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# Synchronous Intersection Management to reduce Time Loss

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**Abstract**

Conventional intersection management that allows multiple vehicles from one road at a time, e.g., Round-Robin (RR), may constitute bottlenecks in urban traffic management. Consequently, new intelligent intersection management (IIM) approaches were proposed to reduce time loss, fuel wastage, and ecological damage. IIM is also suited to take advantage of the new communication capabilities of autonomous vehicles that are gaining relevance, though still co-existing with human-driven vehicles. This paper extends the analysis of a recently proposed synchronous IIM system, the Synchronous Intersection Management Protocol (SIMP), that is compared with the RR scheme in a four-way single-lane intersection as those found in urban residential areas, under maximum vehicle speeds of $30Km/h$ and $50Km/h$ and various traffic arrival rates. We characterize performance by measuring time loss, i.e., the additional trip delay due to forced slowdown, and fuel consumption using a model for standard vehicles with internal combustion engines. The experimental results obtained with the SUMO simulation framework indicate an advantage for SIMP in both metrics, approximately halving the values achieved with the best RR approaches and with high traffic rates.



*Keywords:* Signalized Intersection Management; Time Loss; Energy-Efficiency; Mixed Autonomous and Human-driven Traffic; SIMP.

## 1. Introduction

According to Bared (2016), signalized intersection management (SIM) is one of the critical challenges for efficient urban traffic management (UTM). Intersections can cause bottlenecks responsible for traffic congestion, leading to fuel wastage and time loss, i.e., extra trip delay due to forced slowdown. This is recognized by related organizations, e.g., the U.S. Department of Transportation (Dowling, 2007), that considers speed and trip delays as some of the most important performance measures of effectiveness of a SIM.

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Therefore, new intelligent approaches were developed to improve the efficiency of intersection management (IM), building on Information and Communication Technologies (ICT). The so-called intelligent intersection management (IIM) protocols can play a vital role in mitigating traffic congestion: IIM can interact with a great number of the heterogeneous agents involved in intersections, namely autonomous vehicles (AVs), road-side units (RSUs), vehicle detection sensors and traffic lights control units (TLCs), using communication and coordination for better decision-making (Han et al., 2019). The decisions can also account for and be transmitted to non-communicating human-driven vehicles (HVs) that will still co-exist for many years (Aoki et al., 2019) through standard signalization (i.e., traffic lights, dynamic signage). It has been shown that synchronous management of traffic flows can considerably reduce energy wastage and associated air pollutants (Hemmerle et al., 2016).

In this context, we have recently proposed an IIM Architecture (IIMA) equipped with a Synchronous Intersection Management Protocol (SIMP) (Reddy et al., 2019) aiming at isolated four-way single-lane road intersections that are common in urban residential areas, where the typical management scheme is Round-Robin (RR). The synchronous framework (IIMA/SIMP) has proved its efficiency in controlling mixed AVs and HVs smoothly, particularly reducing energy consumption and associated emission of air pollutants (Reddy et al., 2020). In this paper, we analyze the time loss of IIMA/SIMP in the same context of urban areas, with a range of relatively low traffic density and two typical maximum speeds, $30 Km/h$ and $50 Km/h$ using internal combustion engines. We find that SIMP performs better than multiple configurations of RR, both in time loss and fuel consumption.

## 2. Related Work

There is a rich literature addressing the SIM challenge, particularly for energy-efficiency and congestion-induced trip delays/time loss. For example, Sekhar et al. (2013) built a model to estimate the idling delay and fuel loss at the busiest urban intersection of Ahmedabad, India.

Vujic et al. (2015) investigated the impact of queue length and average vehicle speed on fuel consumption and associated emissions. The study used data from Zagreb, Croatia, and applied adaptive traffic control techniques. Hemmerle et al. (2016) studied the fuel consumption of combustion-engine vehicles and the energy balance (the difference between the energy consumed and the energy regenerated while driving) in electrical vehicles using data from road sections of Düsseldorf, Germany; they show that the energy consumption in over-saturated cities decreases when city traffic is composed of synchronized flow patterns. Hou et al. (2018) used dynamic programming and model predictive control in a two-level joint optimization involving vehicles and TLC to maximize the passage of vehicles through the intersection. They reduced 31% energy consumption and 95% queue length against conventional SIM. Zhu et al. (2019) reduced the traffic delay using an adaptive traffic control method that adjusts the signal timing in traffic lights thanks to two detectors installed in road lanes.

Hadjigeorgiou et al. (2019) formulated a mixed-integer optimization for minimizing both fuel consumption and travel time for connected and autonomous vehicles that are expected to arrive at a non-signalized intersection within a specific time-window. The simulation results reveal that minimizing travel time consumes more fuel and vice-versa. Aoki et al. (2019) proposed the Distributed Synchronous Intersection Protocol (DSIP) for mixed traffic with AVs and HVs. DSIP explores cooperation between AVs and with traffic lights using direct communications. The authors show an improvement in traffic throughput when compared to conventional signalized intersections. Jamal et al. (2020) proposed optimizing the signal timings plan of intersections in Dhahran, Saudi Arabia, using Genetic Algorithms and Differential Evolution. They reported reducing travel delay by 15 to 35%. Mercader et al. (2020) presented a travel time-based max-pressure controller for SIM that accounts for the finite capacity of inflow roads and compared it against the queue length-based max-pressure controller. Simulation results were compared with those of a real implementation at an urban arterial road in Jerusalem and identified that the travel time-based approach avoids spillback; however, it negatively impacts traffic velocity.

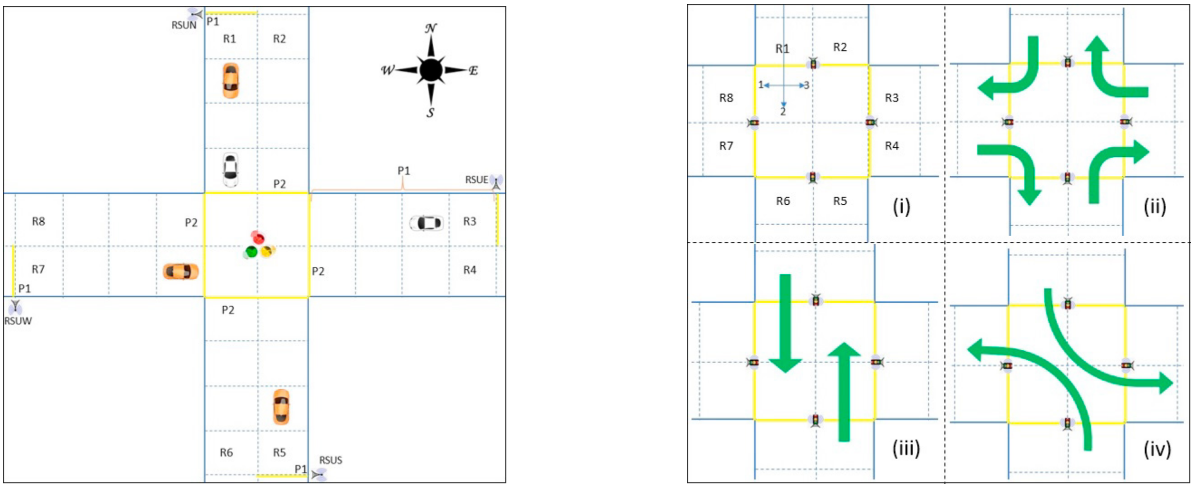
Comparing with these works, we also use the synchronous intersection management approach but aiming at maximal parallel traffic handling not relying on cooperating AVs. Moreover, we address the often neglected case of low density and low-speed traffic in urban residential areas, as surveyed by Pojani et al. (2015).

## 3. Intelligent Intersection Management Architecture

The IIMA is composed of a set of fixed components, namely RSUs, road sensors, and a TLC with communication capability, and a set of mobile users, namely communicating AVs and non-communicating HVs. In this work, the IIMA is deployed on an isolated four-way single-lane road intersection. Figure 1a shows the intersection and associated components as well as some users. An RSU is associated with each road and provided with road sensors $P1$ (vehicle detection on entry and directions) and $P2$ (vehicle exit detection). These sensors are a combination of cameras and induction-loops, appropriately placed to accomplish their function.

The inflow and outflow directions are indexed clockwise starting from the North road and using odd indexes for the former (R1, R3, R5, and R7) and even indexes for the latter (R2, R4, R6, and R8). The AVs inform the intersection management of their presence and target direction and receive access authorization commands via RF wireless communications. Conversely, the presence and target direction of non-communicating vehicles, typically HVs, is detected by sensor $P1$ in each road, and access commands are transmitted via traffic lights. We consider that all vehicles are capable of keeping some safety distance between them.

All sensors communicate with the TLC allowing the intersection management to know the traffic situation at every time $t$. Fig. 1b-(i) shows the direction codes used, namely 1-right, 2-straight and 3-left, while Fig. 1b-(ii) shows the handling of right-crossings, (iii) straight-crossings and (iv) left-crossings. A central element of IIMA is the *conflicting directions matrix* (CDM), which represents the directions, from all pairs of lanes, that imply intersecting paths (conflicts, marked as "1") and those that have non-intersecting paths (conflict-free, marked as "0").




(a) IIMA on a four-way single-lane intersection

(b) Direction codes and examples of crossing maneuvers

Fig. 1: Intelligent Intersection Management Architecture (IIMA); Direction codes: 1-right, 2-straight, 3-left; and Crossing maneuvers: (ii) Right-crossing; (iii) Straight-crossing; and (iv) Left-crossing.

### *3.1. Synchronous Intersection Management Protocol*

The operation of SIMP involves several stages: detecting the total number of vehicles in the intersection access lanes using $P1$ sensors, discriminating non-communicating HVs from communicating AVs using the previous count and the wireless communications, and performing access decisions for the vehicles at the intersection entrance, using the CDM. This sequence corresponds to one synchronous operation cycle that coordinates vehicle access from all lanes to the intersection, which ends (and immediately restarts) when all vehicles exited the intersection as detected by $P2$ sensors. Let $\mathbf{n}(t)$ be the total number of vehicles detected in a given lane using the corresponding $P1$ sensor at time-step $t$. Let $\mathbf{c}(t)$ be the number of pending access requests at time-step $t$ from communication-enabled vehicles. The number of non-communicating HVs on each road lane at time-step $t$ can be estimated as $\mathbf{n}(t)-\mathbf{c}(t)$.

Figure 1b-(ii-iv) shows some of the maneuvers allowed by the CDM that correspond to parallel traffic flows. For example, when turning left, two vehicles from opposite roads can be admitted (iv). The same happens with straight crossing (iii). When turning right, vehicles from all the four roads can be admitted simultaneously.

### 3.2. Performance Measures Of Effectiveness

To characterize the performance of IIMA/SIMP, we used a standardized performance measure of effectiveness as presented in (Dowling, 2007), namely the time loss, i.e., the extra delay induced by the IM. Moreover, we complemented this measure with an evaluation of fuel consumption to assess the energy efficiency of the proposed IM.

We compute time loss as the average time that a vehicle loses due to driving slower than the maximum allowed, including intersection waiting time. At time-step $t$ the time loss $L(t)$ is computed using $\Delta_t * (1 - v(t)/v_{max})$, where $\Delta_t$ indicates the length of a time step, $v(t)$ the velocity in that time step (considered constant), and $v_{max}$ is the maximum velocity considering the speed limit. The total time loss $L$ suffered by a given vehicle is the summation of $L(t)$ from $t_i$, when the vehicle is injected in the system, until $t_j$, when the vehicle arrives at the destination, thus $L = \sum_{t_i}^{t_j} L(t)$. The time loss for the system is the average of $L$ for all vehicles.

In what concerns fuel consumption, we use the HBEFA3.1 (Handbook on Emission Factors for Road Transport) emission model for passenger cars ($PC\_G\_EU4$). This emission model represents passenger cars that use gasoline fuel under European Emissions Standard IV. We consider this model for both AVs and HVs. For a given vehicle, this model allows estimating the fuel consumption $Q(t)$ knowing the velocity $v(t)$ and acceleration $a(t)$ (Keller et al., 2010). The total fuel $C$ consumed by a given vehicle is the integration of $Q(t)$ from $t_i$ to $t_j$, i.e., the beginning and end instants of the vehicle trajectory, thus $C = \int_{t_i}^{t_j} Q(t)dt$ (see (Treiber et al., 2008) for detailed information). The fuel consumption for the system is the average of $C$ for all vehicles.

## 4. Simulation Setup

We study two SIM strategies for comparison purposes, SIMP and Round-Robin, with the latter serving as a baseline due to its widespread use. The RR SIM logic is inspired by Srivastava et al. (2013) and Bui et al. (2017), wherein green and yellow phases are assigned to each road lane in equal-duration cycles initialized from North and turning clockwise, while the other roads are blocked with red. Four RR-$x$ schemes (RR-5, RR-10, RR-20, and RR-30) were defined, where $x$ indicates the green phase followed by a $4s$ yellow-phase in all cases. We used the microscopic mobility simulator SUMO v1.6.0 running on an Intel Core i3-4160 CPU, 3.60Ghz × 4 cores, NVIDIA RTX 2070, 8GB RAM and 64 bit Ubuntu 18.04.4 LTS OS, to build a realistic model of an intersection over a flat urban scenario, to generate synthetic traffic conditions and to execute the management protocols. Each road is $500m$ long until the intersection, and the IIMA management area starts $100m$ away from the intersection. We consider vehicles to be at most $5m$ long and that they keep at least $5m$ of safety distance between them.

Concerning vehicles driving and control, we consider the Krauss and Adaptive Cruise Control car-following models for HVs and AVs, with a maximum acceleration of $2.6m/s^2$, a maximum deceleration of $-4.5m/s^2$, an emergency deceleration of $-9m/s^2$, a minimum $1s$ time headway between vehicles and a driving imperfection factor of 0.5.

To characterize the performance of the IM approaches, we define four simulation scenarios. The first three consider one direction crossing each, only, and they are meant to expose intrinsic behaviors of the IM approaches. Conversely, the last scenario represents a realistic traffic case with vehicles turning to all directions, randomly.

- Scenario-1: **Left-crossing** - all vehicles turn left at the intersection;
- Scenario-2: **Straight-crossing** - all vehicles cross the intersection in a straight direction;
- Scenario-3: **Right-crossing** - all vehicles turn right at the intersection;
- Scenario-4: **Random-crossing** - the vehicles take a random direction at the intersection.

We carried out the comparisons under two typical maximum speeds allowed in urban areas, namely $30Km/h$ and $50Km/h$, and four traffic frequencies per road: $0.05Veh/s$, $0.1Veh/s$, $0.2Veh/s$ and $0.4Veh/s$. In each experiment, we injected 1000 vehicles (50% AVs and 50% HVs). The injection process executed every second in each road and added a vehicle randomly, respecting the referred average frequencies. In **scenario-4**, the traffic was generated with random directions, too, uniformly distributed for left, straight, and right. The simulations were run six times with different random seeds for the same set of parameters in all scenarios; the results are the average of the six runs.

## 5. Results and Discussion

### 5.1. *Time Loss for* $30Km/h$

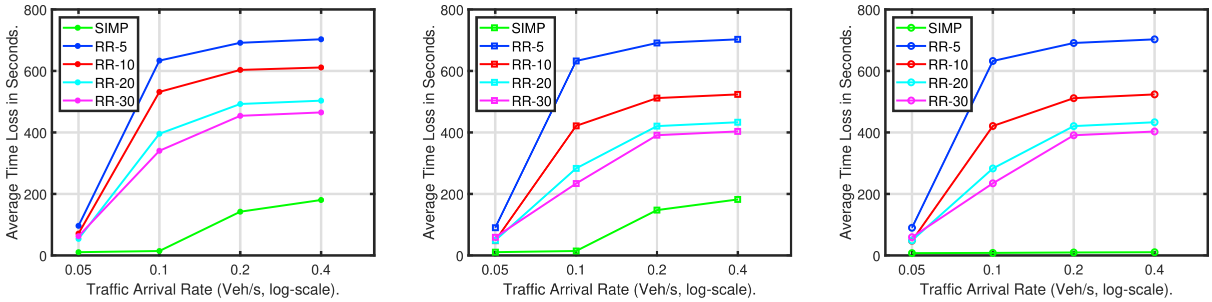



Fig. 2: Average Time Loss results in seconds, for **Scenarios-1, 2**, and **3** with $30Km/h$ speed limit from left to right.

Figure 2 shows the time loss results for **scenarios-1, 2, 3** with $30Km/h$ speed limit. The first observation is that the system saturates for arrival rates between $0.1Veh/s$ and $0.2Veh/s$. In all management approaches and all directions, the time loss becomes approximately constant because the injection of cars is suspended while the roads are full, and then every car takes approximately the same time to reach the destination. For low arrival rates, particularly $0.05Veh/s$, all IM strategies present an average time loss under $100s$, notably, SIMP has $11s$ while RR-$x$ registers between $47s$ and $97s$. In all the three scenarios, SIMP outperforms RR-$x$ with lower time loss, i.e., under $200s$ for higher arrival rates in both **scenario-1** and **scenario-2**, and under $11s$ in **scenario-3**. These are clearly visible in Fig. 2, and particularly with right-crossing since SIMP is capable of serving four vehicles simultaneously.

### 5.2. *Fuel Consumption for* $30Km/h$

Fig. 3 plots the average fuel consumption for **scenarios-1,2,3**, for the same experiments as in Fig. 2. On average, vehicles consume more fuel on left-crossing, given the slightly longer path and longer waiting times (longer idling).

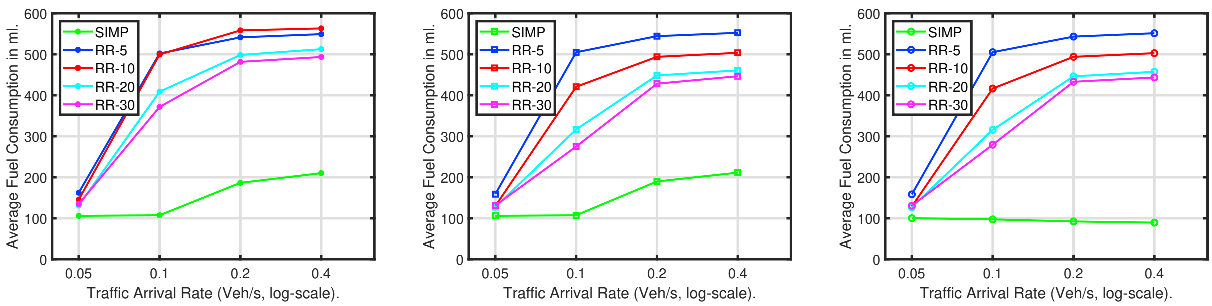



Fig. 3: Average Fuel Consumption results in *ml* for **Scenarios-1, 2**, and **3** with $30Km/h$ speed limit from left to right.

We observe that increasing green time in the RR configurations decreases the fuel consumption in (near) saturated cases. This is expected, too, since shorter green windows imply more breaks in the traffic flow and thus more idling. Concerning SIMP, it also performs better than any RR configuration, and the improvement is more significant, distinctly, for a high arrival rate of $0.4Veh/s$. RR configurations consume two times (**scenario-1, 2**) and four to five times (**scenario-3**) more fuel than SIMP. We observed that this advantage of SIMP arises from the synchronous access of the vehicles to the intersection, leading to smoother traffic handling with less stopping/idling periods than any RR configuration. Another observation concerns SIMP in **scenario-3**. Curiously, fuel consumption for low arrival rate is higher than for higher arrival rates. This is because, in this scenario, vehicles move at a speed that is superior to the cruising speed (a speed at which fuel consumption is optimal) that consumes more fuel in low densities.

### *5.3. Time Loss for* $50Km/h$

The results for time loss with the speed limit increased to $50Km/h$ for **scenarios-1, 2, 3** are shown in Fig. 4. Since vehicles now can travel faster, the RR configurations with longer green windows (RR-20 and RR-30) allow passing more vehicles per cycle, increasing their efficiency. Yet, SIMP shows better performance with inferior time loss. For lower densities, the time loss is under $10s$, and for higher densities, it is approximately equal to the results of $30Km/h$, i.e., under $200s$, for **scenarios-1, 2**. In the case of **scenario-3**, SIMP has its highest time loss ($10s$) at higher densities.

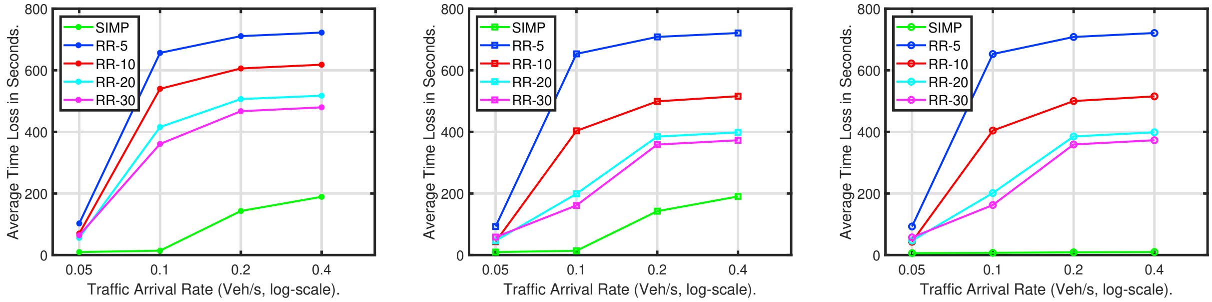



Fig. 4: Average Time Loss results in seconds, for **Scenarios-1, 2**, and **3** with $50Km/h$ speed limit from left to right.

### *5.4. Fuel Consumption for* $50Km/h$

The fuel consumption results for **scenarios 1, 2, 3** with a speed limit of $50Km/h$ are shown in Fig. 5 (representing the same experiments shown in Fig. 4). SIMP maintains a clear advantage over all RR configurations for all arrival rates. Furthermore, these results at $50Km/h$ also show that SIMP exhibits lower fuel consumption than at $30Km/h$, i.e., below $200ml$ (**scenario-1, 2**) and $85ml$ (**scenario-3**). As referred before, this is due to the smoother traffic handling of SIMP as opposed to RR, which always forces stronger traffic accumulation.

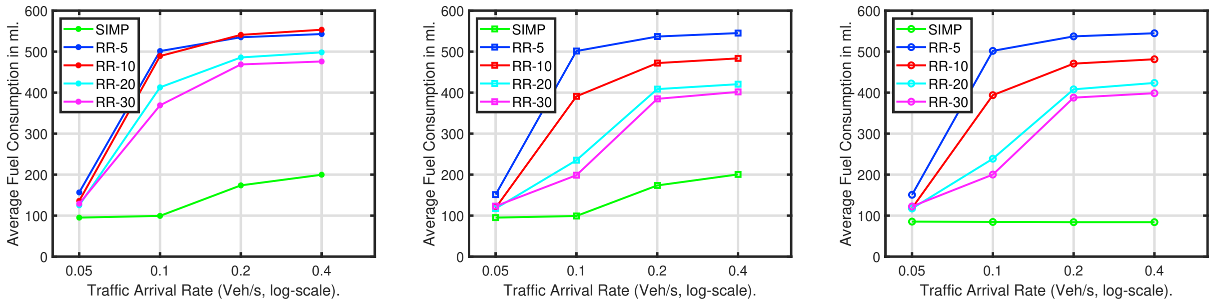
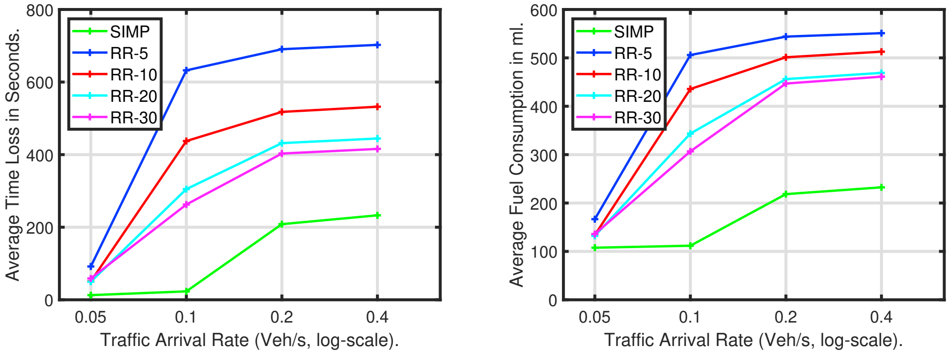



Fig. 5: Average Fuel Consumption results in *ml*, for **Scenarios-1, 2,** and **3** with $50Km/h$ speed limit from left to right accordingly.

### *5.5. Random Crossing*

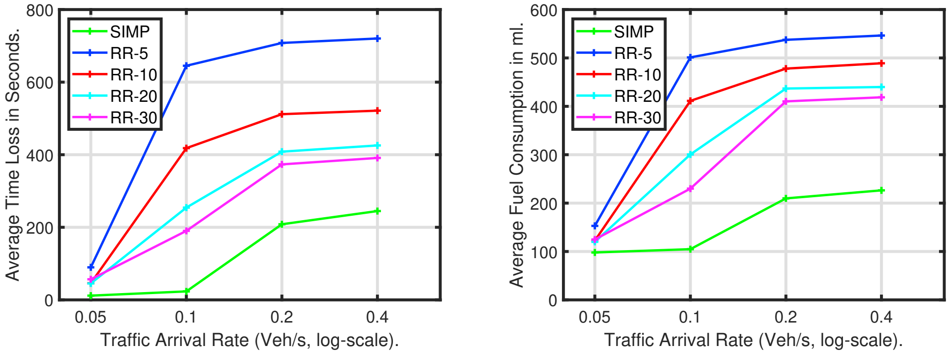
The previous results, corresponding to **scenarios-1, 2, 3**, give indications on intrinsic properties of the IM, namely on how it handles each direction independently. Nevertheless, real situations are always composed of vehicles turning to all directions in random or near-random ways. Thus, the purpose of **scenario-4** is to give an idea of the IM performance under more realistic traffic situations. In this case, we consider that vehicles turn to a random direction, uniformly distributed among the three possibilities, generating all possible combinations of target directions at the entrance to the intersection.

We simulate **scenario-4** under the two speed limits already referred, $30Km/h$ and $50Km/h$. Fig.6 and 7 show the corresponding results, respectively. Naturally, the results for both RR and SIMP appear to be a combination of




(a) Avg. Time Loss in Seconds. (b) Avg. Fuel Consumption in ml.

Fig. 6: Time Loss and Fuel Consumption results for Scenario-4 with $30Km/h$ speed limit.




(a) Avg. Time Loss in Seconds. (b) Avg. Fuel Consumption in ml.

Fig. 7: Time Loss and Fuel Consumption results for Scenario-4 with $50Km/h$ speed limit.

the results achieved in the previous sections. However, particularly for SIMP, the results tend to be worse given the diversity of directions, many of which are conflicting and thus forcing serialization of the access to the intersection. Curiously, the performance that we observed was not worse than the best RR configuration, i.e., RR-30 for both time loss and fuel consumption, which is a positive indication that SIMP can perform well in all realistic scenarios. Overall, SIMP has less time loss in low-speed conditions, i.e., $30Km/h$ ($232.7s$) than high-speed scenarios, i.e., $50Km/h$ ($244.8s$). The fuel consumption results show opposite behavior, meaning that low-speed conditions consume more fuel (i.e., 232.4ml) than high-speed scenarios (i.e., $225ml$).

### 5.6. Discussion

The results shown in the previous sections indicate that SIMP achieves lower time loss than the best RR configuration, namely RR-30. It does so for both speed limits, i.e., $30Km/h$ (Fig. 2 and 6a) and $50Km/h$ (Fig. 4 and 7a), for all traffic arrival rates. A similar result was observed for fuel consumption (Fig. 3, 5, 6b and 7b). Given that the access-decision-making of SIMP is carried out on a per vehicle-basis, multiple vehicles are allowed to enter the intersection if their target directions do no conflict (according to the CDM). This means that, under SIMP, vehicles have an inferior probability (and periods) of idling, leading to vehicles engaging in a smoother and momentum-preserving driving behavior. Opposite to this, the Round-Robin promotes longer alternate periods of consecutive idling and motion, incurring in a higher time and fuel penalty.

We also observed a particular situation that increases fuel consumption. By nature, HVs have a jerky speed profile. When an HV is followed at a certain controlled distance by an AV, the latter inherits the speed jerkiness, which increases fuel consumption. This is typically called a leader-follower behavior. It turns out that RR management policies accumulate vehicles during the red light periods, promoting the leader-follower situations while SIMP, by processing vehicles one-by-one, breaks the leader-follower situations.

Finally, another observation we can make from the achieved results is that a small intersection as the one we used has a relatively low saturation point. In this case, this point was achieved with as low as $0.1Veh/s$ injected in each road. Above this value, the vehicles accumulate in unbounded lines along the roads. We also observed that, when using the RR management, there was no benefit in increasing the green window beyond $30s$. We believe this is also associated with the intrinsic capacity of the intersection.

In summary, we conclude that SIMP fits well intersections in urban residential areas where the traffic frequency is typically below $0.1Veh/s$, and the vehicles seldom go above $30Km/h$ speed.

## 6. Conclusion

Signalized intersections have been identified as potential bottlenecks in urban traffic, and IIM protocols have been proposed to tackle such inefficiencies. Recently we proposed IIMA/SIMP to manage four-way single-lane intersections that are common in urban residential areas. This cycle-based synchronous approach allows several vehicles to cross the intersection simultaneously, whenever there is no risk of collision. In this paper, we assessed the performance of SIMP on time loss and fuel consumption in comparison with typical Round-Robin IM for two different speed limits that are typical in urban residential areas. Simulation results show that SIMP exhibits lower time loss than the best RR configuration along with lower fuel consumption. The advantages of SIMP are noticeable across all tested cases, with lower and higher speed limits and various traffic intensities.

In the future, we plan to explore the trade-off between vehicle speed and traffic arrival rate that allows SIMP to outperform RR, and possibly identify an objective formula to identify the tipping point given some scenario's parameter values. We will coordinate multiple intersections connected in a grid using multi-agent systems (MASs), and we will also analyze how the rate of AVs penetration influences the performance measures.

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