Connected and Automated Transportation System in Multi-agent Environment*

Ohay Angah, Yiran Zhang, and Xuegang (Jeff) Ban

Abstract— **Traffic simulation is important for transportation researchers, analysts, and policymakers. It can be used to test vehicle/traffic control algorithms, gain insights into traffic dynamics, and develop traffic management strategies that can improve the efficiency and safety of transportation systems. Unfortunately, many existing simulation platforms have limitations to cater to diverse simulation scales. This study presents a comprehensive multiscale vehicle-traffic-demand (VTD) simulation platform tailored for connected and automated transportation systems. This platform integrates Unity 3D, Simulation of Urban Mobility (SUMO), and Multiagent Transport Simulation (MATSim) to facilitate an in-depth analysis of both micro and macro-level traffic behaviors. A critical aspect of our work involves the meticulous setup and calibration of traffic networks in Greater and Downtown Seattle, ensuring effective integration and communication between the various simulation tools. This advanced platform not only serves as a robust tool for testing and refining vehicle/traffic control algorithms but also opens new avenues for research into traffic dynamics learning and the development of sophisticated traffic control solutions.**

I. Introduction

Traffic simulation has become an increasingly important tool for researchers, analysts, and policymakers. It enables the testing of vehicle and traffic control algorithms, provides a deeper understanding of microscopic and macroscopic traffic dynamics, and assists in crafting effective traffic management strategies. Given the diverse nature of transportation applications that range from specific corridors to extensive city or regional networks, each application demands an appropriate simulation scale. However, existing simulation platforms often fall short in offering a comprehensive perspective that encompasses all these varying scales. To address this gap, this study introduces a multiscale framework for vehicle-traffic-demand (VTD) simulation. This framework is designed to be adaptable, catering to the nuanced needs of connected and automated transportation systems, and is particularly effective in environments with a mix of connected and automated vehicles (CAVs) and human driven vehicles (HDVs).

In exploring the landscape of traffic simulation tools, we encounter a range of software tools designed for different aspects of transportation studies. Notable among these are the macroscopic Multi-Agent Transport Simulation (MATSim) [1], the mesoscopic DTALite [2], the widely-adopted microscopic simulator Vissim [3], the innovative microscopic model A/B Street [4], and the popular open-source tool Simulation of Urban MObility (SUMO) [5]. Each of these platforms offers unique capabilities: MATSim excels in large-scale traffic simulation but lacks in detailed vehicle interaction modeling, DTALite offers a theoretically sound and efficient traffic network modeling but requires users to have a strong background in dynamic traffic assignment (DTA) and traffic flow theory, Vissim is a versatile multimodal simulator but is not open-source, A/B Street boasts an impressive user interface but might have limited underlying traffic models, and SUMO, although it is open-source and has a wide range of users, it lacks macroscopic simulation functionalities. Despite individual strengths, none of these platforms offer a truly multiscale simulation experience. Efforts to integrate different models to simulate traffic networks at various scales have been undertaken [5], [6], but developing a new multiscale platform from scratch is both resource-intensive and challenging, particularly in capturing the full spectrum of traffic flow and demand patterns. Combining different simulation tools to represent various levels of detail, such as macroscopic and microscopic [7], enables presenting additional complexities in achieving compatibility and efficient communication between the models.

The primary objective of this study is to develop a transportation simulation platform that can demonstrate the behaviors of transportation systems at both macroscopic and microscopic levels by integrating existing microscopic and macroscopic simulation models. Our research team has previously developed a microscopic vehicle-in-the-loop (VIL) simulation platform [8], which harnessed the strengths of Unity 3D for simulating and visualizing vehicle operations and dynamics, alongside SUMO for traffic flow dynamics. The model, utilizing TCP/IP communication protocols, facilitates seamless coordination and data transfer between vehicle and traffic simulations. The VIL platform has been instrumental in researching, testing, and validating various vehicle and traffic control strategies, including eco-driving and integrated traffic-vehicle control systems.

Building upon this foundational work, the VTD simulation platform extends the capabilities of the VIL platform. It is expected to empower researchers to explore and validate more comprehensive vehicle-traffic control models over larger areas, thus providing a more holistic view of transportation systems. By enabling the development and application of concerted

*Research supported by C2SMART.

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management strategies across multiple scales, the VTD platform offers a path to research and test more integrated, efficient, and adaptive transportation systems.

II. Framework of VTD Platform

The VTD platform integrates MATSim, SUMO, and Unity, as depicted in Figure 1. This integration comprises two distinct intergration modules: MATSim-SUMO and SUMO-Unity, reflecting their individual simulation frameworks. MATSim simulates all agents' 24-hour activities and demand in one go, whereas SUMO and Unity model and visualize individual behaviors in real time. As a result, MATSim provides overall activity data post-simulation, while SUMO and Unity model real-time behavior tracking. This difference necessitates separate, specialized integration approaches for MATSim-SUMO and SUMO-Unity.

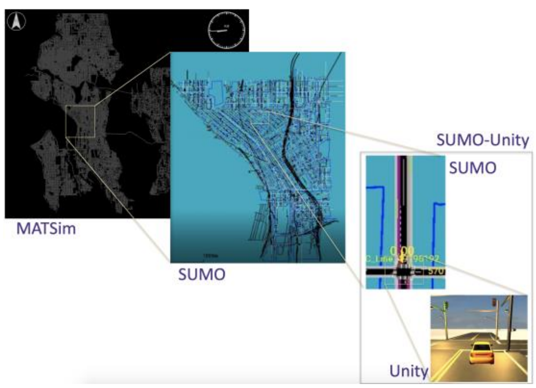


Figure 1. VTD Platform Environment

A. MATSim-SUMO Integration

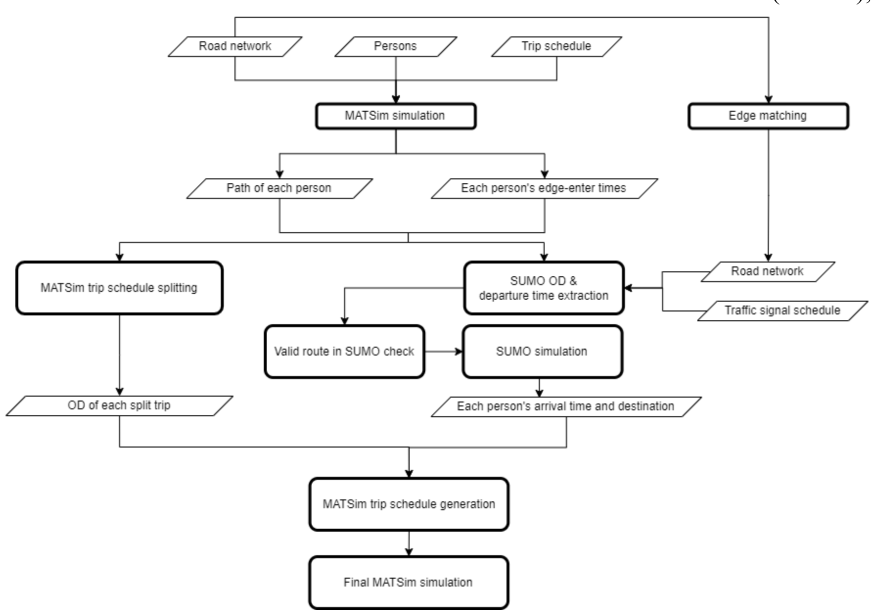


Figure 2. MATSim-SUMO Integration

The MATSim-SUMO integration aims to merge large-scale traffic demand data with detailed local traffic movements. MATSim is an activity-based multi-agent simulation model, whose optimization is to find equilibrium through co-evolutionary search [1]. On the other hand, SUMO is a microscopic intermodal simulation tool, which models interactions between vehicles, vehicles to pedestrians, etc. Each road user makes decisions about their behaviors based on the traffic conditions at the current moment.

In light of the distinctive features of the two models, we implement MATSim to address the broader demand perspective across a large region and for an extended period (i.e., a day). Conversely, SUMO is employed to deliver detailed traffic dynamics in local areas over a shorter timeframe (i.e., two hours). A crucial aspect of integrating the two models is to ensure trip and network consistency at the MATSim-SUMO network boundaries. We develop a trip integration process to synthesize trip information for this purpose.

The goal of the integration process is to ensure the consistency of when and where road users enter and exit local (SUMO) areas on both MATSim and SUMO simulation environments. Firstly, to ensure the consistency of entering local areas, we run MATSim first to get road users' trips for the day. We split the trips into portions with partial in the larger (MATSim) region and the other in local (SUMO) areas. Then, we run SUMO to simulate the behaviors in the local areas based on the portion of the split trips, including timestamps and locations of entering. Secondly, to ensure the consistency of exiting, after SUMO simulation the information of when and where road users exiting local areas will be fed into MATSim to update road users' schedules. The detail process is illustrated in Figure 1. Specifically, the trip integration process begins by MATSim providing a macroscopic view of traffic dynamics, including link departure and arrival times for each traveling agent. Trips at the boundaries are segmented into portions with partial in the larger region (MATSim) and the other in local areas (SUMO), where the portions in local areas serve as inputs for SUMO microscopic simulation. The trip arrival times after SUMO simulation are fed into MATSim as boundary departure times to maintain consistency.

Network integration can be challenging, especially when the network sources used in MATSim and SUMO are different. Our approach involves matching network links at the boundaries to ensure compatibility between the different network representations. This involves detailed comparison and occasionally manual matching, especially for complex and disparate networks.

Developing the MATSim-SUMO integration encompasses ensuring both network and trip consistency. This involves addressing resolution differences between the two simulation models, which might lead to road disconnections and traffic volume distribution challenges. The integration framework includes preparing road networks and trip plans for MATSim, alongside local area networks and traffic signal schedules in SUMO. Post-MATSim simulation, trips are divided and validated for feasibility within the SUMO network. The integration process concludes with an updated MATSim simulation incorporating data from SUMO to finalize overall demand. The complete process is shown in Figure 2.

B. *SUMO-Unity Integration*

In the SUMO-Unity integration module, the main task is to facilitate real-time information transfer between the two platforms. We develop a control center based on the VIL platform's design [8] to manage the message sharing, encompassing both static (e.g., traffic signal locations) and dynamic (e.g., vehicle states) data.

While transferring information between SUMO and Unity, the control center receives information including traffic signal states, current states of the subject vehicle and its surrounding vehicles from SUMO, and transfers it to Unity when Unity is idle. In addition to information transfer, the control center can also be adapted for traffic control through the implementation of control algorithms, such as signal and vehicle-traffic control. By adding control algorithms, the overall VTD simulation can be used for traffic strategy testing and validation purposes.

Unlike the VIL platform that uses the dynamic road generation approach, the SUMO-Unity integration applies RoadArchitect and CityGen3D packages in Unity for creating comprehensive traffic environments from OpenStreetMap (OSM). Although the dynamic road generation approach was designed for saving memory usage, we have noticed that this approach can sometimes cause delays in information transfer, as the control center needs to be involved in each time step to assess whether the subject vehicle enters a new road segment. Pre-generating the road system in Unity can significantly mitigate this issue. We compress the generated road system, which includes many objects, as an image for large networks to save CPU and memory usage.

III. Simulation Calibration

In order to verify the simulation smoothness of the VTD platform, we conduct a traffic simulation of the Greater Seattle region, which includes Seattle and Bellevue cities. This involves the use of MATSim to model the overall region, while SUMO is utilized to model Downtown Seattle. In the following, we detailed the procedures employed to calibrate MATSim and SUMO simulations.

A. *MATSim Setup and Calibration*

The MATSim simulation is set up for the Greater Seattle area, covering Seattle and Bellevue, connected by State Route 520 (SR520) and Interstate 90 (I90). The network datasets are obtained respectively from the Seattle Department of Transportation (SDOT) and the Bellevue Department of Transportation. We simplify the diverse road categorizations into five types: motorway, primary arterial, secondary arterial, tertiary arterial, and unclassified. The "Greater Seattle road network" was created by merging the SR520 and I90 links from both cities, initially featuring 223,800 one-way road links. In order for efficient macroscopic simulation, we refined the network to primarily include motorways and primary arterials, using a two-step process involving connectivity checks and manual reconnections, reducing the network to 34,631 road links.

Additionally, we integrate the top 25% most used (in terms of ridership) bus routes from the King County Metro [9] into the MATSim model. This step involves mapping these routes onto the MATSim network, a process detailed in five steps, including sorting bus stops, identifying nearest links, creating a pseudo graph, locating least-cost paths, and establishing a link sequence with added artificial links for unconnected stops [10]. This integration extends the network to 36,295 road links. The complete MATSIM network is shown in Figure 3.

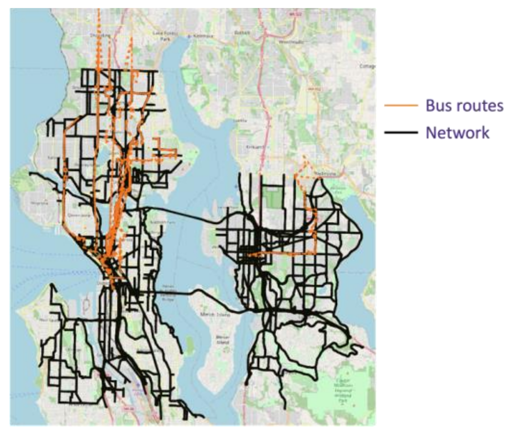


Figure 3. The greater Seattle Area in MATSim

MATSim calibration focuses on speed and capacity. Speed limits and capacities were calibrated using INRIX data and the Sensys traffic volume data. Speed factors were computed for different time periods and road types, and capacities were adjusted using the Simultaneous Perturbation Stochastic Approximation algorithm [11], [12], [13] until the average calibrated capacity closely matched observed traffic volumes. The calibrated network accounts for differences in highway and arterial speeds and capacities, with the average differences between calibrated and observed data falling within acceptable ranges. The final calibrated network, reflecting these adjustments, is illustrated in Figure 4 and Figure 5.

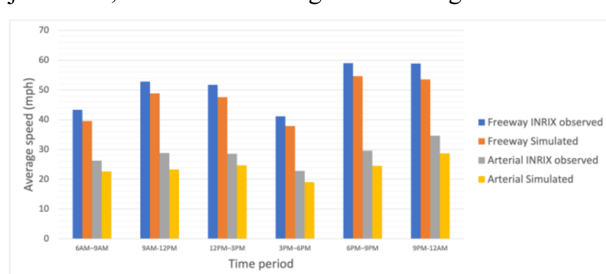


Figure 4. Speed Calibration

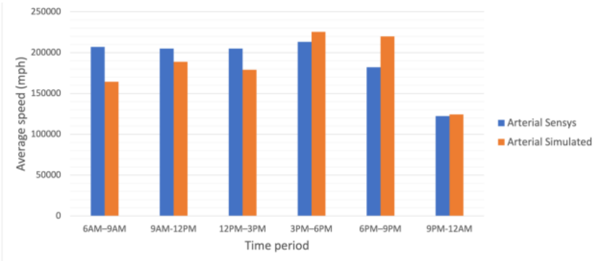


Figure 5. Capacity Calibration

B. *SUMO Setup and Calibration*

The SUMO network focuses on Downtown Seattle, as shown in Figure 6. Its setup encompasses three key elements: network, routes, and additional files, detailing network infrastructure, vehicle and pedestrian routes, and additional elements like traffic analysis zones (TAZs) and traffic signals. The resulting network features a comprehensive set of elements, including thousands of edges, junctions, and connections. Traffic modes include passenger vehicles, public buses, pedestrians, and link light rails.

Figure 6. Downtown Seattle in SUMO

The route file generates vehicle and pedestrian routes using SoundCast data [14] and public transit routes from the General Transit Feed Specification (GTFS) [15], resulting in 62 public transit routes. The additional file setup requires defining TAZs based on Puget Sound Regional Council (PSRC) data [16] and bus stops from the General Transit Feed Specification (GTFS) data, along with traffic signals provided by Seattle Department of Transportation (SDOT). Noteworthy is that we develop an approach for translating traffic signal timings from Synchro [17] to SUMO, accommodating the distinct features of both simulation platforms. This traffic signal conversion between Synchro and SUMO involves comparing input network features, identifying transferable features, and addressing the challenges in conversion due to differences in simulation scales and network complexity. To convert traffic signal plans from Synchro and SUMO efficiently, we propose a four-step approach including intersection mapping, signal direction bound mapping, feature extraction and mapping, and phase mapping, ensuring accurate and effective signal simulation in SUMO (see more details in [18]). This approach is crucial for translating complex traffic signal information between the macroscopic level of Synchro and the microscopic level of SUMO.

SUMO calibration is based on traffic volumes and travel times using three data sources: SoundCast for origin-destination (OD) demands, TRACFLOW, provided by the Washington DOT for highway traffic volumes (https://tracflow.wsdot.wa.gov/), and the National Performance Management Research Data Set (NPMRDS) for travel times on highways and local streets. The goal is to align the simulation closely with real-world measurements, using the Federal Highway Administration (FHWA) freeway model calibration criteria as our benchmark [19]. Calibration involves 15 highway segments for volume and 25 local street segments for travel time, using the Geoffrey E. Havers statistic (GEH statistic) [22], as shown in equation 1 to evaluate the performance. Typically, a GEH value below 5.0 indicates successful calibration.

$$GEH = \sqrt{\frac{(E-V)^2}{(E+V)^2}} \tag{1}$$

Our findings indicate that 80% of link volumes and 50% of link travel times meet the established calibration criteria. While these results may not seem exceptionally high, they are considered reasonably satisfactory given the complexities of large-scale simulation and the challenges inherent in integrating SUMO with MATSim and Unity. We will discuss possible avenues to further improvement in Section V. This calibration was crucial in ensuring the reliability and validity of the SUMO network simulation.

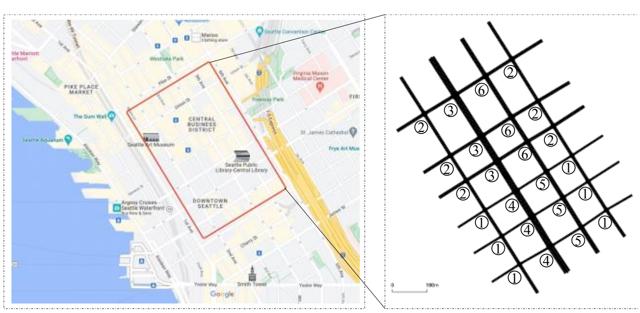
IV. Testing Results

We apply the VTD platform to test a two-scale signal-vehicle coupled control model [18]. The model aims to control signal timing and surrounding CAVs simultaneously to improve mobility and save fuel consumption. The traffic signal control system is designed to run at a macro-spatial scale, at the intersection scale specifically, and a low-frequency temporal scale. The vehicle control system, on the other hand, is implemented at a micro-spatial scale and at a high-frequency temporal scale. In the implementation, the signal system is modeled for optimal signal phases of maximizing the total vehicle throughput using a mixed integer nonlinear programming formulation, whereas the vehicle system is modeled for minimizing fuel consumption with acceptable travel time by adjusting longitudinal vehicle accelerations using a nonlinear programming formulation [20]. Additionally, the signal system will produce reference trajectories for surrounding vehicles at a low-frequency temporal scale. The surrounding controlled vehicles will subsequently be controlled at a higher time frequency to achieve their reference trajectories. This step is to ensure consistency between the two scales. More details can be found in [20].

The coupled control framework is tested with a 24-intersection network in Downtown Seattle, as shown in Figure 7. With one-way and two-way directions, roads in the network in total can be categorized into six distinct intersection types, as tagged in numbers on the right illustration of the figure. To achieve optimal traffic performance for the multiple-intersection network, we develop an information sharing algorithm to enable communication between neighboring intersections. The OD volume data for the network is from the same source as discussed in the previous section. The test encompasses cases from full CAV, mixed-traffic, to full human-driven vehicles (HDVs). In the latter two cases, the

HDVs' driving states are estimated from linear interpolation. The driving states of HDVs and CAVs at the intersection are all considered by the signal system for determining the optimal signal phasing. To ensure driving safety, we develop a safety checker to adjust the vehicle control commands. Details can be found in [20] and [21].

Table I presents the comparison of traffic performances and improvements between the actuated and the proposed coupled control scenarios. In the actuated scenario, traffic signals are actuated, whereas vehicles are simulated as human-driven vehicles, i.e., they are all controlled by the default car-following models in SUMO. In the proposed coupled control scenario, on the other hand, signals and vehicles (depending on the penetration rate) are controlled for maximizing the total vehicle throughput and minimizing fuel consumption, respectively. For discussion convenience, we denote our proposed coupled control scenario as *Multiscale* while the actuated scenario as *Actuated*. The comparison is based on the average waiting time, time loss, queue length, and fuel consumption, where the waiting time is defined as the number of seconds a vehicle has a speed of less than 0.1 m/s, time loss is defined as the time lost due to traveling at speed below the maximum speed. We calculate the queue length using the end of the last vehicle. The two values in the *Multiscale* rows, such as 6.66% and 46.75% under the average waiting time column, are the results of under zero (0%) and full (100%) CAV penetrations, respectively. The comparisons in Table I show that *Multiscale* outperforms *Actuated* on all evaluation metrics. It is because *Multiscale* allows the communication between vehicles and signals. Signals generate the optimal signal phases according to the current traffic conditions to maximize throughput while vehicles respond to signal phases by adjusting their vehicle accelerations to minimize fuel consumption. Results demonstrate that the coupled control framework can overall achieve higher traffic efficiency with consuming less fuel. In the *Multiscale* scenario, traffic performs better when there are more CAVs on the network. This is because higher CAV penetration provides more controllability and more accurate traffic state estimation. The lowest performance gain is 2.65% average queue length under zero CAV penetration case, whereas the highest gain is 46.75% average waiting time under full CAV penetration.



Google map SUMO

Figure 7. Multi-scale Signal-vehicle Coupled Control Area

V. Conclusion and Discussion

This research established a multiscale transportation simulation platform for connected and automated transportation systems at multiple scales. To achieve this, we integrated traffic simulation platforms including MATSim and SUMO for macro to microscopic simulation. In summary, this project has three key contributions: (i) development and implementation of the VTD multiscale simulation platform, (ii) calibration of the MATSim and SUMO networks, and (iii) applications utilizing this platform in the Greater Seattle area.

TABLE I. Performance of Multi-scale Signal-vehicle Coupled Control

Method		Performance indexes			
		avg. waiting time (s)	**avg. time loss (s)**	**avg. queue length (m)**	**avg. fuel (mg/s)**
Actuated		19.06	44.78	9.04	0.144
Multi-scale	**value**	17.79 - 10.51	40.12 - 33.23	8.80 - 7.00	0.140 - 0.110
	Improve-ment	6.66% - 46.75%	10.41% - 25.79%	2.65% - 22.57%	2.78% - 23.61%

The MATSim network was calibrated to represent the traffic in the real world. The calibration, however, has three major drawbacks. First, datasets were from different years, which may limit the calibration's ability to accurately represent actual traffic conditions. The network data from the City of Seattle and City of Bellevue dates back to 2020, while traffic volume data is from 2018 and demands were from 2014. These datasets were the latest available data we could obtain during the research period due to the survey year and the State Route 99 tunnel project. Second, capacity calibration only focused on arterial links. We calibrated the speed limits for both the major and the arterial links individually, but the capacity calibration for major links remained undone. Third, the calibration was specifically tailored to the Seattle area due to some complications. The research team will continue to extend the calibration to all the links in all the study area.

SUMO calibration also has limitations. First, the major issue for travel time calibration is due to the lack of auxiliary data resources. With only OD demand in hand, it is hard to speculate the traffic state for each road segment accurately. The research team continues to find data for traffic volume calibration along the local streets. Second, as discussed in the previous paragraph, the data resource for the input OD data (2014) and the filed measurement data (2018) are from different years. Third, more calibration for SUMO could be conducted, such as route calibration and car-following model calibration suggested by the FHWA. Although the smoothness of the VTD simulation is not affected by calibration performance, traffic behaviors in the simulation can be influenced due to imprecise simulated interactions among road users. In VTD, the MATSim simulation outcomes are utilized to be the demand of the local area, whereas SUMO outcomes are used to update road users' schedule of traveling to the larger region. If MATSim calibration is inaccurate, not only will the simulated trips be impacted, but the demand of the local area. Furthermore, inaccurate calibration of SUMO can affect the interactions within the local area and the updated schedule. The research team will continue to explore and gather more data for further calibration.

The VTD platform implementation and the case study demonstrated the capability of the platform to simulate traffic behaviors at multiple scales. VTD also allows users to implement new traffic strategies in the simulation. From the case study, the platform demonstrated flexibility of testing and validating complex control algorithms. The resulting simulation provided plentiful data to evaluate the effectiveness of the control algorithms with various indexes. Although this case study employed only the SUMO simulation, the integration of the macroscopic simulation in MATSim can potentially provide additional simulation functionalities, control flexibilities, and design possibilities.

Here we break the future research directions into three parts including (i) network calibrations, (ii) VTD platform extension, and (iii) multi-scale signal-vehicle coupled control modeling. As discussed above, the MATSim network calibration can extend from only major and arterial links to all links of the study area; the SUMO calibration may need to gather more data to improve travel time calibration performance and conduct driving calibration, e.g., routing and car-following models. Furthermore, calibration can consider different types of vehicles and modes other than passenger vehicles. The VTD platform holds potential for future expansion. First, this platform can be extended to involve real-time sensor data. The VTD module can be enhanced to simulate CAVs equipped with LiDAR, Radar, and camera sensors. These CAVs may then report the latest sensor data to the control center, which can provide additional information for traffic controls. The development of this feature may rely on the utilization of techniques such as computer vision (CV) algorithms and Simultaneous Localization and Mapping (SLAM). Second, the VTD platform can help investigate existing traffic dynamics and discover behaviors from newly emerging technologies. One can take advantage of the abundant amount of data produced by the simulation in the VTD platform to gain insights of traffic dynamics. The trajectory data from simulation can involve interactions from only between HDVs, CAVs-HDVs, to CAVs-HDVs-vulnerable road users (VRUs). With the increasing amount of CAVs, the simulation can also help identify the impact on safety for other vehicles and VRUs. Similarly, users can test and verify link-level traffic dynamic models, such as the point queue model, link transmission model, and double queue model, by utilizing this platform. By analyzing link-level fundamental diagrams, researchers can better understand the relationship between network link properties, such as capacities and speed limits and characteristics of the fundamental diagram including the shape and the slope of the diagram. Testing and validating the existing link dynamic models can also be done with the simulation data generated by the VTD platform.

Acknowledgment

The research team would like to thank the financial and administrative support by the C2SMART University Transportation Center housed at the New York University.

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