Conference Paper

Work-In-Progress: Worst-Case Response Time of Intersection Management Protocols

Radha Reddy
Luís Almeida
Miguel Gutiérrez Gaitán
Harrison Kurunathan
Pedro Miguel Santos
Eduardo Tovar

CISTER-TR-211003

2021

Work-In-Progress: Worst-Case Response Time of Intersection Management Protocols

Radha Reddy, Luís Almeida, Miguel Gutiérrez Gaitán, Harrison Kurunathan, 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, mjggt@isep.ipp.pt, jhk@isep.ipp.pt, pss@isep.ipp.pt, emt@isep.ipp.pt

https://www.cister-labs.pt

Abstract

Intersections are critical elements of urban traffic management and are identified as bottlenecks prone to traffic congestion and accidents. Intelligent intersection management plays a significant role in improving traffic efficiency and safety determining, among other metrics, the waiting time that vehicles incur when crossing an intersection. This work presents a preliminary analysis of the worst-case response time of intersection management protocols that handle mixed traffic with autonomous and human-driven vehicles. We deduce theoretical bounds for such time considered as the interval between the injection of a vehicle in the road system and its departure from the intersection, considering different intersection management protocols for mixed traffic, namely the Synchronous Intersection Management Protocol (SIMP) and several configurations of the conventional Round-Robin (RR) policy. Simulation results validate the analytical bounds partially. Ongoing work addresses the queue dynamics and its reliable detection by traffic simulators.

Work-In-Progress: Worst-Case Response Time of Intersection Management Protocols

Radha Reddy*[†] Luis Almeida Miguel Gaitan*[†][‡] Harrison Kurunathan Pedro Santos Eduardo Tovar
*CISTER/ISEP, Porto, Portugal, reddy@isep.ipp.pt
[†]CISTER/FEUP, Porto, Portugal, lda@fe.up.pt
[‡]U. Andres Bello, Santiago, Chile, mjggt@isep.ipp.pt
CISTER/ISEP, Porto, Portugal, jhk@isep.ipp.pt
CISTER/ISEP, Porto, Portugal, pss@isep.ipp.pt
CISTER/ISEP, Porto, Portugal, emt@isep.ipp.pt

***Abstract*—Intersections are critical elements of urban traffic management and are identified as bottlenecks prone to traffic congestion and accidents. Intelligent intersection management plays a significant role in improving traffic efficiency and safety determining, among other metrics, the waiting time that vehicles incur when crossing an intersection. This work presents a preliminary analysis of the worst-case response time of intersection management protocols that handle mixed traffic with autonomous and human-driven vehicles. We deduce theoretical bounds for such time considered as the interval between the injection of a vehicle in the road system and its departure from the intersection, considering different intersection management protocols for mixed traffic, namely the Synchronous Intersection Management Protocol (SIMP) and several configurations of the conventional Round-Robin (RR) policy. Simulation results validate the analytical bounds partially. Ongoing work addresses the queue dynamics and its reliable detection by traffic simulators.**

***Index Terms*—Smart Cities, Intelligent Transportation Systems, Intersection Management, and Worst-Case Response Time.**

I. INTRODUCTION

Intersections are identified as bottlenecks of traffic flows and are prime sources of traffic congestion and associated accidents. As per the Global Mobility Report, nearly 40 to 50 percent of vehicle collisions in urban traffic occur at intersections [1]. Intersections are also known to be critical elements of Urban Traffic Management (UTM), having a strong impact on metrics such as travel time, fuel/energy consumption, and polluting emissions. UTM leverages intelligent Intersection Management protocols (IMs) to mitigate such issues, taking advantage of the prospective pervasiveness of Autonomous Vehicles (AVs) and Vehicle-to-anything (V2X) communication technologies. However, Human-driven Vehicles (HVs) are expected to continue having a significant presence in urban traffic until 2045 [2], requiring, until then, adequate IMs that handle mixed traffic. One such IM is the Synchronous Intersection Management Protocol (SIMP) [3] that uses sensors to detect HVs and process AVs/HVs on a vehicle-by-vehicle cyclic approach. Conversely, the conventional Round-Robin (RR) intersection management strategy [4] uses time windows allocated exclusively to each lane in sequence.

This work focuses on the impact of IMs suitable for mixed traffic on the worst-case time that a vehicle may take since it enters the road system until it exits the intersection. We call this the Worst-Case Response Time (WCRT) of the IM, following the similar concept used in real-time computing systems. The WCRT is an indicator of IM reliable performance as needed for safety-critical or mission-critical traffic [5], [6] and collision avoidance [7], [8].

We analyze a simple four-way single-lane intersection running under SIMP and RR with several green-time configurations. The analytical results are then compared with simulation experiments carried out with SUMO [9]. The simulations validate the analytical results partially, exposing the problem of reliable queue detection in traffic simulators.

II. RELATED WORK

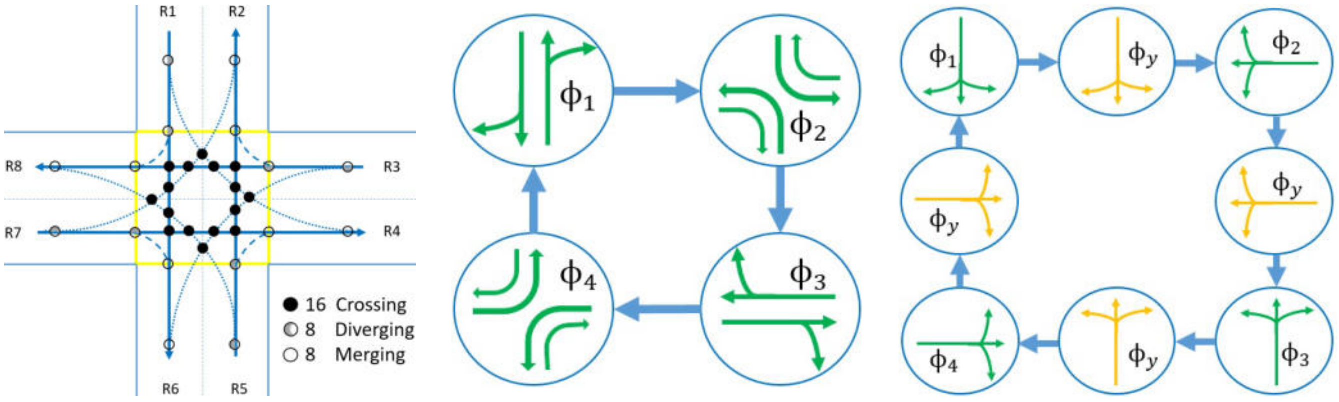
The literature on the worst-case analysis of IMs is relatively scarce, with examples in [5]–[8]. In [5], Oza and Chantem provide bounds on worst-case vehicle waiting times to show the reliability and safety of their adaptive real-time server-based management against pre-timed approaches. The work was further analyzed in the presence of an emergency response vehicle using a preemption strategy [6]. In [7], Khayatian et al. presented a robust and resilient IM for connected AVs to prevent accidents and provide safety even when a rogue vehicle is within the intersection. Differently, Essa et al. employed traffic conflicts and a full Bayesian approach to avoid rear-end collisions and provide real-time safety at the Traffic Light Control (TLC) cycle level [8].

These studies have explored guaranteed performance and safety in terms of bounded waiting time and collision avoidance considering worst-case traffic conditions. We add to this set the WCRT achieved with SIMP, a specific IM developed for mixed traffic, and RR conventional approaches.

III. INTERSECTION MANAGEMENT APPROACHES

As we referred before, this work considers a four-way single-lane intersection typical in urban residential areas. This type of intersection presents a number of intrinsic traffic conflicts that we discuss next, which motivate the WCRT analysis. These conflicts are mitigated differently by SIMP and RR IM strategies, leading to significantly different worst-case behaviors.

This work was supported by Fundação para a Ciência e a Tecnologia (Portuguese Foundation for Science and Technology) through the Carnegie Mellon Portugal Program under Grant CMU/TIC/0022/2019 (CRUAV) and through the Research Unit UIDP/UIDB/04234/2020 (CISTER).



(a) Single-lane intersection with conflicts. (b) SIMP control phases. (c) RR control phases.

Fig. 1: Intersection conflicts and control phases of the management protocols.

A. Four-way Single-lane Intersection

Fig. 1a shows a four-way single-lane intersection in which inflow lanes are indexed with odd numbers (R_1, R_3, R_5, R_7) and outflow lanes are indexed with even numbers (R_2, R_4, R_6, R_8), assigned in a clockwise direction starting from North. The same figure shows the number and type of conflicts as defined in [10], namely 16 crossing, 8 diverging and 8 merging conflicts. Crossing conflicts, marked with black dots, occur when two vehicles coming from different inflow lanes and going to two different outflow lanes have to cross their trajectories. Merging conflicts, marked with white dots, occur when vehicles from different inflow lanes go to the same outflow lane. Finally, diverging conflicts, marked with half-grey dots, occur when two vehicles from the same inflow lane go to two different outflow lanes. Merging and diverging conflicts can lead to rear-end and sideswipe collisions that may occur at the intersection exit or entrance lanes, respectively.

Providing safe passage to vehicles, even during worst-case traffic scenarios, requires avoiding these conflicts. This is accomplished by IM strategies that imply additional traffic delays to organize the vehicle's movements as needed. However, it is also desirable to provide reduced waiting times, which justifies the importance of the WCRT analysis of IM approaches. Moreover, we also consider that overtaking and U-turn of vehicles are not permitted at the intersection area. Finally, we assume that AVs, HVs, and the road infrastructure, namely TLC, Road Side Units (RSUs), and road sensors, are all provided with the appropriate components and functioning correctly.

B. SIMP Synchronous Framework

As the name says, SIMP follows a synchronous approach, handling the traffic arriving at the intersection in cycles, vehicle-by-vehicle. At each cycle, a set of road sensors, e.g., induction loops and cameras, complemented with V2X communication capabilities, allows the TLC to identify the presence of vehicles at the entrance of the intersection and their intended crossing directions. The TLC then consults the **Conflicting Directions Matrix** (CDM) to grant or block the vehicles access to the intersection area from different lanes. The CDM encodes all the crossing conflicts of the intersection, shown in Fig. 1a and it is used every cycle to grant permission to all vehicles (at most one from each inflow lane) that follow non-conflicting trajectories. The TLC decisions are communicated to AVs, or communication-enabled HVs, via V2X data messages and to non-communicating HVs as TLC light signals with a short duration to allow one vehicle only. Once all admitted vehicles leave the intersection, the cycle is ended, and a new cycle is triggered.

Despite using the CDM to provide access to vehicles with collision-free trajectories, SIMP uses an arbitration mechanism to decide which vehicles to handle at each cycle. This is done using a sequence of four phases (ϕ_1, ϕ_2, ϕ_3, ϕ_4) as shown in Fig. 1b that already correspond to collision-free trajectories. If, in a given cycle, there are no vehicles in the inflow lanes with the directions corresponding to a given phase, SIMP passes immediately to the next phase. This is repeated until at least one vehicle with the corresponding direction is present in the inflow lanes of the respective phase, triggering a new cycle.

C. Round-Robin Intersection Management

Figure 1c illustrates the RR IM strategy for the same intersection. RR is a pre-timed signal control policy that assigns green phases (green traffic light) to the inflow lanes in sequence, in a circular order starting from North and rotating clockwise. The intersection control cycle is shown in Fig. 1c, being composed of four control green phases (ϕ_1, ϕ_2, ϕ_3, ϕ_4) with a yellow phase (ϕ_y), with yellow traffic light, in between each green phase. While one inflow lane is in one of these phases, the other lanes are blocked with a red traffic light. The total intersection control cycle time is four times the sum of the green and yellow phase durations.

IV. WORST-CASE RESPONSE TIME ANALYSIS

For our WCRT analysis, we use the following notation:

- D is the road length to and from the intersection;
- v_x is the velocity of vehicle x, considered constant until arriving at the intersection;

- $I_t(IM)$ is the worst-case intersection service time provided by the concerned IM protocol, thus $I_t(SIMP)$ for SIMP and $I_t(RR)$ for RR;
- $\Phi(IM)$ is the set of phases that compose the intersection control cycle under a given IM protocol, including green $(\phi_1, \phi_2, \phi_3, \phi_4)$ and yellow (ϕ_y), as appropriate;
- $T_\Phi(IM)$ is the time required for the execution of one complete intersection control cycle $\Phi(IM)$.

For any vehicle x we define the $WCRT(IM)$ provided by the intersection as the combination of the vehicle travel time to reach the intersection entrance (D/v_x) and the worst-case intersection service time of the concerned IM policy $I_t(IM)$. Therefore, the $WCRT(IM)$ can be obtained from Eq. 1.

$$WCRT(IM) = D/v_x + I_t(IM) \tag{1}$$

The worst-case intersection service time $I_t(IM)$ can be obtained for SIMP and RR IM strategies based on their intersection control cycles as in Fig. 1b and 1c, respectively. For SIMP, in a worst-case scenario there will be always vehicles from all inflow lanes at the intersection in all control phases (ϕ_i for $i \in \{1, 2, 3, 4\}$). Thus, all phases will take their corresponding time in order, in a control cycle $\Phi(SIMP) = \{\phi_1, \phi_2, \phi_3, \phi_4\}$, and any vehicle at the entrance of the intersection may suffer a delay up to one complete intersection control cycle $T_\Phi(SIMP)$ until it gets service. Note that SIMP handles vehicle by vehicle. If vehicles queue up at the entrance of the intersection, in the worst-case each vehicle will take $T_\Phi(SIMP)$ to be served, thus $I_t(SIMP)$ can be obtained from Eq. 2 where N_q is the number of vehicles queued ahead of vehicle x including itself.

$$I_t(SIMP) = T_\Phi(SIMP) \times N_q \tag{2}$$

For RR, the service of each inflow lane is independent of each other and constant along the time. It depends on the assigned green time, which implies a certain capacity to admit vehicles per control cycle and the cycle time, too. The control cycle, in this case, is $\Phi(RR) = \{\phi_1, \phi_y, \phi_2, \phi_y, \phi_3, \phi_y, \phi_4, \phi_y\}$ and its period is $T_\Phi(RR) = 4 \times (T_{\phi_i} + T_{\phi_y})$, where T_{ϕ_i} and T_{ϕ_y} are the green and yellow times, respectively. The maximum number of vehicles that can access the intersection during a green phase is N_g, a direct function of its duration T_{ϕ_i}. In the worst-case, a vehicle reaches the intersection when the corresponding green phase just ended, having to wait for the next one. However, if there are more queued vehicles, up to N_g can cross in each control cycle. Thus, a simple upper bound on the worst-case service time for RR, with N_q vehicles queued, is given by Eq. 3.

$$I_t(RR) = T_\Phi(RR) \times \left\lceil \frac{N_q}{N_g} \right\rceil \tag{3}$$

V. PERFORMANCE EVALUATION

To evaluate the WCRT of SIMP and RR configurations, we simulated the isolated for-way single-lane intersection shown in Fig. 1a with $D = 500m$ and $v_x = 30km/h$ $(8.33m/s)$, with 50 vehicles injected in each inflow lane following the uniform distribution executed every second with an average rate of $0.2veh/s$. The vehicles are $5m$ long and spaced at least $5m$, too. For SIMP, we considered that vehicles take at most $2.5s$ and $3s$ to traverse the intersection with right/straight crossing and left crossing, respectively. Since the control cycle $\Phi(SIMP)$ has two phases of straight/right crossings (ϕ_1 and ϕ_3) and two phases of left/right crossing (ϕ_2 and ϕ_4), the total cycle time is $T_\Phi(SIMP) = 11s$. For RR, we consider four different configurations of the green phase (RR-5, RR-10, RR-20 and RR-30), with $T_{\phi_i} = 5s, 10s, 20s$ and $30s$, respectively. Assuming a yellow phase of $T_{\phi_y} = 4s$, the control cycle time is $T_\Phi(RR) = 36s, 56s, 96s$ and $136s$, with a corresponding number of vehicles that can cross the intersection in each green phase given by $N_g = 2, 4, 8$ and 12, respectively.

Fig. 2 shows the worst-case intersection service time $I_t(IM)$ as a function of the queue length N_q for all IMs (Eqs. 2 and 3). All $I_t(RR)$ curves show the typical step-wise behavior corresponding to the green phases of the control cycles. Note that Eq. 3 considers whole phases, only, even if the last cycle uses just a part of it. This introduces some pessimism for the sake of simplification, which affects essentially the left side of each step. The right side is accurate, representing the situation in which the last phase is fully used, too. $I_t(SIMP)$ is linear given that SIMP cycles handle vehicles from each lane one at a time. Fig. 2 also shows that $I_t(SIMP)$ is lower than all $I_t(RR)$ curves (lower worst-case service time), for any queue length N_q.

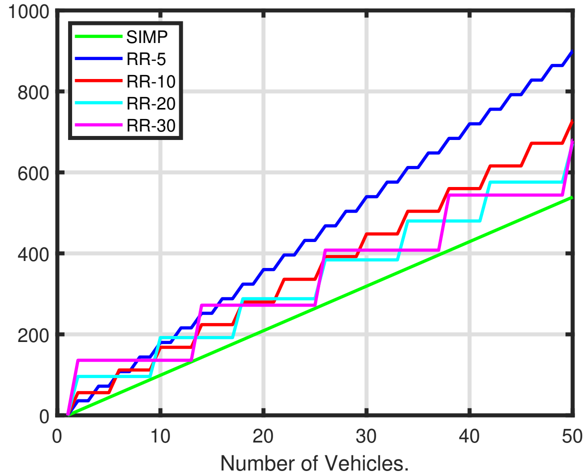


Fig. 2: Worst-case intersection service time for N_q queued vehicles.

To validate the analytical WCRT values, we simulated the referred scenario using the SUMO v1.9.2 simulator running on an Intel Core i5-8265U 1.60GHz processor with 8GB RAM and 64 bit Windows OS. The main SUMO simulation parameters are presented in Table I.

Figure 3 shows the observed maximum response time of 50 vehicles at $0.2veh/s$ for a 100 simulation runs using SUMO. The following WCRT values are observed $274s$ (SIMP), $781s$ (RR-5), $607s$ (RR-10), $536s$ (RR-20), and $541s$ (RR-30). Clearly, the observed WCRT values are below the analytical

TABLE I: Parameters used in the simulations

Parameters	**Values**
Road Network Area	1000 X 1000 m^2.
Simulated Vehicles	50 vehicles.
Vehicle Length	5 $meters$.
Vehicle insertion process	Random and Uniform between (0,1).
Traffic Arrival Rate	$0.2veh/s$.
Vehicle Types	HVs (Krauss CFM), AVs (ACC CFM)
Min. Gap - d_s	5 $meters$.
Acceleration	2.6 m/s^2.
Deceleration	4.5 m/s^2.
Emergency Braking	-9 m/s^2.
Maximum Speed	30 Km/h, i.e., 8.33 m/s.

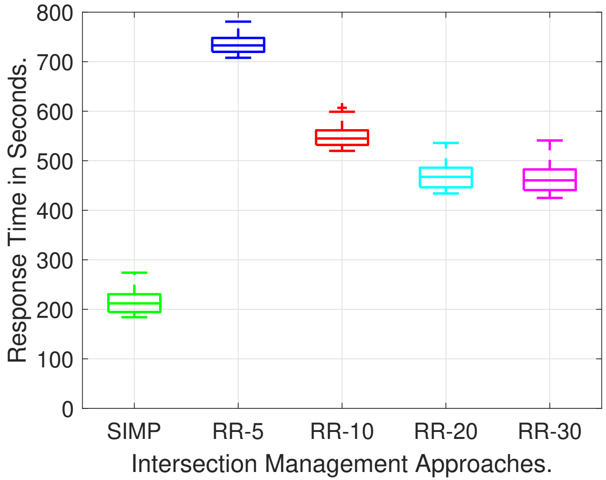


Fig. 3: Observed response time of 50 vehicles for a 100 simulation runs, with an average traffic injection rate of $0.2veh/s$.

values given by Eq. 1, i.e., $550s$ (SIMP), $900s$ (RR-5), $728ss$ (RR-10), $672s$ (RR-20), and $680s$ (RR-30), are displayed in Fig. 2.

For these SUMO produced WCRT values, Fig. 4 shows the intersection queue dynamics, displaying the queue length in one inflow lane for all IMs during the simulation. Until $t \approx 350s$, we observe the queue building up given an arrival rate that is higher than the service rate. When the vehicle injection stops, the queue is served until exhaustion.

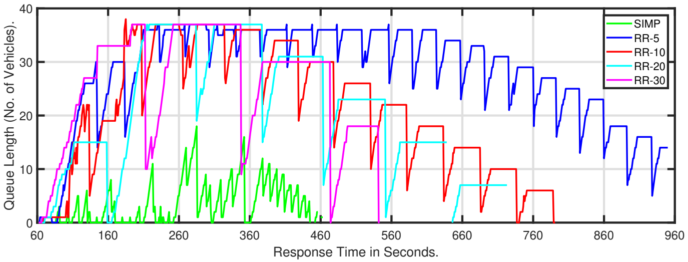


Fig. 4: Queue length (number of vehicles) along time, with an average traffic injection rate of 0.2veh/s.

During the service periods, the whole queue moves forward and SUMO does not detect it as a queue until the vehicles stop again and re-queue. This causes the deep valleys that can be observed in the figure. SIMP is specially affected by this issue because its per vehicle service model causes the queue to be always moving, making SUMO under assess its length.

As a preliminary validation, we assessed the last vehicle WCRT with all IMs. SUMO reports a queue length of 16 (SIMP) and 37 (RR-5 to RR-30), upon vehicle arrival at the intersection. The observed response times were the following, in the same order of IMs, with the respective analytical WCRT in parenthesis: $274s(313s)$, $713s(780s)$, $542s(620s)$, $369s(540s)$ and $328s(468s)$. The observed values are below the WCRT, as expected.In this case, the analytical WCRT is optimistic due to an optimistic assessment of queue length by SUMO as referred above. Similar observations were made for random vehicles in the simulation.

VI. CONCLUSIONS

This paper analyzed the worst-case performance of an isolated four-way single-lane intersection. Particularly, we studied and compared the worst-case response time results of SIMP and RR IM protocols both analytically and with a realistic simulation. SIMP has the potential for lower worst-case responses. However, its WCRTs can be affected by optimistic queue length assessment by traffic simulators such as SUMO. We are currently working on a simulation queue detector that produces reliable length estimates, relying on deterministic queuing analysis, such as Network Calculus, to produce safe upper bounds. We will also refine the analysis and extend it to more complex intersections and other management protocols.

REFERENCES

[1] Sustainable Mobility for All., 2017. Global Mobility Report 2017: Tracking Sector Performance. Washington DC, pp.1-107.

[2] Bansal, P. and Kockelman, K.M., 2017. Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies. Transportation Research Part A: Policy and Practice, 95, pp.49-63.

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

[4] Alekszejenkó, L. and Dobrowiecki, T.P., 2019, August. SUMO Based Platform for Cooperative Intelligent Automotive Agents. In SUMO Conference, pp.107-123.

[5] Oza, P. and Chantem, T., 2019, August. A real-time server based approach for safe and timely intersection crossings. In 25th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA), pp.1-12.

[6] Oza, P. and Chantem, T., 2021, April. Timely and Non-Disruptive Response of Emergency Vehicles: A Real-Time Approach. In 29th ACM International Conference on Real-Time Networks and Systems (RTNS'2021), pp.1-12.

[7] Khayatian, M., Dedinsky, R., Choudhary, S., Mehrabian, M. and Shrivastava, A., 2020, September. R^{2}IM-Robust and Resilient Intersection Management of Connected Autonomous Vehicles. In 23rd IEEE International Conference on Intelligent Transportation Systems (ITSC), pp.1-6.

[8] Essa, M. and Sayed, T., 2019. Full Bayesian conflict-based models for real time safety evaluation of signalized intersections. Accident Analysis & Prevention, 129, pp.367-381.

[9] 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, November. Microscopic traffic simulation using sumo. In 2018 21st Int. Conf. on Intelligent Transportation Systems (ITSC), pp.2575-2582.

[10] Chandler, B.E., Myers, M., Atkinson, J.E., Bryer, T., Retting, R., Smithline, J., Trim, J., Wojtkiewicz, P., Thomas, G.B., Venglar, S.P. and Sunkari, S.R., 2013. Signalized Intersections Informational Guide (No. FHWA-SA-13-027). US Federal Highway Admin., Office of Safety.