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SIMULATION PLATFORM FOR TESTING AND EVALUATION OF CAV TRAJECTORY OPTIMIZATION AND SIGNAL CONTROL ALGORITHM INTEGRATED WITH COMMERCIAL TRAFFIC SIMULATOR

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ABSTRACT

Connected and Autonomous Vehicles (CAVs) and their applications have the potential to increase the safety and efficiency of highway networks. Therefore, it is essential to test and evaluate how CAVs affect traffic operations before they are widely deployed. However, there are limitations in testing these systems in the real world due to the limited number of CAVs and safety concerns. This paper develops a simulation platform to allow testing of CAV. The platform is used to test a previously developed algorithm that optimizes signal operations by exploiting CAV capabilities. The simulation platform leverages its performance evaluation capabilities to VISSIM. Simultaneously, the external algorithm jointly optimizes signal control and CAV trajectories. The paper demonstrates how the simulation platform can integrate other CAV applications to VISSIM, allowing for comparison of different trajectory and/or signal control optimization algorithms.

1 INTRODUCTION

Connected and Automated Vehicles (CAVs) have received considerable attention in transportation research. Most attention is due to the result of several studies that claimed that significant improvement in traffic performance can be achieved by taking advantage of CAVs capabilities (Fayazi and Vahidi 2017; Jiang et al. 2017; Mohebifard et al. 2019; Wan et al. 2016). CAVs can be driven autonomously while sharing information with surrounding vehicles and infrastructure. This exchange of information between CAVs and infrastructure can improve traffic management. For instance, at signalized intersections, CAVs and signal controllers can share information to optimize the Signal Phasing and Timing (SPaT) according to vehicles' arrival reducing vehicles' delay (Y. Feng et al. 2018). Similarly, vehicles' trajectories can be optimized to ensure vehicles' arrival during the green interval maximizing throughput (Tajalli 2020; Pourmehrab et al. 2020).

Simulation is used to evaluate these traffic management strategies. However, such simulations usually develop their own logic for conventional vehicles (CNVs), which may or may not be valid. There are existing microsimulators that have been used and validated extensively. The objective of this research is to lay out a path for the integration of CAVs' control logic into a microsimulator.

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Among simulation packages, VISSIM (2022) is one of the few that offers a simulation framework with adequate flexibility for implementing and testing optimization algorithms. As previous studies have shown, VISSIM can provide a very realistic driving behavior and the model parameters can be adjusted to reflect different traffic situations (Fellendorf and Vortisch 2001). Although VISSIM provides good flexibility in terms of the development and testing of new control strategies, in the literature most of the existing studies do not fully integrate CAV's logic (i.e., optimized SPaT, optimized trajectories) in the VISSIM loop. Rather, VISSIM is only used for animation or to extract performance measures.

VISSIM allows their users to modify the parameters of car-following and lane-changing for a set of models available with the software. However, this solution may not be sufficient for researchers who are interested in developing and testing new car-following and lane-changing models for CAV that are not distributed with VISSIM. Similarly, their simulation environment has only a limited set of models for traffic signals.

VISSIM provides additional tools to utilize external driver models and to overwrite the signal status within the simulation loop through the use of programming tools. However, there are no clear guidelines on how to integrate intersection optimization frameworks into the simulation's loop. Thus, the objective of this study is to provide the guidelines for integrating such optimization algorithms with VISSIM.

This paper develops a procedure for integrating a custom signal control optimization algorithm for CAVs with a well-established microsimulator (VISSIM). We use a case study to compare the CAV logic used within VISSIM with a Real-time Intersection Optimizer (RIO) algorithm to demonstrate the use of the procedure. The paper also provides guidance for others who want to test their algorithms within a well validated commercial microstimulator.

2 LITERATURE REVIEW

This section briefly reviews some of the previous efforts to integrate CAV logic into a well-established microsimulation package (VISSIM) and how such an integration is used in the assessment of various strategies. Then, we review recent optimization strategies that consider CAVs to enhance traffic performance, focusing on how researchers have simulated their control strategies. A summary of the literature review findings is provided at the end of this section.

Although some studies have used the VISSIM platform to analyze CAV's impact, most such studies do not consider the modification of SPaT or vehicle trajectories. To fill these gaps Zhang (2017) developed a signal-free optimization framework for CAV. In this study, they send trajectory information to vehicles in the simulation using the VISSIM Component Object Model (COM) interfaces, VISSIM COM (2022). Wang et al. (2019) tested the performance of a joint control model in VISSIM/MATLAB simulation. The optimization model is solved in MATLAB and the resulting trajectories and signal plan are transferred to VISSIM through COM. In these studies, researchers managed to achieve an integration between control algorithms and VISSIM, however, they did not provide clear guidelines on how to achieve this integration. and; Manjunatha et al. (2022) developed a simulation platform with VISSIM through COM API and External Driver Model (EDM) Zephaniah (2019). Although this project did not consider signal control optimization and only uses a fixed signal control plan, it laid out some clear guidelines on how to achieve this interaction considering CAVs and signal control. In that study, they achieved control of vehicle dynamics by combining the VISSIM COM API and the EDM. The COM data fetching was coded in Python which is a free-license programing language, compared to the previous approach that relied on MATLAB which requires license purchasing.

Several studies have evaluated the possibility of integrating CAVs' capabilities into existing highway networks. Although the assessment of these studies is typically done through simulation, researchers usually developed their own custom-made numerical simulations. For example, Yang et al. (2016) developed a micro-simulation platform coded in Java to test a signal control algorithm. Guo et al. (2019) proposed a model that combined dynamic programming and a shooting heuristic approach to solve a mathematical model that generates CAV trajectories and optimal signal timing plan on MATLAB. Similarly, Kamal et al. (2020) proposed and evaluated a new traffic signal control scheme for mixed traffic flow (CAVs, CNVs) on MATLAB. Similarly, (Pourmehrab 2019; Pourmehrab et al. 2020; Pourmehrab, et al. 2020) proposed a real-time intersection optimization (RIO) algorithm to efficiently serve mixed traffic i.e., CAV and CNVs. CNVs were assumed to follow the Gipps car-following model while a novel trajectory algorithm controlled CAV movement, ensuring vehicle arrival during the green interval. They used the Python programming language to formulate and solve the optimization model.

Although creating new simulation platforms is very useful, it makes comparison of different algorithms very difficult, if not impossible. These custom-made simulators are not thoroughly validated, and they are rarely available for testing by external evaluators (Gora et al. 2020). Thus, to facilitate the evaluation of these algorithms in a more realistic environment, and to allow an apples-to-apples comparison, it is necessary to use a well validated platform, preferably a well-established commercial simulation software. Some commercially available simulation packages are validated for a broad set of conditions (Li et al. 2013) however, most of them do not allow easy development and testing of new control strategies for CAVs. Usually, it is necessary to go through several layers of controls (i.e., customizable driving behavior models, accessing vehicles and signal attributes through programing scripts, etc.) to test new strategies. In addition, there is no clear documentation on how to integrate optimization strategies into the loop of the simulation.

VISSIM is a widely validated microsimulator, and it offers more freedom in terms of development and testing compared to other simulation software as it allows the test of new driving behavior through the COM interface or the EDM feature. For this reason, VISSIM is increasingly being employed by researchers to simulate CAVs' impact on traffic flow (Evanson 2018). This has been supported more recently by Raju and Farah (2021), who surveyed the evolution of microstimulators for CAVs. They found that VISSIM, and SUMO usage have been increasing since 2001 compared to others microsimulators. However, VISSIM has the major share of citations among research journals.

Several CAVs' studies have used VISSIM as their simulation platform. Liu and Feng (2019) combined a real-world testing facility (one physical CAVs, traffic signal controllers, and other infrastructures) with a virtual environment (simulated traffic) to test railway crossing and red light running situations with a limited number of vehicles. In the resulting platform, CAVs' position and movement in the real world were synchronized with a traffic simulation. The information from simulated background traffic is fed back to the real-world CAVs. These past works reveal the potential of combining simulated traffic with CAVs trajectories produced outside of the simulation environment. However, these hardware-in-the-loop (HIL) simulation platforms are designed to test vehicle behaviors in specific real-world scenarios and are not suitable for large-scale traffic flow simulations.

In summary, the following are some of the gaps identified in the literature:

- In most of the CAVs' studies, researchers have developed their own numerical simulation to assess the effectiveness of their approaches.
- Some studies have used VISSIM to test CAVs capabilities with HIL in real-world scenarios. These have generally used a limited number of vehicles (typically one vehicle).
- There are no clear guidelines on how to integrate VISSIM, CAV's dynamics, and optimization algorithms.

3 METHODOLOGY

This section describes the methodology used for integrating a previously developed CAV joint optimization algorithm with the microsimulation package VISSIM. Also, a description of the optimization algorithm, the integration methodology with VISSIM, the testing environment, and demand scenarios are provided.

3.1 Simulation Platform Description

The simulation platform has two main components: 1) the Real-time Intersection Optimizer (RIO) and 2) the microsimulation software VISSIM. RIO jointly optimizes SPaT and the trajectory of CAVs (Pourmehrab et al. 2020). CAVs are generated by VISSIM. Once generated, CAVs dynamics are controlled by RIO along with the SPaT. The simulation platform is developed on a Windows system with Python 3.6 version with a time-step frequency of 1 Hz.

The overall architecture of the simulation platform is shown in Figure 1. The simulation platform operates at a loop frequency of 1 Hz. Note that both the RIO and VISSIM must operate under the same frequency. Although a low refresh rate may reduce the accuracy of the vehicles trajectories, we have opted for this loop frequency due to limitations with the system computational efficiency as discussed in further sections. An iteration of the control algorithm works as follows. For a given time-step n, the RIO gathers the trajectory of every CAV at time-step $n-1$ as well as the current signal status. Then, these variables are used to solve an optimization model which outputs an updated SPaT and the optimized trajectories for each CAV. Then, the updated CAVs trajectory and SPaT are fed back to VISSIM. The trajectories are generated by VISSIM for the next simulation time-step under the updated SPaT and CAVs trajectories. This marks the end of the current time step. At the end of the simulation, the VISSIM evaluation module can export the selected performance measurements i.e., delay, travel time, throughput, etc.

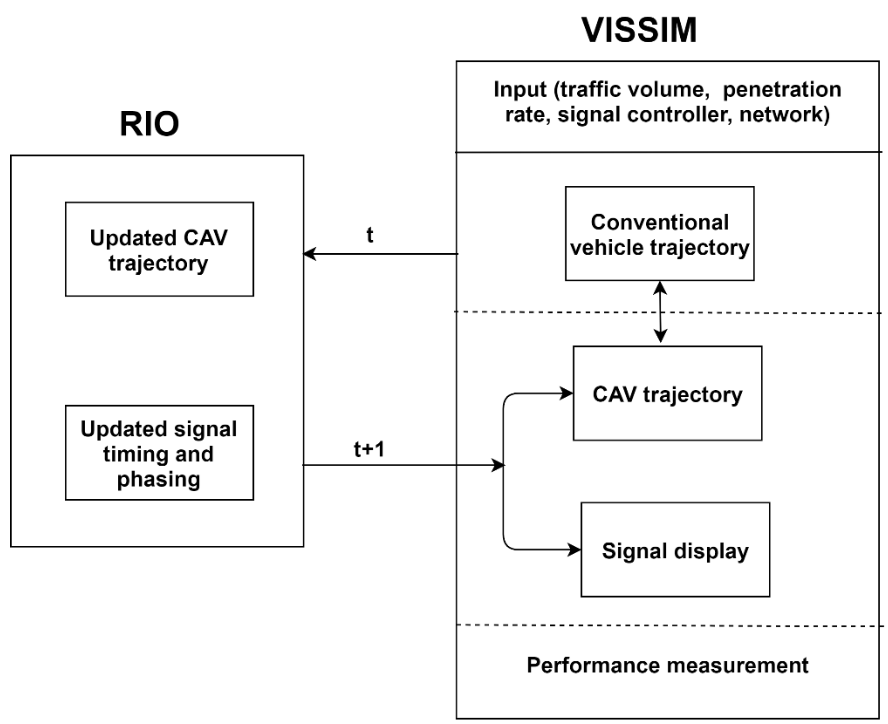

Figure 1. Design of the simulation platform.

3.2 RIO

The RIO is based on the algorithm proposed by Pourmehrab et al. (2020), The author developed the Intelligent Intersection Control Algorithm (IICA) which optimizes CAV trajectories and SPaT in mixed traffic flow. The proposed algorithm minimizes the space occupied by a vehicle during its travel time interval, which in turn optimizes the performance of the vehicles and, therefore, of the intersection. RIO implements a modified adaptive signal control logic to decide SPaT based on the computed trajectories.

The lead CAV trajectory is optimization is subject to a set of constraints of distance, speed and acceleration/deceleration. Similarly, for a follower CAV, in addition to the same set of constraints of lead CAV, constraints to keep a safe headway with the lead vehicle is added.

As for the adaptive signal control, RIO updates the signal control at every iteration of the IICA loop. It requires the trajectory of the lead vehicle, follower vehicle, and signal control status. The flowchart of the traffic signal generation module is shown in Figure 2. It shows that after the generation of traffic, the position of vehicles arriving at the beginning of each lane in the current time-step is updated. The algorithm then determines an optimal phase order based on the expected time of arrival at the stop-bar (ATS) for all vehicles. Then, the trajectories for all vehicles on each phase is optimized, and finally the green time duration for each phase is determined based on the last vehicle's expected departure time.

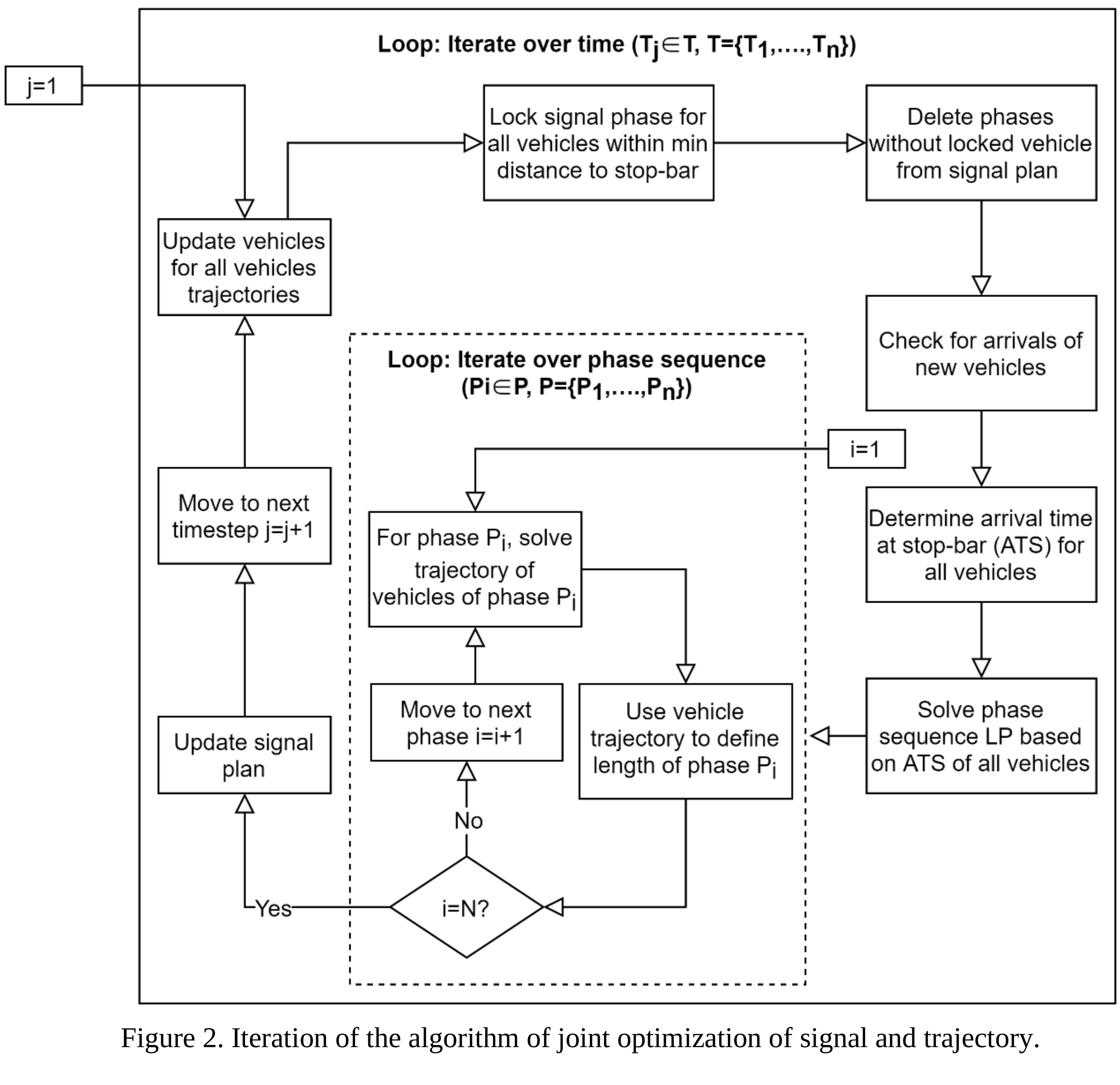

Figure 2. Iteration of the algorithm of joint optimization of signal and trajectory.

3.3 Platform Implementation within VISSIM

This research uses the microscopic simulator VISSIM (Version 10.0). VISSIM provides various external interfaces which enables users to develop their own applications based on VISSIM. In this study, two of these interfaces are used: Component Object Model (COM) Application Programming Interface (API) and the EDM.

The COM API is used to transfer data between RIO and VISSIM. Through COM API, users can connect VISSIM with many programming languages such as VBA, Python, C++, and so on. There are three main parameters related to vehicle longitudinal movement in COM API used for this study: desired speed (the speed the vehicle/driver desires to travel at unless the acceleration is bound by vehicle dynamics), instant speed (instantaneous speed), and position (vehicle's current location, measured from the beginning of the link it is on). The COM API can also control the current state of the signal controller. The relevant parameters for this task are signal controller ID, signal state (green, red, amber, etc.). These three parameters are both readable and writeable.

The EDM is used to control the longitudinal and lateral movement of vehicles. The EDM is programmed in C++ to substitute the default driver model of VISSIM. Hence, it enables users to define and test their own vehicle control model in VISSIM. In each simulation step, the EDM dynamic-link library (DLL) receives the current state of vehicles from VISSIM and then computes the acceleration/deceleration and lateral behavior of each vehicle, which will be fed back to VISSIM to be used in current time step.

Thus, the combination of COM API and EDM allows us to create a robust environment for CAV applications.

The flow chart of the implementation of COM API and EDM in the simulation platform is shown in Figure 3. The simulation platform fetches VISSIM data through the COM API which includes vehicle type, position, desired speed, instant speed, signal phasing status and other parameters. This data is forwarded to RIO, which generates acceleration/deceleration for CAVs and SPaT for the next simulation step. The optimized vehicle trajectory data in RIO contains timestamp, position, speed and acceleration. The outputs of acceleration are exported into a text file, which is read and implemented in VISSIM by the EDM in the next time step. Likewise, the COM API parses the SPaT information and implements it in VISSIM. Finally, VISSIM updates the vehicles trajectories using the received data of CAV trajectory and SPaT. This concludes a loop iteration of the simulation platform.

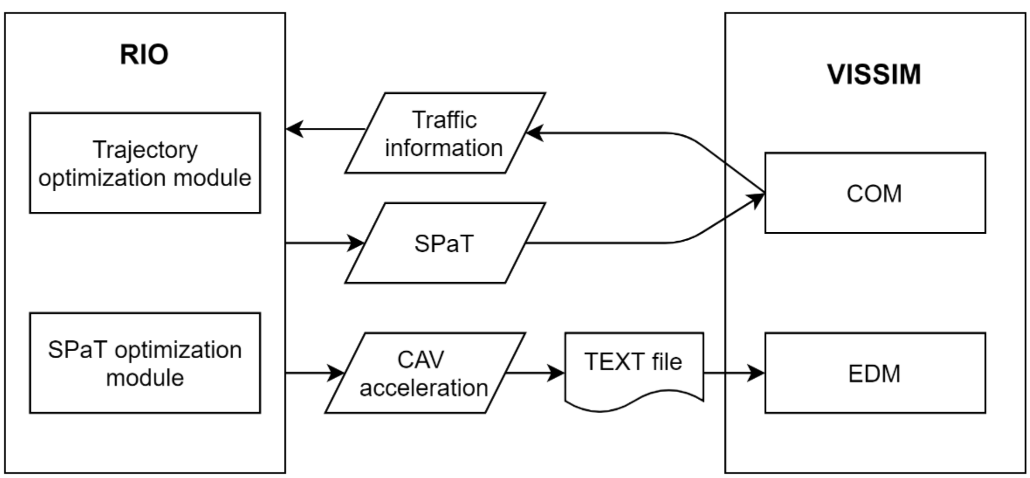

Figure 3. The flowchart of data exchange between VISSIM and RIO.

4 CASE STUDY

We have conducted a case study to evaluate the integration of RIO within the VISSIM loop. In the baseline environment vehicles and SPaT are fully controlled by VISSIM's logic and the rules VISSIM uses to control CAVs, while for the comparison environment CAVs' trajectories and SPaT are fully controlled by RIO's logic. Performance measures are collected in both environments by using the VISSIM's inbuild data collection tool.

4.1 Experiment Design

We have created a VISSIM network consisting of a four-legged intersection, with one lane per approach. The geometry of this intersection is based on an existing intersection located in Gainesville, Florida, as shown in Figure 4. A two-phase signal control plan is adopted in this experiment, with one phase for the north and southbound movements, and another for the east and westbound movements. For the baseline scenario (VISSIM), we utilize an actuated signal while in test environment (RIO-VISSIM), the SPaT is optimized by RIO considering maximum and minimum thresholds in the signal timing as shown in Table 1.

Figure 4. Intersection of Stadium Road and Gale Lemerand Drive (photo courtesy of Google Maps).

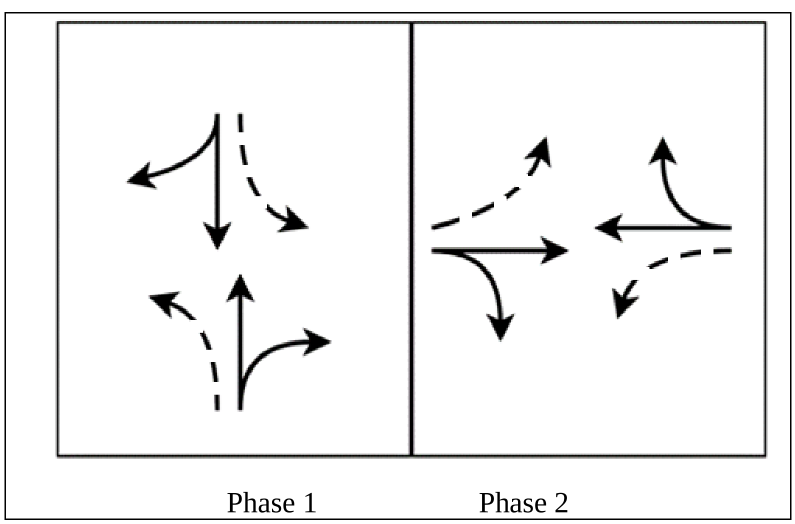

Figure 5. Phases for the intersection.

Table 1. Signal timings for RIO and VISSIM.

Parameter/ Value (s)	VISSIM		RIO
	NB-SB	**EB-WB**	**All**
Min Green	15	8	5
Veh Extension	6	6	-
Max Green	60	60	25
Yellow	4	4	4
All Red	1	1	1

Six scenarios of varying traffic demand were tested. These scenarios are divided into two groups. The first three scenarios have the total network demand evenly split among the four approaches. The other three scenarios have 70% of the demand assigned to the North-South approaches, and 30% assigned to the East-West approaches. In all scenarios we assume that all vehicles are CAV for both environments (VISSIM, and RIO-VISSIM). Table 2 presents the traffic demand distribution for each scenario. The maximum speed in all scenarios is 20 mph (32 km/h).

Table 2. Traffic demand for each scenario.

Scenario	Demand per approach (veh/h)				Network demand (veh/h)
	Eastbound	**Northbound**	**Westbound**	**Southbound**	
1	200	200	200	200	800
2	400	400	400	400	1600
3	600	600	600	600	2400
4	120	280	120	280	800
5	240	560	240	560	1600
6	360	840	360	840	2400

On each iteration, each scenario is executed twice: once using only VISSIM with the default CAV car-following CoEXist parameters (Suvennik P. 2020), and a second time using the integrated RIO-VISSIM platform. Both runs use the same random number seed for generating traffic, which means that both runs have the exact same time of arrival in the network for each vehicle. We run two iterations for each scenario. Although a higher number of iterations would be desired, the current RIO-VISSIM implementation is not computationally effective as discussed further in the results. Thus, the choice of the number of iterations was constrained by the time available.

Each simulation runs for 30 minutes. The performance measurements for the first 15 minutes are discarded, given that this initial period is considered as a warm-up. The values of average delay (s/veh) are collected on a network level. Average delay is obtained by averaging the difference between actual and ideal travel time of each vehicle and is calculated by VISSIM, which then stores it in an SQL database. We have extracted these results using an SQLite implementation in Python, and the results are shown next.

4.2 Simulation Results

Table 3 shows the network delay for VISSIM and RIO for each scenario. These measurements are the average of two replications of each scenario. The delay difference is given by subtracting RIO delay from

VISSIM delay. Thus, positive values indicate that RIO causes an average delay reduction per vehicle when compared to VISSIM.

Table 3. Network delay for each scenario.

Scenario	Network demand (veh/h)	Demand split	Average delay/vehicle (s/veh)			Percent. diff.
			VISSIM	RIO	Difference (VISSIM - RIO)	
1	800	Evenly	7.7	5.1	2.6	34%
2	1600	Evenly	17.9	8.4	9.5	53%
3	2400	Evenly	22.5	13.2	9.3	41%
4	800	70/30	6.9	4.0	2.9	42%
5	1600	70/30	14.0	9.8	4.2	30%
6	2400	70/30	24.4	16.9	7.4	30%

As shown, RIO outperforms VISSIM for delay reduction in all 6 scenarios, providing at least 30% reduction of average delay. Both RIO and VISSIM perform better at lower network demand levels (scenarios 1 and 4). Within the tested scenarios, RIO provides the greatest delay reduction when the network has a demand 2400 veh/h evenly split across all approaches.

The computational efficiency of RIO and VISSIM was also evaluated. All simulation runs were executed on a Windows PC with the following specifications: i7-7700 @ 3.60 GHz, 8 GB RAM, Hard Disk Drive. All VISSIM runs of 30 simulated minutes are completed in less than 3 seconds. Meanwhile, RIO runs may take between 20 and 30 minutes to complete. The bottleneck of our algorithm performance has been observed to be the implementation of the EDM, which requires a read/write of a text file with the CAV accelerations on each timestep. Although this solution might be sufficient for running the system in real-time, it sacrifices one of the advantages of performing traffic simulation, which is to obtain results at a faster pace than in real-time.

5 CONCLUSIONS AND RECOMMENDATIONS

In this study, we have implemented a procedure for integrating and testing a previously developed CAV's optimization framework by (Pourmehrab et al. 2020) into the VISSIM loop. This integration is achieved by combining the COM interface and the EDM as proposed by Manjunatha et al. (2020).

We have presented a case study where we compared our algorithm performance when serving CAV demand to VISSIM default car-following model for CAVs. Using VISSIM inbuilt performance measurement tools, we have observed that our algorithm can provide at least 30% delay reduction for CAVs in a signalized intersection.

We have observed that the current implementation of our algorithm may not be computationally effective for conducting extensive simulation analysis. We have detected that our implementation of an EDM that relies on read/writing of a text file for obtaining the accelerations computed by our trajectory optimization algorithm is the main cause for the low computational performance. However, the main contribution of this study is to provide the initial guidelines and considerations for future research to implement their own intersection optimization algorithms in VISSIM. Thus, we recommend that future research that involves creating EDMs for VISSIM focuses on the communication effectiveness between VISSIM and the trajectory/signal phase and time optimization algorithms.

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