Advantages of Synchronizing Vehicles Intersection Access

Radha Reddy
Luís Almeida
Pedro Miguel Santos
Eduardo Tovar

CISTER-TR-230405

2023

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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

Intersection space is a common resource that must be efficiently shared between vehicles with conflicting trajectories from several road lanes. The main objective of traffic light control (TLC) strategies is to periodically switch intersection access between road lanes by permitting vehicles either sequentially, parallelly, or synchronously. In this work, we compare the performance of five state-of-the-art TLC approaches in a road network of intersections. Among them, three approaches serve vehicles sequentially from one road lane at a time, one approach permits vehicles parallelly from opposite lanes, and the last one synchronizes the vehicles access to the intersection from all non-conflicting road lanes, one vehicle per road lane. SUMO simulation results suggest that the synchronous approach outperforms the sequential and parallel approaches in a multitude of situations in terms of network throughput, travel time loss and associated fuel consumption.

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Transportation Research Procedia 00 (2023) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

25th Euro Working Group on Transportation Meeting (EWGT 2023)

Advantages of Synchronizing Vehicles Intersection Access

Radha Reddy[a,b,c,d,∗], Luis Almeida[a,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] *Faculty of Engineering of University of Porto (FEUP), Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*
[d] *Dept. of Computer Science and Engineering, Amrita School of Computing, Coimbatore, Amrita Vishwa Vidyapeetham, India*

Abstract

An intersection area is a common space that must be efficiently shared over time between vehicles with conflicting trajectories from several road lanes. Numerous traffic light control (TLC) strategies have been presented to address this. The main objective is periodically switching intersection access between road lanes by permitting vehicles sequentially, parallelly, or synchronously. This work addresses which intersection access type is more efficient for throughput, travel delays, fuel consumption, and associated tailpipe emissions. We compare the performance of five state-of-the-art TLC approaches in two types of road networks. Among the five TLC approaches, three are sequential, one is parallel, and the other is synchronous. In the first road network, all four intersections are homogeneous with four legs. The second network is heterogeneous, with two intersections with four legs and the other two with three legs, i.e., T-intersections. We also consider two maximum speeds (30 and 50km/h) representing low-speed urban settings. SUMO simulation results suggest all access types have similar throughput, with a minor advantage of synchronous access (up to 3%). However, compared to the other best approaches, synchronous intersection access significantly reduces travel time loss (up to 130.5%) and fuel consumption (up to 37.2%).

Keywords: Vehicles intersection access, sequential, parallel, synchronous, throughput, travel time loss, and fuel efficiency;

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1. Introduction

In urban transportation, signalized intersections are traffic bottlenecks with the potential to generate queuing, waiting delays, and associated adverse effects. The area within an intersection is a common resource that must be efficiently shared among vehicles crossing it. Hence, numerous traffic light control (TLC) techniques were presented to manage this intersection space, initially using simple techniques such as Round-Robin (RR) (Chaudhuri et al., 2022), but recently exploring a myriad of intelligent techniques, such as reinforcement learning (Wei et al., 2019), metaheuris-

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[∗] Corresponding author.
E-mail address: reddy@isep.ipp.pt

tics (Jamal et al., 2022), connected and autonomous vehicles (CAV) technologies (Khayatian et al., 2020), or simply autonomous vehicles (AVs), in some cases mixed with human-driven vehicles (HVs) (Namazi et al., 2019).

Among multiple possible taxonomies, the TLC techniques can also be categorized based on vehicle intersection access. In the related literature, we find three primary ways of managing the intersection area, namely sequential (Wei et al., 2019; Chaudhuri et al., 2022; Genders and Razavi, 2019; Varaiya, 2013), parallel (Younes and Boukerche, 2015; Abdulhai et al., 2003; Björck et al., 2018; Özkul et al., 2018), and synchronous (Tlig et al., 2014; Aoki and Rajkumar, 2019; Reddy et al., 2022, 2023). The sequential and synchronous classes are explicitly discussed by Wei et al. (2019) and Aoki (2020). We introduce a new class to accommodate the TLC approaches that simultaneously admit traffic from opposite road lanes and do not fit in the other two classes and named it parallel.

Sequential TLC strategies admit vehicles from one road at a time for a defined temporal slot and then shift to the next road cyclically, e.g., Round-Robin (RR) (Chaudhuri et al., 2022) and the adaptive version of Webster's TLC (WTLC) (Genders and Razavi, 2019). The max-pressure control algorithm (MCA) also admits vehicles from one road at a time, but the next road depends on the traffic inflow; thus, MCA is still sequential but acyclic (Varaiya, 2013).

Parallel TLCs admit vehicles from two opposite road lanes and then shift to the next pair of opposite lanes, either cyclically or acyclically, e.g., Intelligent Traffic Light Controlling (ITLC) (Younes and Boukerche, 2015), Q-learning based traffic light controlling (QTLC) (Abdulhai et al., 2003), conventional trivial traffic light control (TTLC) (Björck et al., 2018), and context-aware secure traffic control (Özkul et al., 2018).

Synchronous approaches synchronize vehicles intersection access from several road lanes. They can admit vehicles from synchronized lanes in time slots (Tlig et al., 2014) or one vehicle at a time (Aoki and Rajkumar, 2019). Differently, the synchronous intersection management protocol (SIMP) admits one vehicle at a time but from all non-conflicting road lanes (Reddy et al., 2022, 2023).

In this paper, we compare the performance of five TLC protocols (RR, WTLC, MCA, TTLC, and SIMP) that follow the three referred categories of intersection access (sequential, parallel, and synchronous). We consider two simple road networks, a homogeneous one with four intersections of four legs and a heterogeneous one with two four-legged intersections together with two three-legged ones. We employed the SUMO simulator for building the road networks and the five TLC protocols. The simulations ran for various traffic arrival rates and speeds corresponding to low, moderate, and high-intensity traffic conditions in urban scenarios. The number of vehicles leaving the road network per hour (i.e., the network throughput), travel delays, fuel consumption, and emissions of air pollutants were used as the performance indicators. Simulation results suggest the synchronous approach outperforms all other approaches in all the tested cases concerning the reduction of travel time and fuel consumption, with a residual advantage in throughput.

The rest of the paper is organized as follows. We briefly review the relevant related works in Section 2. Section 3 describes the road networks and signalized intersections that are used in this study. Section 4 outlines the state-of-the-art TLC protocols used for comparison. Section 5 presents the simulation scenarios, parameters, and associated values. The performance of the comparing TLC approaches is presented in Section 6. Final remarks are drawn in Section 7.

2. Related works

This section presents the relevant related works that employ one/two/three of the three intersection area managing techniques (i.e., sequential, parallel, and synchronous). In the literature, the majority of approaches are observed to be sequential. For example, Genders and Razavi (2019) compared the performance of both cyclic and acyclic sequential TLC approaches, including the MCA (Varaiya, 2013) and WTLC (Genders and Razavi, 2019), at a network of two intersections. Chaudhuri et al. (2022) compared a set of TLC algorithms that serve vehicles sequentially at intersections, namely the RR, feedback control, and reinforcement learning algorithms (Deep Q Networks and Actor-Critic), and found different algorithms perform better in different traffic settings. One step ahead Barman et al. (2022) studied the performance of MCA against other acyclic sequential approaches on a real road network in Minnesota. However, the common assumption of most of these TLC approaches is that they are all sequential and serve only HVs and possibly connected vehicles.

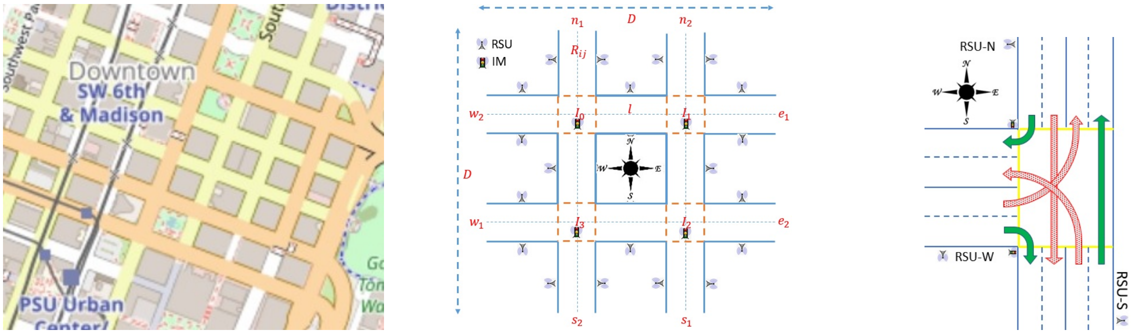
Conversely, several studies have focused on parallelly serving vehicles from opposite road lanes. For example, (Björck et al., 2018) compared several configurations of fixed-time TTLC with the QTLC (Abdulhai et al., 2003) and ITCL (Younes and Boukerche, 2015) approaches where all three TLC approaches operate parallelly. Differently, Özkul et al. (2018) compared their approach against sequential approaches like the RR and WTLC.

Chen et al. (2020) presented a special case in which deep reinforcement learning is utilized for TLC signals adaptation that can serve vehicles sequentially or parallelly based on vehicle crossing directions and compared it against sequential RR and MCA and other parallel approaches. These approaches also serve HVs, possibly AVs.

The related works on synchronous intersection access are very recent and limited, too. For instance, Tlig et al. (2014) is the first work presented in this class and compared its performance against an RR-like approach for different configurations. Similarly, Aoki and Rajkumar (2019) presented their Distributed Synchronous Intersection Protocol (DSIP) and compared it against the RR/TTLC-like fixed time approach. More information on synchronous protocols can be found in (Aoki, 2020). In the same research line, Reddy et al. (2022, 2023) proposed SIMP, a synchronous approach, and compared it in an isolated intersection against several TLCs of different natures. Note that most of these synchronous class approaches support either HVs or AVs or the mixed operation of AVs and HVs. As opposed to other comparisons that were limited in the intersection access classes they considered, this comparison already includes TLCs of multiple classes. This work compares all three classes to a small network of four intersections. We believe it is the first comparison to cover these three classes in networks of intersections.

3. Road Network with Four Signalized Intersections

Figure 1a displays the real-world grid road network with four-legged and three-legged (or T) intersections. By motivating on this real-world road network, we designed two road networks that are homogeneous and heterogeneous with 2×2 intersections. Note that the designed road networks reflect only real-world road networks but do not employ the exact road length settings.



(a) Grid network in Portland, Oregon. (b) Modelled 2 × 2 network of intersections. (c) Three-legged intersections.

Fig. 1: Motivational road network (a), modeled 2×2 network of intersections with four legs (b), and three-legged intersections (c).

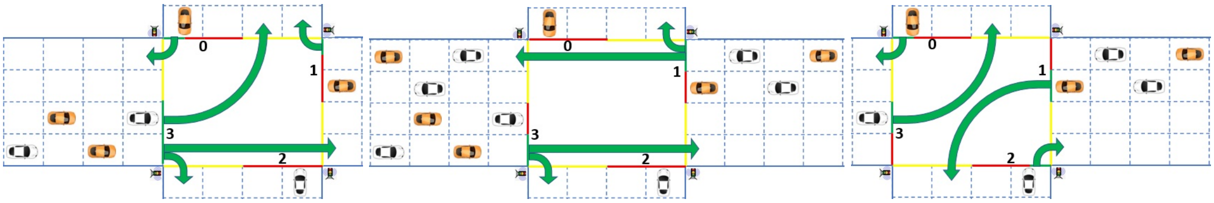
Figure 1b presents the 2 × 2 homogeneous road network in which all four intersections (I_0, I_1, I_2, and I_3) are four-legged and are arranged in a $D \times D$ road area; thus, the length of any road lane is the same. These intersections connect outer space and neighboring intersections with two inflow and two outflow lanes. The roads that connect outer space with the four intersections are n_1 and w_2 (I_0), n_2 and e_1 (I_1), e_2 and s_1 (I_2), and s_2 and w_1 (I_3). In the network, each intersection is equipped with an intersection manager (IM) unit, possibly an edge component for implementing the TLC decision-making. Each road is also equipped with a roadside unit (RSU) for providing communication support between AVs and road infrastructure like the IM unit. AVs share their arrival information and the desired crossing direction (i.e., left, straight, right) when they arrive within the communication range of RSUs via Vehicle-to-Infrastructure communication to access the intersection. Then, the IM unit decisions are returned to AVs on whether access is granted to cross the intersection. Each road is equipped with road sensors like induction loop detectors and camera sensors to feed the traffic information to the intelligent and adaptive TLC approaches. The camera sensors are only needed for SIMP when road lanes are shared between vehicles of different crossing directions. We assume the connection between the road sensors and the IM unit is wired due to ultra-low latency.

In a heterogeneous road network, the two left-side intersections (I_0 and I_3) are four-legged similar to the homogeneous road network, and the remaining two intersections (I_1 and I_2) on the right side are three-legged. Figure 1c shows the three-legged intersections, in which the rightmost lane is a free-flow lane; thus, the traffic does not yield or stop on that specific road lane. All the non-conflicting right-crossing directions are permitted. Hence, the TLC protocols only need to manage the traffic of left-crossing lanes from the South and the West and the straight-crossing lane from the North. For right-hand driving, the rightmost lane is shared between straight- and right-crossing vehicles, while the left lane can be either dedicated to left-crossing or shared between left- and straight-crossing vehicles.

4. Signalized Intersection Management Approaches

As mentioned earlier, TLC approaches permit vehicles access to the intersections in three ways: sequential, parallel, and synchronous. We illustrate these types using the dedicated left-crossing lane intersections. Sequentially operating TLC strategies permit a set of vehicles from one road (both left- and straight-/right-crossing road lanes) at a time and then shift to the next. Figure. 2a shows a sequentially operating four-way intersection permitting vehicles from the West (3) while blocking the remaining conflicting roads of North (0), East (1), and West (2). If the green phase sequence is fixed, after completing the green time in the West, the green phase will be cyclically shifted to the North (clockwise) or the South (anticlockwise). RR and WTLC approaches are of this kind (Chaudhuri et al., 2022; Genders and Razavi, 2019). When this green phase sequence is not fixed, the TLC approach is acyclic and thus can jump to any road. MCA is an example of this kind (Varaiya, 2013).

When vehicles access the intersections, the green time defines whether the TLC approach is fixed or adaptive. For instance, the green phase time of any road in RR is fixed, and we employ the 30s followed by 4s of yellow time, thus the total cycle time is 136*s*. Unlike RR, the WTLC adapts the green phase times between a minimum and maximum values leading to a variable control cycle. The actual green time is decided by WTLC depending on the inflow traffic information. This paper uses 100s and 180s as the minimum and maximum cycle times corresponding to a minimum green time of 21s and a maximum green time of 41s, followed by a yellow phase of 4s. MCA, on the other hand, uses a minimum green time of 30s followed by a yellow time of 4s. Then the maximum green time allocation and phase sequence depend on the traffic inflow, trying to reduce the pressure on each intersection acyclically.



(a) Sequential intersection access. (b) Parallel intersection access. (c) Synchronous intersection access.

Fig. 2: Vehicles accessing dedicated left-crossing lane intersections sequentially, parallelly, and synchronously.

Parallel TLC operation permits vehicles from two opposite road lanes to cross the intersection during a certain green phase time and then shifts to the next pair of opposite road lanes. Figure 2b illustrates the parallel intersection access of vehicles from two opposite lanes, namely straight- and right-crossing from East (1) and West (3). Then, the left-crossing vehicles of the same East and West roads are allowed to cross. These two phases are then repeated on the North (0) and South (2) roads. The control cycle is obtained considering a yellow phase betwwen any of the referred four phases. In this paper, we are employing the conventional TTLC (Björck et al., 2018) in which the straight- and right-crossing lanes are assigned 30s of green time, and the left-crossing lanes are assigned 15s of green time, both followed by a yellow phase of 4s. Thus, the total cycle time is 106*s*. In the case of adaptive TLC approaches, the sequence and time of green phases changes based on their working nature.

Synchronous approaches synchronize vehicles intersection access from non-conflicting road lanes, relying on vehicle presence at the intersection entrance. This paper employs the SIMP protocol that permits one vehicle together with one vehicle per road lane that is non-conflicting. Figure 2c illustrates this synchronous nature, meaning that it permits the left-crossing vehicle from the West (3) together with the left-crossing vehicle from East (1) and the right-crossing vehicles from all other roads, North, East and South, if present, too (from North (0) and South (2) in this case). The green phases are just long enough to allow those vehicles to enter. Then, the TLC checks sequentially all lanes, one at a time, for vehicles presence, always together with all other non-conflicting lanes. Note that the pattern of opposite road lanes is similar, thus the SIMP control cycle can be obtained considering the green times allocated to East/West and North/South left turns plus the straight/right turns. Considering 2.5s green phases for straight-/right-crossing and 3s for left-crossing, the SIMP control cycle takes $11s$.

Table 1 summarizes the comparing IM approaches. In the table, the R-lane indicates the rightmost lane sharing the straight-/right-crossing vehicles, and the L-lane indicates the left-crossing lane that can be either dedicated to left-crossing or shared between straight-/left-crossing vehicles. MCA is acyclic but with a minimum green time, so we indicated it with +. For T-intersections, the TLC cycle times were adapted considering the missing road. Therefore, the TLC cycle times for RR, TTLC, MCA, WTLC, and SIMP are 102, 72, 102, [75 135], and 8.5s, respectively.

Table 1: Summary of the IM approaches under comparison for homogeneous intersections.

IM	Type	R-lane Green Time (s)	Yellow (s)	L-lane Green Time (s)	Yellow (s)	TLC cycle time (s)
RR	Sequential	30	4	30	4	136
TTLC	Parallel	30	4	15	4	106
MCA	Sequential	30+	4	30+	4	136+
WTLC	Sequential	[21 41]	4	[21 41]	4	[100 180]
SIMP	Synchronous	2.5	0	3	0	11

5. Simulation Scenarios

We employed the SUMO simulator for building both homogeneous and heterogeneous road networks shown in figures 1b and 1c; and for testing the five comparing IM approaches - RR, TTLC, MCA, WTLC, and SIMP (Lopez et al., 2018). We designed two simulation scenarios for each homogeneous and heterogeneous road network.

- ***Scenario-1***, all intersections are homogeneous and are configured with dedicated left lanes.
- ***Scenario-2*** is similar to scenario-1, but with shared left lanes instead (i.e., the straight-crossing vehicles share both road lanes).
- ***Scenario-3***, intersections I_1 and I_2 are now T-intersections, but all intersections use dedicated left lanes.
- ***Scenario-4*** is similar to scenario-3, but with shared left lanes instead.

We set the intersection area and road length values as $20m^2$ and $l = 500m$, respectively. Thus, $D = 1540m$ in the homogeneous road network. In the case of the heterogeneous road network, the vertical distance is the same as $D = 1540m$, but the horizontal distance is $D - l = 1040m$. Five traffic arrival rates (0.025, 0.05, 0.067, 0.1, and $0.133veh/s$) are employed, each for 1h, representing low, moderate, and (below) saturated traffic conditions (arrival rates above $0.133veh/s$ would generate spill-backs and over-saturation). *Poisson distribution* is used to generate traffic on all external inflow lanes and the simulations run until all the generated vehicles exit the network. In the homogeneous networks, the external inflow lanes are eight, i.e., n_1, n_2, e_1, e_2, s_1, s_2, w_1, and w_2, thus the generated traffic is equally distributed to seven outflow lanes (14.3% each) without U-turns to the outflow lane of the source. For the heterogeneous networks, the external inflow lanes are six, i.e., n_1, n_2, s_1, s_2, w_1, and w_2; hence the generated traffic is again equally distributed to the five external outflow lanes (20% each) aso without U-turns to the outflow lane of the source.

To study the aforementioned scenarios in urban road settings, we tested two different maximum speeds, 30 and $50km/h$. We used equal amounts of HVs and AVs, each using a suitable car-following model (CFMs), Krauss for HVs, and Adaptive Cruise Control (ACC) for AVs. These CFMs describe the cars motion both when encountering another car ahead and when driving alone Reddy et al. (2022). We set appropriate values for the simulation parameters, such as acceleration ($2.6m/s^2$), deceleration ($-4.5m/s^2$), and emergency deceleration ($-9m/s^2$). We used the default car-following model values of SUMO for HVs and AVs, such as the minimum time headway (the time/space distance between vehicle front bumper and the preceding vehicle back bumper $1s$) and the imperfection of the human driver (0.5). The fuel consumption and emission models are presented in Reddy et al. (2020).

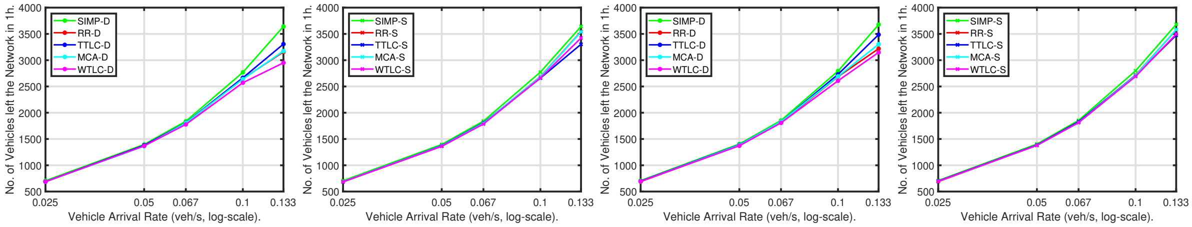
6. Results of Homogeneous and Heterogeneous Road Networks

We measured the number of vehicles that left the road network in $1h$ as the road network throughput (veh/h). We also measured the average results of travel time loss, fuel consumption, and associated emissions (CO, CO_2, HC,

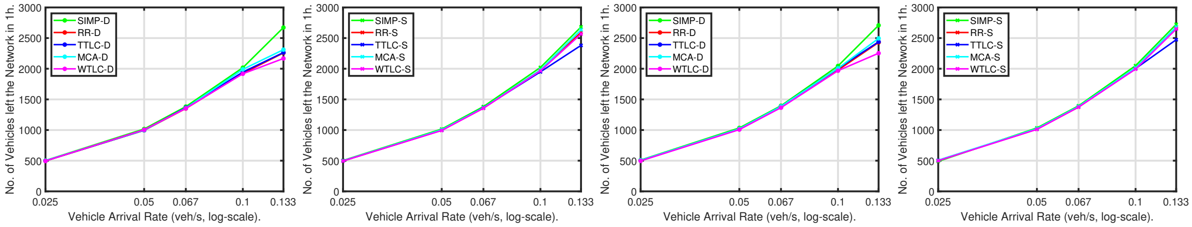
PMx, and NOx) for 2500 vehicles. The results of dedicated left lane approaches are identified with $* - D$ and shared left lane approaches with $* - S$.

6.1. Network Throughput (veh/h)

The network throughput results of both homogeneous (scenarios 1 and 2) and heterogeneous (scenarios 3 and 4) road networks are presented in Fig. 3 for $30km/h$ (left plots) and $50km/h$ (right plots). The results of homogeneous road networks show that using shared left-lane intersections (scenario 2) tends to improve throughput slightly under dense traffic when compared to using dedicated left-lane intersections (scenario 1). Similarly, a higher maximum speed also tends to improve throughput slightly for dense traffic scenarios. The results with heterogeneous road networks show very similar trends, but scaled down, given the lower throughput of the T-intersections. All these results seem to be expected given the higher intersection service rate with two lanes serving the straight-crossing traffic, with higher vehicle speeds or using all intersections with four legs, thus dispatching more traffic.



(a) Scenario-1 at $30km/h$. (b) Scenario-2 at $30km/h$. (c) Scenario-1 at $50km/h$. (d) Scenario-2 at $50km/h$.



(e) Scenario-3 at $30km/h$. (f) Scenario-4 at $30km/h$. (g) Scenario-3 at $50km/h$. (h) Scenario-4 at $50km/h$.

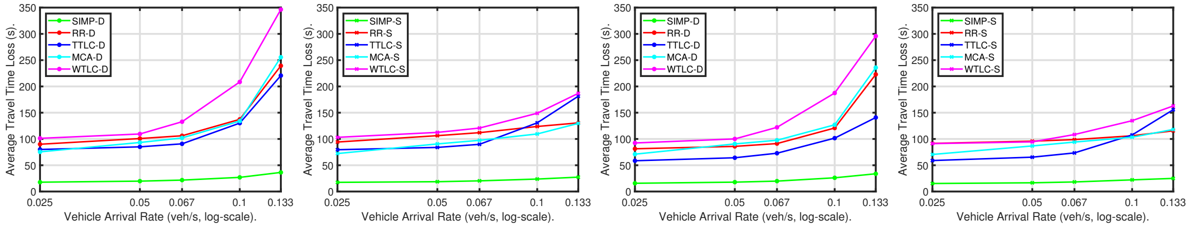
Fig. 3: Network throughput (veh/h) of homogeneous (top plots) and heterogeneous (bottom plots) road networks at $30km/h$ and $50km/h$ maximum speeds of comparing IM approaches.

Overall, SIMP protocol exhibits the highest throughput values under dense traffic conditions in both homogeneous and heterogeneous road networks and at both maximum speeds. These results indicate that synchronizing vehicles access to the intersections can significantly reduce traffic congestion and improve throughput under intense traffic. On the other hand, WTLC typically shows the lowest network throughput for high traffic intensity in all scenarios that use dedicated left lanes. This behavior can be related to WTLC's inadequate adaptation to its sequential operation. However, when using shared left lanes, then TTLC tends to exhibit the lowest network throughput with intense traffic. This behavior arises from the fact that sharing the left lane raises conflicts between straight- and left-crossing vehicles in parallel operation and blocks the opposite road lanes.

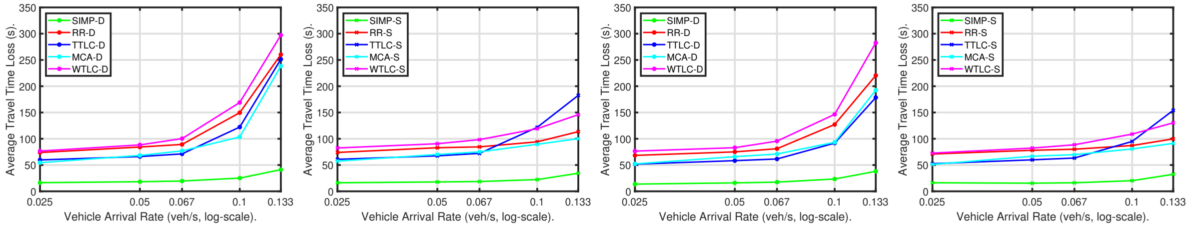
6.2. Average Travel Time Loss (seconds)

The average travel time loss of 2500 vehicles for the same scenarios, arrival rates, and speeds are presented in Fig. 4. The travel time loss combines the waiting time at intersections and the time lost due to eventual speed adaptations in the journey between origin and destination. These adaptations occur when vehicles travel in close proximity and the following vehicle adapts its speed depending on the front vehicle to avoid collisions. Whenever there is a red signal, vehicles must decelerate before stopping and accelerate to access the intersection during the green signal. Thus, some time will be lost in these situations too.

As expected, the travel time loss is lower for higher speeds, lower for intersections with shared left lanes and lower for heterogeneous networks. An outstanding result is that SIMP's maximum waiting time is below $8s$. This means that, on average, the vehicles wait for less than one SIMP control cycle, i.e., $11s$. This confirms the advantage of synchronizing the access to intersections in urban settings, effectively reducing waiting times of vehicles, given simultaneous admission from multiple lanes and the short control cycle.



(a) Scenario-1 at $30km/h$. (b) Scenario-2 at $30km/h$. (c) Scenario-1 at $50km/h$. (d) Scenario-2 at $50km/h$.



(e) Scenario-3 at $30km/h$. (f) Scenario-4 at $30km/h$. (g) Scenario-3 at $50km/h$. (h) Scenario-4 at $50km/h$.

Fig. 4: Average travel time loss (s/veh) of 2500 vehicles for homogeneous (top plots) and heterogeneous (bottom plots) road networks at $30km/h$ and $50km/h$ maximum speeds imposed by the comparing IM approaches in both dedicated and shared left lane intersections.

On the contrary, WTLC-D is the worst-performing approach with the highest waiting time values due to its poor adaptations in serving arriving vehicles sequentially. This is particularly notorious in scenarios with dedicated left lanes and for both maximum speeds. However, for shared left lanes the travel time loss with TTLC grows for dense traffic due to the parallel operation and it becomes the worst approach in this metric with heterogeneous networks.

6.3. Fuel and Emissions Efficiency

The average fuel consumption and associated emissions results show patterns that correlate directly with the travel time loss results. Thus we omit the respective plots. Similarly to the previous results, scenario 4 at $50km/h$ shows the best situation with all IM approaches reaching their best performance. Again SIMP shows the best energy efficiency results, emerging from smooth driving between consecutive vehicles imposed by the synchronous intersection access, and its short TLC cycle. Consequently, the tailpipe emissions are reduced because of the proportional relationship between fuel consumption and associated emissions.

7. Conclusions

This work highlighted the advantages of synchronizing vehicle intersection access in a road network with four signalized intersections. We compared one synchronous approach (SIMP) against three sequential approaches (RR, MCA, and WTLC) and one parallel approach (TTLC) in a small network of four intersections in two configurations, homogeneous (four equal four-legged intersections) and heterogeneous (two four-legged and two three-legged intersections). In both networks, we considered two configurations of the left lane: dedicated and shared left lanes. Finally, we considered two speed limits typical of the urban setting, namely 30 and 50km/h, resulting, for each TLC, in eight different configurations. In all configurations, the synchronous approach (SIMP) outperformed all others. The difference in throughput is small and only visible with high-intensity traffic. However, the benefits of reducing travel time loss and fuel consumption/emissions are very significant. In future work, we will study the applicability of the SIMP to real-world city-wide general road networks.

Acknowledgements

This work was supported by FCT/MCTES (Portuguese Foundation for Science and Technology) under grant UIDP/UIDB/04234/2020 (CISTER unit); by FCT through the European Social Fund (ESF) and the Regional Operational Programme NORTE2020, under grants 2021.05004.BD, NORTE-01-0145-FEDER-000062 (RETINA); and by FCT and EU ECSEL JU within ECSEL/0010/2019 - JU grant nr. 876019 (ADACORSA) - The JU receives support from the European Union's Horizon 2020 research and innovation programme and Germany, Netherlands, Austria, France, Sweden, Cyprus, Greece, Lithuania, Portugal, Italy, Finland, Turkey (Disclaimer: This document reflects only the author's view and the Commission is not responsible for any use that may be made of the information it contains).

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