Comparing the Ecological Footprint of Intersection Management Protocols for Human/Autonomous Scenarios

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Abstract

The design of Intelligent Intersection Management (IIM) schemes for fully Autonomous Vehicles (AVs) and mixed with Human-driven Vehicles (HVs) has focused mainly on throughput maximization and users' safety. However, new IIM strategies should consider environmental factors and human health conditions in their design, given their impact on fuel wastage and emission of dangerous air pollutants. In this paper, we compare the ecological footprint of two IIM protocols for mixed traffic flows (AVs and HVs) that follow opposite paradigms. We consider Round-Robin (RR) that favors the crossing of multiple consecutive cars from one road at a time and the recently proposed Synchronous Intersection Management Protocol (SIMP) that favors the crossing of multiple cars simultaneously, one from each road.Through experiments in the SUMO simulator, we observe that SIMP promotes more fluid traffic flows causing traffic throughput to be up to 3.7 times faster and consume less fuel than the RR schemes, with similar results for vehicular emissions (PMx, NOx, CO, CO2, and HC).

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Abstract— **The design of Intelligent Intersection Management (IIM) schemes for fully Autonomous Vehicles (AVs) and mixed with Human-driven Vehicles (HVs) has focused mainly on throughput maximization and users' safety. However, new IIM strategies should consider environmental factors and human health conditions in their design, given their impact on fuel wastage and emission of dangerous air pollutants. In this paper, we compare the ecological footprint of two IMM protocols that follow opposite paradigms in handling AVs and HVs with an internal combustion engine. We consider Round-Robin (RR) that favors the crossing of multiple consecutive cars from one road at a time and the recently proposed Synchronous Intersection Management Protocol (SIMP) that favors the crossing of multiple cars simultaneously, one from each road. Through experiments in the SUMO simulator, we observe that SIMP promotes more fluid traffic flows, causing traffic throughput to be up to 3.7 times faster and consume less fuel than the RR schemes, with similar results for vehicular emissions (PMx, NOx, CO, CO_2, and HC).**

I. INTRODUCTION

As self-driving Autonomous Vehicles (AVs) become an everyday reality, Intelligent Intersection Management (IIM) protocols will enable safe and fluid traffic flows at intersections, improving over traditional round-robin schemes designed for human drivers [1]. IIM protocols will also play an essential role in tackling the severe environmental and health challenges that strain urban mobility [2], namely:

Lowering pollutant emissions: the INRIX[1] global traffic scorecard survey shows that the cost of traffic congestion, fuel wastage, and vehicular emission for France, Germany, the UK and the US in 2013 was $200 billion (0.8% of global GDP); and can reach $300 billion by 2030.

Reducing fossil resource dependency: according to the International Energy Agency (IEA), between 50 and 75% of total produced oil is consumed by transportation, and it forecasts that by 2040 the transportation fuel requirement will worth more than $2 trillion [9].

Improving the population health: the United States Environmental Protection Agency (EPA)[2] and the European Environment Agency (EEA)[3] have described the dangers of high vehicular emissions, namely from Particulate Matter (PMx), Nitrogen Oxides (NOx) and Carbon Monoxide (CO) for human health, including dysfunction of heart, lungs, and respiratory system, unconsciousness and premature death.

The referred forecasts already consider potential scenarios for the evolution of electric vehicles (EV), given the positive impact of these vehicles on those challenges. But they also make it clear that internal combustion engine (ICE) vehicles will still dominate the roads for several years, justifying current environmental and health concerns. In this scope, IIM can offer the traffic control needed to reduce traffic congestion, fuel wastage, and emissions of relevant air pollutants. Moreover, making use of Information and Communication Technologies (ICT), IIM leverage vehicular communications to improve overall safety and traffic throughput [3], [4].

However, a scenario where fully connected AVs will be the exclusive users of urban roads is not expected before 2045 [5]. Until then, IIM protocols will need to handle mixed scenarios where AVs and HVs co-exist; solutions include hybrid-IIM [6], Model-Predictive Control (MPC)-based IIM [7] and HVs prioritization [8].

In prior work, we proposed a grid-based Intelligent Intersection Management Architecture (IIMA) for a four-way single lane intersection and a Synchronous Intersection Management Protocol (SIMP) [10] to improve the fluidity of mixed traffic in low-speed urban residential areas. In this work, we address the intersection throughput with mixed traffic flows together with the ecological footprint in terms of fuel consumption and air pollutants (PMx, NOx, CO, CO_2, and HC). We compare all metrics between SIMP (in particular, SIMP-M as defined in [10]) and simple Round-Robin (RR) intersection management, with multiple green-time intervals. These protocols follow opposite traffic management paradigms. While SIMP admits one vehicle at a time per road, but from multiple roads simultaneously, this type of RR admits multiple consecutive vehicles from each road, but from one road at a time.

We carried out experiments in the SUMO simulation framework to this end, inspecting independently scenarios of only left intersection crossing (*left turn*), right crossing, and straight crossing. We observe that SIMP outperforms RR in terms of traffic throughput, fuel consumption, and pollutant emissions, due to promoting a smoother road usage (i.e., with less braking and acceleration). In the case of right crossing, the traffic throughput of SIMP can reach up to 3.7 times that of RR, at only the cost of 23% of the fuel consumption of RR.

The following section reviews relevant related work. Section III describes IIMA/SIMP and Section IV lists the ecological metrics. The simulation parameters and results are reported in Section V. Section VI concludes the paper.

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[1] http://inrix.com/products/ai-traffic/

[2] https://www.epa.gov/criteria-air-pollutants

[3] https://www.eea.europa.eu/themes/air

II. RELATED WORK

Several related works on urban mobility address vehicular emissions, particularly CO_2 [11], [13], [14] but also CO, NOx, and PMx [12]–[14]. The authors of [11] present a traffic control algorithm for urban areas where vehicles exhibit a stop-and-go behavior with low speeds in low vehicle gears. They propose that the use of traffic intensity detectors that tune the Traffic Lights Controller (TLC) could lead to a considerable reduction of fuel consumption and CO_2 emission. In [12], the authors apply a Lagrangian model to predict the traffic and air pollutants in the city of Hong Kong, especially CO, NOx, and PMx; the predicted data were compared with real-time data showing a good correlation. The authors of [13] describe *eCoMove*, an energy-efficient traffic management and control approach that uses an adaptive balancing and control mechanism. The authors study different traffic conditions such as rerouting, green priority, and speed advice, showing that *eCoMove* reduces fuel consumption as well as CO_2 and NOx emissions while increasing PMx. In [14] the authors propose the Intelligent Green Traffic Congestion (IGTC) model for urban traffic management. IGTC is a combination of traffic flow modeling, vehicles' emission modeling, and air quality modeling. An extensive analysis of IGTC results indicates a considerable reduction in all significant vehicular emissions (CO_2, CO, PMx, NOx) in urban areas.

A more thorough review of fully connected AVs and their impact on the environment can be found in [15]. Most existing approaches in the literature focus on CO_2 emissions only, with a few works also addressing more harmful vehicular emissions, such as CO, PMx, and NOx. However, there is a lack of studies on the ecological footprint of these protocols. This paper contributes to this trend comparing SIMP and RR concerning throughput, fuel consumption as well as relevant vehicular emissions.

III. IIMA AND SIMP PROTOCOL

In this work, we consider our IIMA instantiated on a four-way single lane intersection, as shown in Fig.1, which is common in urban residential areas. We assume the coexistence of AV and HVs (yellow and white cars in Fig.1, respectively) and consider all AVs to be connected, i.e., equipped with V2X technology, while HVs may or may not be connected. The intersection is managed by the central traffic lights controller (TLC) (shown in the center of Fig.1) that implements a management protocol.

Our architecture breaks down the intersection roads into a virtual grid with fixed-size cells (Fig.1) that account for one vehicle each plus a safe inter-vehicle distance. It also assumes the existence of the following infrastructural elements, in addition to the aforementioned traffic lights and TLC: one road-side unit (RSU) at the center of the intersection running the TLC; one RSU in each road; and two classes of sensors in each road, namely P1 and P2, connected to the respective RSU. The sensors P1 identify vehicle arrivals to the grid area, while sensors P2 signal their exit from the intersection. All RSUs are connected among themselves through a wired backhaul; for convenience, we use the term *TLC* interchangeably for the management entity and its associated RSU.

For convenience, we label the incoming road lanes as R1, R3, R5, and R7, while outgoing lanes are R2, R4, R6, R8. As each vehicle enters the intersection, it has three possible outflow directions ($m=$1-right, 2-straight and 3-left, see intersection area in Fig.1). We consider a First-In-First-Out (FIFO) policy in the access to the intersection, i.e., no overtaking is allowed when approaching the intersection.

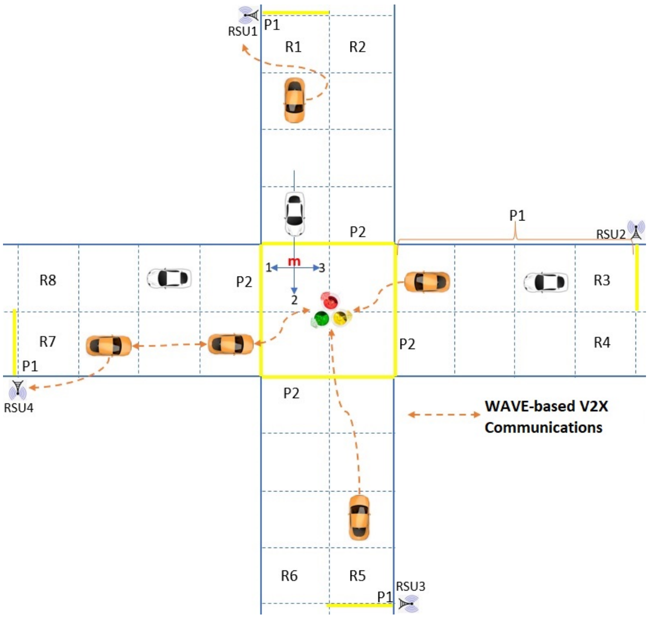

Fig. 1: Grid-based IIMA and V2X Communications

The SIMP protocol leverages information from multiple sources to manage intersection access. AVs and V2X-enabled HVs communicate with the RSU in their road, informing about their presence and which direction they wish to take. In turn, non-communicating HVs have to be detected by sensors P1 and P2. To this end, sensors P1 can be made of multiple sources, from simple induction loops that detect vehicle presence to cameras that identify the desired direction inspecting the vehicle's turn signal. The information received by the RSUs and sensed by sensors P1 and P2 is transmitted to the TLC, which executes the SIMP protocol. The TLC communicates to connected vehicles the permission to enter or not the intersection while signaling simultaneously with traffic lights the non-communicating HVs. Communicating vehicles confirm their exit of the intersection through V2X, while the exit of non-communicating ones is detected by P2.

The SIMP protocol operates in a step-wise fashion to synchronize the access of vehicles from all the lanes to the intersection. In each step, the protocol checks whether there are vehicles at the entrance to the intersection and which directions those vehicles wish to take. The protocol uses a **Conflicting Directions Matrix** (CDM) to allow into the intersection vehicles following conflict-free directions, only. With this knowledge, and given a speed limit in the intersection, SIMP can estimate the time interval at which a given vehicle will arrive at the intersection entrance and provide: (i) to AVs: information about whether they can go in or not; (ii) to HVs: have the corresponding traffic light ready to allow or not entrance in the intersection. The protocol waits until these vehicles exit the intersection, after which the current step is considered finished, and a new one can start. By default, the traffic lights are all red and switch to green for 2.5s, where appropriate to admit a single vehicle at a time.

The features and benefits of SIMP towards throughput and fuel consumption can be summarized as follows:

1) If the intersection is not occupied, an oncoming vehicle can enter the intersection immediately (whereas in a round-robin scheme it has to wait, with some likelihood);
2) If multiple vehicles are arriving at the intersection and they have no conflicting directions (as informed by the vehicles through V2X or detected by the P1 sensors), they can be allowed in the intersection simultaneously;
3) By deciding on a per-vehicle basis using the CDM, SIMP breaks the leader-follower dependency that may cause additional fuel consumption when AVs are following HVs (due to inheriting their more irregular speed).

IV. ECOLOGICAL FOOTPRINT

In this paper, we analyze the fuel consumption and associated air pollutants (PMx, NOx, CO, CO_2, and HC). To analyze vehicular emissions, we used the PC_G_EU4 emission class for both AVs and HVs, which represents a typical passenger car using gasoline as fuel under European Emissions Standard IV. The Handbook on Emission Factors for Road Transport (HBEFA3.1[4]) proposes using vehicle's velocity v and acceleration a to reduce the impact of error-prone operational aspects in the calculation of vehicular emissions, together with the fuel consumption.

In turn, to analyse the total fuel consumption for every vehicle trajectory, we use Eq. 1, where t_i and t_j represent the starting and the ending instants respectively, and $Q(t) = Q(v(t), a(t))$ represents the fuel flow where $v(t)$ and $a(t)$ are velocity and acceleration over time t [16].

$$C = \int_{t_i}^{t_j} Q(t)dt. \tag{1}$$

The vehicular emissions are finally estimated using C × Emission Factor (EF). This factor is a continuous real number that depends directly on the velocity and indirectly on the acceleration [17], as expressed in Eq. 2:

$$EF(v,\alpha) = \frac{e_0 + e_{va_1}va + e_{va_2}va^2 + e_1 v + e_2 v^2 + e_3 v^3}{\text{total simulation time in seconds}} \tag{2}$$

Note that $\alpha = arctan(\frac{rs}{100})$ represents the slope of the road in degrees (rs is the slope of the road in %), the acceleration a is evaluated from α using $a = \sin(\alpha)g_0$ (g_0 is the standard gravity), and e_{va_1}, e_{va_2}, e_0, e_1, e_2 and e_3 are specific parameter values for the PC_G_EU4 vehicle emission class.

V. SIMULATIONS AND RESULTS ANALYSIS

To characterize the throughput, fuel consumption, and ecological performance of SIMP, we carried out several experiments using the mobility simulator SUMO v1.5.0 on Intel Core i5-8265U 1.60GHz processor, 8GB RAM, and 64 bit Windows OS laptop. SUMO is an open-source microscopic simulation package that allows modeling of intermodal traffic systems, including car-following models (CFM) to represent vehicle types (AVs and HVs), roads, type of intersection, TLC, and other sensors (e.g., loop detectors). Each component has several parameters to describe the real-world behavior of IM, such as traffic arrival rates (t.a.r.), vehicle velocity, acceleration, and deceleration are a few. For fuel consumption and emission metrics, we use SUMO's embedded version of the HBEFA3.1 model. Vehicles are assumed not to be equipped with Start/Stop system.

A. Scenario and Driving Behaviour

The length of each road from the intersection is set to 500 meters, and the intersection area size is $20 \times 20m^2$ (this option simplifies road network creation and has a negligible impact in observed results). The entire scenario is completely flat, with null inclination. The grid-area in IIMA starts from 100 meters away from the intersection and is divided into 10 meters grid-cells that can accommodate a vehicle 5 meters long while leaving 5 meters of minimum safety gap between consecutive vehicles.

The maximum acceleration and deceleration for both AVs and HVs are set to $2.6m/s^2$ and $-4.5m/s^2$; in the case of emergency, the braking value is $-9m/s^2$. The maximum speed is specified to 30km/h (i.e., 8.33m/s) as suggested for urban residential areas by the International Traffic Safety Data and Analysis Group[5] (IRTAD). For generating mixed traffic flows, we considered two CFMs', namely Krauss [20] and Adaptive Cruise Control (ACC) [21]. The idea behind Krauss CFM is to let vehicles drive as fast as possible while keeping a safeguard distance to the vehicle ahead by adjusting velocity. The distance is kept by the driver, with some jerkiness; thus, it is suitable for HVs. The ACC is an advanced driving-assistance system that controls speed and gap to provide collision avoidance; it requires sensing technologies typically available in AVs. Hence, AVs are set to use this model in our scenario. Both CFM models have a parameter regarding driving imperfection in making decisions (σ), which we set to 0.5. An additional parameter of ACC, the drivers' desired (minimum) time headway (τ), is set to $1s$. These values are the default in SUMO.

B. Simulation Setup and Experiment Description

We consider two IM protocols: SIMP (described in Section III) and Round-Robin (RR). The RR TLC logic has been implemented based on [18], [19], in which a similar sequence of green and yellow phases is assigned to each road lane starting from North and rotating clockwise, while the remaining roads stay red. We have defined four configurations for the operation of the RR, which differ on the duration of the green phase: 5s (RR-5), 10s (RR-10), 20s (RR-20) and 30s (RR-30). The yellow phase has a constant duration of 4s in all configurations. In each of these five cases (SIMP plus the four RR configurations), we consider three intersection crossing scenarios that reveal intrinsic properties of the protocols, namely left-crossing (all vehicles turn left), straight-crossing (all vehicles go straight), and right-crossing (all vehicles turn right).

For each one of these scenarios, we perform an experiment composed of six simulation runs, each with 1000 mixed AVs and HVs (50% each), sampled from a uniform distribution in [0 1]. We employed (target) t.a.r. of [0.05, 0.1, 0.2, 0.4] vehicles per second (veh/s) from each direction and each injection is decided by sampling a uniform distribution in [0 1]. In other words, the traffic arrival rate values can be seen as the probability of a new vehicle being injected at each second, in each road; e.g., for target 0.1Veh/s, there is a 10% chance of a new vehicle being injected in each road every second. The injection is suspended when there

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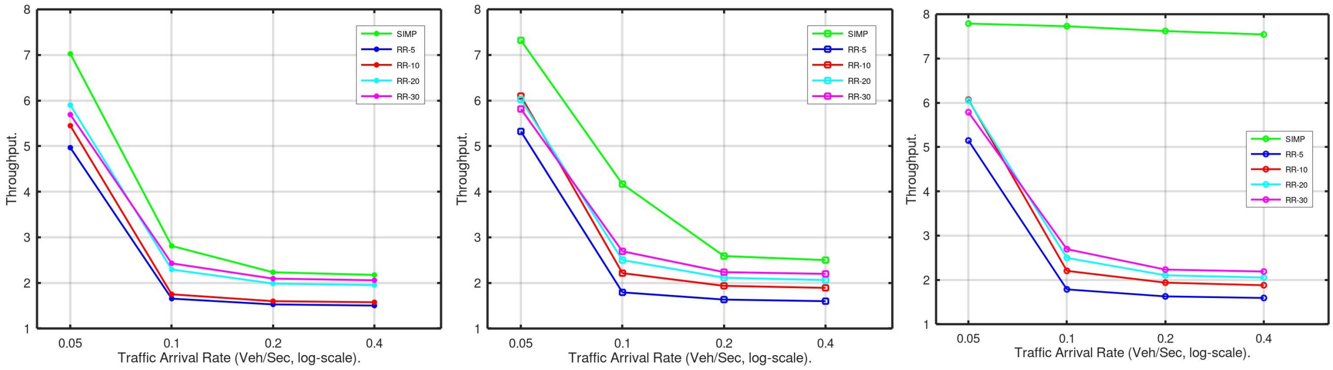
[4] https://www.hbefa.net/e/index.html

[5] https://www.itf-oecd.org/sites/default/files/docs/speed-crash-risk.pdf



(a) Throughput for Left Crossing (b) Throughput for Straight Crossing (c) Throughput for Right Crossing

Fig. 2: Throughput (average of all individual average speeds) in m/s, for various crossing scenarios.

is saturation (in this case, the t.a.r. is implicitly reduced). The six runs are performed with different non-sequential values as random seeds; the same seed set is used across experiments.

C. *Traffic Throughput*

We first compare the performance of considered IIM strategies in terms of traffic throughput, i.e., the average of all individual average speeds (i.e., for 1000 vehicles). Fig. 2 displays the throughput results for the three scenarios: left-crossing, straight-crossing and right-crossing, with respect to mixed traffic arrival rate (between 0.05 and 0.4 veh/s). Each data point represents the average of the six runs of each experiment.

In all three scenarios, RR performs similarly as expected, with RR-5 exhibiting the lowest throughput. Conversely, SIMP shows more variation but higher throughput. The remaining RR configurations show intermediate results but still lower than SIMP. We also observe that the RR configurations improve throughput as green time increases, except for 0.05 veh/s. We believe the inversions observed at this relatively low t.a.r. are due to the phasing of the traffic lights cycle. On the other hand, with 0.2 veh/s, the system is already saturated. In case of right crossing (Fig. 2c), SIMP produces a significantly higher throughput because the CDM allows four vehicles to access the intersection simultaneously.

D. *Fuel Consumption*

Figure 3 shows the average fuel consumption results for the same experiments. We observe that in general, fuel consumption is higher for the left-crossing, which is consistent with the longer distance that has to be traveled, and higher waiting times (i.e., longer engine idling time). For 0.05 veh/s, SIMP has 127.81ml (left), 120.42ml (straight), and 109.21 (right) which are lower than all RR configurations, i.e., 136.17ml (RR30, left), 128.22ml (RR20, straight), and 128.66ml (RR20, right). For arrival rates higher than 0.05 veh/s, the RR strategies present higher average fuel consumption: above 350ml. We also observe that RR-5 outperforms RR-10 in the left-crossing scenario for (near) saturated cases. We believe this is due to more idling and leader/follower behavior in the RR-10 case, which in turn leads to higher fuel consumption.

For a better insight on the presented results, we inspect individual fuel consumption patterns until the vehicles cross the intersection (Fig. 4). We selected a random AV vehicle from mid-simulation, from the left crossing scenario, for the configurations RR5, RR30, and SIMP with t.a.r. 0.4 veh/s (saturation case). For RR-5, the AV experiences consecutive phases of acceleration and deceleration, with several periods of stopping during which the vehicle is idling and consuming. The HBEFA3.1 model considers a significant idling consumption). In RR-30, we observe a similar behavior but with longer moments of motion and waiting. The total travel time and average consumption are lower than for RR-5 (436s vs. 604s and 398.61ml vs. 429.98ml). For SIMP, in this particular case, we observe 512s for transit time and 321.87ml of fuel consumption. The main takeaway for SIMP is that, by allowing vehicles one-by-one in the intersection instead of using fixed time periods, SIMP causes less stopping/idling periods than any of the RR options (in which stop times are always above 15s). The impact of idling in fuel consumption shows that Start/Stop systems may contribute significantly to fuel economy. We will address this possibility in future work.

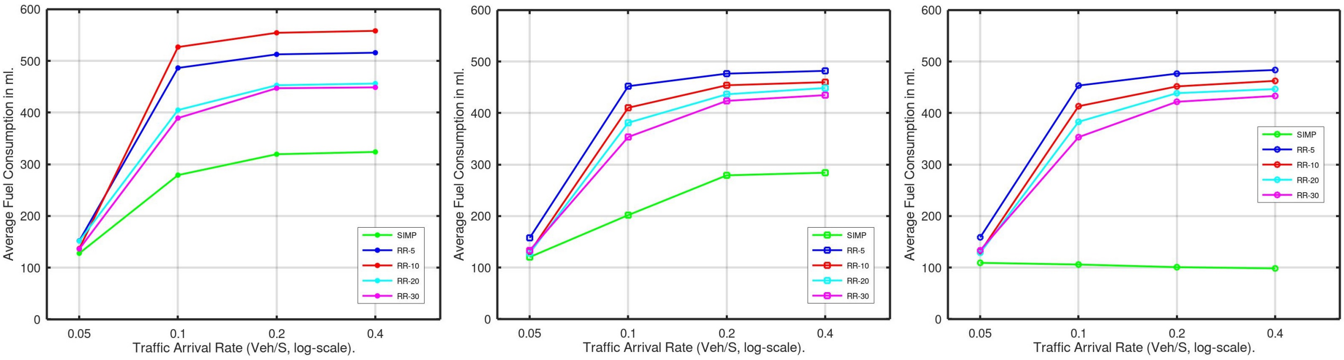
E. *Vehicular Emissions*

The vehicular emissions (PMx, NOx, CO, CO_2, and HC) for the aforementioned experiments are presented in Table I.

1) Particulate Matter: The average PMx emissions show that, in all three scenarios, SIMP leads to considerably lower emissions: at most 15.5mg for left crossing, 13.2mg for straight crossing, and 3.2mg for right crossing. Note that the SUMO simulator does not consider the PMx emissions caused by braking.

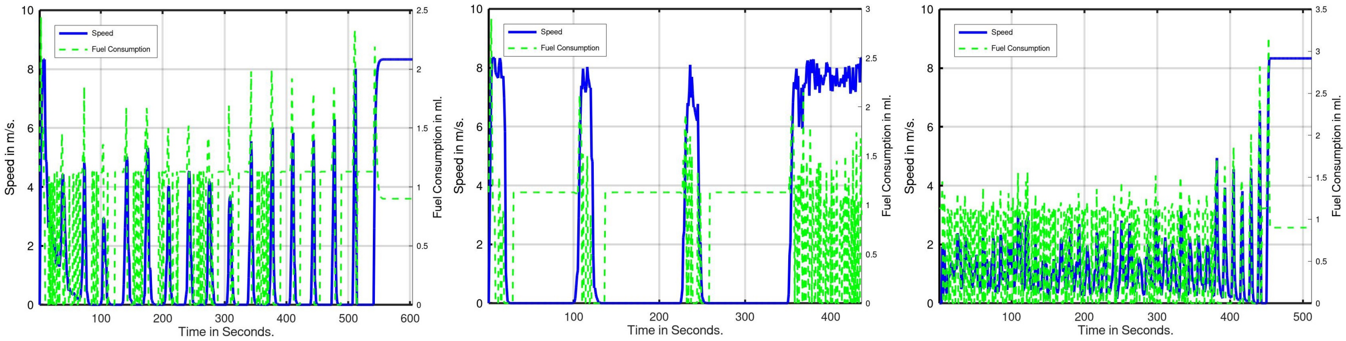
2) Nitrogen Oxide: The average NOx emission results show that SIMP is superior to all RR configurations. The NOx emissions of SIMP for left crossing are 326mg for an arrival rate of 0.4veh/s, which is a saving of 40%, 44%, and 31% with respect to RR-5, RR10 and both RR-20 and RR-30. In the case of straight and right crossing, SIMP shows even better performance. Particularly, for right crossing, SIMP has three times lesser NOx emissions. This is due to the high traffic fluidity of SIMP in this scenario. We also observe that SIMP leads to inferior emissions as traffic density increases (from 96.1mg in the 0.05veh/s scenario to 89.24mg in the 0.4veh/s case).

3) Carbon Monoxide: In Table I, the average CO emissions are represented in grams for left, straight, and right-crossings accordingly. In all three cases, SIMP shows better performance with lower emission of CO, i.e., less than 35g for left, 30g for straight, and 5g for right crossing. As in the case of NOx, this can



(a) Left Crossing (b) Straight Crossing (c) Right Crossing

Fig. 3: Average fuel consumption (ml) for various crossing scenarios.



(a) RR5 Left Crossing (b) RR30 Left Crossing (c) SIMP Left Crossing

Fig. 4: Speed and fuel consumption for representative individual AVs and selected IIM schemes.

t.a.r.	**Left Crossing**					**Straight Crossing**					**Right Crossing**				
	SIMP	RR-5	RR-10	RR-20	RR-30	SIMP	RR-5	RR-10	RR-20	RR-30	SIMP	RR-5	RR-10	RR-20	RR-30
Average PMx Emission in mg.															
0.05	4.02	6.5	5.58	4.85	5.15	3.65	6.20	4.63	4.63	4.98	3.09	6.25	4.66	4.65	4.99
0.1	12.9	25.3	27.9	21	20.1	8.5	23.4	21.1	19.6	18.1	3.12	23.4	21.3	19.7	18
0.2	15.2	26.8	29.5	23.8	23.5	12.9	24.8	23.6	22.8	22.2	3.15	24.8	23.5	23	22.1
0.4	15.5	27	29.7	24	23.6	13.2	25.1	24	23.5	22.8	3.16	25.2	24.1	23.4	22.7
Average NOx Emission in mg.															
0.05	115.07	155.54	137.52	123.13	128.10	107.52	149.89	120.43	119.21	125.02	96.10	150.95	121.02	119.68	125.3
0.1	278	501	545	416	400	196	465	421	391	362	94.08	466	424	393	361
0.2	321	529	575	468	462	278	491	468	450	437	90.75	491	465	452	435
0.4	326	536	585	473	464	284	497	474	463	449	89.24	499	477	461	447
Average CO Emission in grams															
0.05	6.9	12.96	10.8	9.1	9.8	6.12	12.22	8.6	8.6	9.5	4.9	12.3	8.6	8.6	94.77
0.1	28.3	58.2	64.4	47.9	46.2	17.1	53.3	47.5	44.7	41.2	4.85	53.4	47.9	44.9	42.9
0.2	34.1	62	68.3	54.8	54.5	28.2	56.8	53.6	52.6	51.3	4.76	56.7	53.3	52.8	51.1
0.4	34.8	62.4	68.8	55.2	54.7	28.9	57.5	54.5	54.3	52.9	4.74	57.7	54.8	53.97	52.7
Average CO_2 Emission in grams															
0.05	297.32	379.5	338.95	306.61	316.8	280.14	367.07	302.31	298.3	310.29	254.05	369.47	303.7	299.3	311
0.1	649	1132	1226	942	906	740	1052	955	887	823	246.5	1055	962	891	822
0.2	743	1193	1290	1054	1040	649	1109	1056	1016	986	234.5	1109	1051	1021	982
0.4	754	1200	1299	1061	1044	661	1121	1070	1044	1012	229	1125	1076	1039	1008
Average HC Emission in mg.															
0.05	38.46	67.68	56.91	48.27	51.84	34.11	64	45.84	45.92	50.12	28.06	64.35	46	46.1	50.21
0.1	144	291	322	240	231	89	267	238	224	207	27.6	268	240	225	207
0.2	173	310	341	274	272	143	284	269	263	257	26.9	284	267	264	255
0.4	175.7	312	343	276	274	147	288	273	272	265	26.7	289	274	270	263

TABLE I: Average emission of air pollutants.

be attributed to higher traffic fluidity. Likewise, average emissions decrease as traffic density increases.

4) Carbon Dioxide: The CO_2 results also show a better performance of SIMP. The highest CO_2 emission for this protocol is 754g, 740g, and 254.05g for left, straight, and right crossing, respectively; RR varies from 740g to 1299g. In this case, the average emission values of SIMP in the right crossing are lower in the straight crossing case (unlike the two previous metrics, NOx and CO).

5) Hydro Carbons: Finally, the lower part of Table I represents the average HC in mg. Overall, for left crossing SIMP shows a reduction of 36%, 39%, 28% and 27% with respect to RR-5 through RR-30, respectively. For straight and right crossings, SIMP shows between 50% and 56% less HC emissions than RR configurations.

F. Discussion

The simulation results show that SIMP performs better than RR in all configurations tested and in all tested traffic scenarios, for throughput, fuel consumption, and emissions metrics. Particularly, SIMP shows a lower emission of dangerous air pollutants like PMx, NOx, and CO (mentioned by the EPA and EEA) as well as the other emissions, i.e., CO_2 and HC. The results clearly indicate that it is better, at low speeds, to handle vehicles one at a time but simultaneously from multiple roads than consecutive vehicles from one road at a time. This leads to more fluid traffic flows and better throughput. Consumption- and emissions-wise, the smoother management of vehicle flows by SIMP leads to less stopping and idling, allowing to better preserve vehicle momentum and improve the controllability of transient engine operations. All these elements lead to lower fuel consumption and associated emissions.

RR shows inferior performance due to the conservative nature of allowing vehicles from one road at a time, which forces vehicles to come to a complete halt even if the intersection is free of other cars. The fact that multiple vehicles can cross consecutively also keeps leader/follower relationships. Finally, the lower throughput achieved also causes stronger congestion. This combination imposes significant variations on the speed of the vehicles, with the frequent slowdown, braking, and acceleration.

In practice, existing Round-Robin traffic lights try to compensate these issues by combining features of more fluid management, e.g., allowing to turn right during red periods using a specific flashing yellow light. This combination leads to a hybrid behavior that improves throughput. However, it relies on the vehicles' autonomous behaviors to avoid collisions, and thus, it is not inherently safe.

VI. CONCLUSIONS

This paper studies the traffic management of mixed AVs and HVs at an isolated intersection and its relationship with fuel consumption and harmful vehicular emissions, namely PMx, NOx, CO, CO_2, and HC. Two intersection management protocols were used: a simple Round-Robin protocol that admits consecutive cars from one road at a time and the SIMP protocol, proposed in previous work, that operates synchronously on a per-vehicle basis and admits vehicles simultaneously from multiple roads. We ran multiple experiments with the SUMO mobility simulator in scenarios of left, straight, and right-crossing, using 1000 vehicles in each experiment and testing different traffic arrival rates. The fluidity of SIMP leads cars to accelerate/decelerate and idle less, causing lower fuel consumption and vehicular emissions across all traffic patterns.

In the future, we will analyze the impact of V2X communications on IIMA and SIMP. We will also consider the impact of speed on the study we presented here. Finally, we will compare SIMP with other IIM, including enhanced RR variants and other adaptive approaches.

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