In Transportation Research Procedia, 52, pp.364-372.

[10] Reddy, R., Almeida, L., Gaitán, M.G., Santos, P.M. and Tovar, E., 2021. Synchronous Framework Extended for Complex Intersections. In 24th Euro Working Group on Transportation Meeting, pp.1-8.

[11] Webster, F.V., 1958. Traffic signal settings, road research technical paper no. 39. Road Research Laboratory.

[12] Lopez, P.A., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flötteröd, Y.P., Hilbrich, R., Lücken, L., Rummel, J., Wagner, P. and Wießner, E., 2018. Microscopic traffic simulation using sumo. In 21st IEEE International Conference on Intelligent Transportation Systems, pp.2575-2582.