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Modeling Wireless Communications in Traffic Simulation Models

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16. Abstract

In recent years, the deployment of wireless communication technologies in transportation systems has gained momentum due to their potential to enhance safety, efficiency, and mobility. Vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-everything (V2X) communication systems enable real-time data exchange, enabling vehicles to communicate with each other and with the surrounding infrastructure. This communication facilitates the implementation of new advanced traffic management and safety applications or improvements to existing applications.

To determine which applications to implement, transportation agencies will need to develop, test, and evaluate numerous potential strategies using analysis, modeling, and simulation (AMS) techniques, prior to selecting the most effective applications for implementation. Conducting such analysis requires accurate modeling and simulation of wireless communications among vehicles and between vehicles and infrastructure. However, there appears to be limited information on how transportation agencies can incorporate wireless communications into their traditional modeling and simulation activities. Through a comprehensive examination of literature, this white paper seeks to advance the understanding of modeling wireless communications in traffic simulators by documenting the current state of practice, and providing insights on limitations, challenges, gaps and research needs. Potential projects to address the research and development needs are also provided.

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Executive Summary

The purpose of this document is to examine the various methodologies and approaches for modeling wireless communications in traffic simulators. It investigates the state of practice and research, highlighting the different simulation frameworks and tools available for modeling wireless communication systems in traffic simulators. The review focused on three key modeling approaches: 1) modeling efforts that modify driver behavior parameters to simulate impacts of information exchanged through wireless communication channels, 2) modeling efforts that integrate traffic simulators and wireless network simulators, and 3) hardware-in-the-loop simulation efforts. Ultimately, this document seeks to provide a comprehensive overview of the existing approaches for modeling wireless communication in traffic simulators, identify gaps and needs, and suggest future trends to inform future research and development planning activities in the modeling of wireless communication in traffic simulators.

The literature review was shaped by five key questions of interest. The following questions and findings are listed below.

Question #1: How are wireless communications currently modeled in traffic simulators?

- Traffic and communications network simulators are integrated through appropriate interfaces/conversion tools to simulate impacts of wireless-based V2X/CAV applications. In an offline environment (i.e., one of the simulators is running a time), conversion tools are used to convert vehicle positions obtained via traffic simulators to trace files that are usable by the wireless network simulator. In this scenario, the information exchange is unidirectional (i.e., from traffic simulator to network simulator).
- In online coupling (i.e., both traffic and network simulators running at the same time), traffic and network simulators are combined with the help of an interface tool interlinking them in a bi-directional way. This ensures that information is exchanged in both directions in real-time.
- APIs of traffic simulators are used to develop wireless communication models that enables V2V and V2I/I2V interactions.
- Some traffic simulators have built-in network simulators to facilitate V2V and V2I/I2V interactions. In such traffic simulators, network parameters like latency, range, and packet loss can be specified and tested.

Question #2: What are the key characteristics or operational constraints of wireless communications and how are they modeled in traffic simulators?

- The key characteristics of wireless communications mostly mentioned in the literature review includes signal propagation effects, obstacles, line of sight issues, density of nodes, signal attenuation (i.e., loss of signal strength), packet loss (i.e., transmitted data packets fail to reach receiver), multipath effects (i.e., signal being emitted from a transmitter is directed to the receiver through multiple paths, leading to signal deterioration), interference, refraction (i.e., signal passing through a medium with a different density, causing direction of signal to change), reflection (i.e., signal bounces back to transmitter), diffraction (i.e., the bending and spreading around of a signal when it encounters an obstruction), and range (i.e., longest distance from transmitter to receiver while maintaining sufficient signal strength) .

- Per the literature reviewed, these characteristics should be accounted for in the signal propagation and wireless communication models.

Question #3: What are the key challenges and gaps in modeling wireless communications in traffic simulators?

The following issues were identified as key challenges in modeling wireless communications in traffic simulations.

- **Cost and computational requirements limit the level of detail when modeling wireless communications in traffic simulations** – Wireless communications modeling involves several individual models such as signal propagation models, network models, interference models, and others. Therefore, a realistic model of a vehicular communications environment can be very slow. Even with position updates and message generation frequency set to low values (1s both) and using moderately powerful simulation computer, the run of 2400 simulation seconds can take up to one day of the CPU time, i.e. 24 hours, to finish.
- **Building/Running an interface/conversion tool between traffic and communication network simulators requires considerable amount of time and expertise** – To couple traffic and network simulators, there is a need for a conduit through which the two simulators can exchange data. In an offline environment (i.e., one of the simulators is running a time) conversion tools are used to convert vehicle positions obtained via traffic simulators to trace files that are usable by the wireless network simulator. In this scenario, the information exchange is unidirectional (i.e., from traffic simulator to network simulator). In online coupling (i.e., both traffic and network simulators running at the same time), traffic and network simulators are combined with the help of an interface tool interlinking them in a bi-directional way. This ensures that information is exchanged in both directions in real-time. Using these conversion and interface tools requires training and specialized skills. In instances where already existing conversion/interface tools don't work for a particular combination of traffic and network simulators, new conversion/interface tools would have to be built.
- **Lack of field data to calibrate signal propagation and interference models for different wireless communication protocols** – Accurate wireless communication models rely on realistic representation of the network environment, including how signal is propagated and the level of interference experienced. Modeling signal propagation and interference for different wireless protocols (e.g., DSRC, 5G, LTE, etc.) requires accurate and adequate field data to build and test these models. Such data may not be readily available to most stakeholders. Consequently, resulting signal propagation models built with limited data may not adequately represent the real-world.
- **Lack of trained and skill personnel to develop and incorporate wireless communications into traffic simulations limits adoption by agencies** – Modeling wireless communications in traffic simulations requires additional skillsets and training.

Whether a communications model is being built using a traffic simulator's API or traffic simulators and network simulators are being coupled, the technical and computing skills required may not be readily available in many transportation agencies. This may be a hinderance to widespread adoption of traffic management and safety applications enabled by wireless communications.

The following research gaps on modeling wireless communications in traffic simulators were identified.

- **There are no benchmarks or standards on the accuracy of wireless communication models** – Nearly every study reviewed discusses the development and incorporation of a realistic wireless communication models (i.e., signal propagation models, network models, interference models, and others) in their integrated traffic-network communication simulations. However, there is no means of deducing whether the presented models truly represent real-world conditions. Hence, there is a need for common benchmarks to evaluate the accuracies of these models.
- **Realistic modeling of mobile obstacles in signal propagation models is lacking** – Signal propagation models that aim to realistically model the complex environment surrounding the communicating vehicles, must account for both static objects (e.g., buildings, overpasses, hills), as well as mobile objects (other vehicles on the road). Per the literature reviewed, most network simulators have models to account for static obstacles. On the contrary, mobile obstacles such as vehicles on the road are sometimes not accounted for in the signal propagation models used in traffic simulations. This may lead to inaccurate simulation results. Hence, there is a need to always account for mobile obstacles in signal propagation models, even in less dense traffic conditions.
- **There is lack of information on how to simulate handoff between different wireless data transmission protocols and its resulting impacts on the transportation network** – In a heterogeneous network environment, there are plethora of wireless communication protocols including DSRC, WiFi, LTE, 5G, and others. There is a need to understand how vehicles or onboard applications equipped with multiple wireless communication protocols can switch between these protocols depending on what protocol is available and how the handoffs between them may affect wireless-based traffic management and safety applications. For example, in a Forward Collision Warning scenario, the lead vehicle is equipped with both DSRC and LTE while the following vehicle is equipped with only LTE communication protocol. If the lead vehicle stops abruptly, it would have to send a forward collision warning to the following vehicle through LTE by switching from DSRC to LTE communication protocol (i.e., assuming it was initially transmitting information through DSRC) to avoid a rear-end crash. There is a need to understand how these types of handoffs impact the mobility and safety of a transportation network.
- **There is lack of information on the effectiveness of hybrid wireless communication environment** – The different wireless communication protocols such as DSRC, 5G, LTE, satellite and others have their strengths and weaknesses. In a hybrid environment where two or more different wireless communication protocols are integrated for one or more applications, they will complement each other and minimize some of the individual weaknesses such as limited range, latency, and others. There is a need to research the

feasibility of a hybrid wireless communication environment and its impact on traffic management and safety applications and the overall transportation network.

- **There is general lack of guidance on how to model wireless communications in traffic simulation models** – Per the literature reviewed, researchers are devising creative ways to incorporate wireless communication models in traffic simulators to help assess effectiveness of wireless-based traffic management and safety applications. However, it was noted that most of these efforts are led by universities and research institutions. There was little to no information about state and local transportation agencies championing the modeling of wireless communication in traffic simulations. This may be due to lack of guidance on how to carry out such tasks. Hence, there is a need for guidance on how to model wireless communications in traffic simulations.

Question #4: What is the best approach for modeling wireless communications in traffic simulators?

- While there is no best approach mentioned in the literature reviewed, coupling traffic and communication network simulators appears to be the most used approach for modeling wireless communications in traffic simulations. This includes (i) integrating individual traffic and communication network simulators (e.g., VISSIM and OMNeT++); (ii) using traffic simulator API to develop a wireless communication model; and (iii) using traffic simulators that have built-in network simulators.

Question #5: What are the research and development needs to advance methods to model wireless communications in traffic simulators?

- To increase confidence in the outputs of simulation models used to assess the impacts of wireless technology-based traffic management applications, there is a need for realistic modeling of the wireless communication component. Currently, there are no benchmarks or standards on the accuracy of wireless communication models. As a result, there may be numerous communication models used in traffic simulations that do not have realistic and technically acceptable assumptions. Hence, there is a need for common benchmarks and standards to evaluate the accuracies of communication models used in traffic simulation models.
- One key characteristic of wireless communication modeling that needs to be carefully considered is how to realistically account for the impacts of mobile obstacles during signal propagation. Signal propagation models that aim to realistically model the complex environment surrounding the communicating vehicles, must account for both static objects (e.g., buildings, overpasses, hills), as well as mobile objects (other vehicles on the road). While most network simulators have models to account for static obstacles, mobile obstacles such as vehicles on the road are sometimes not accounted for in the signal propagation models used in traffic simulations. This may lead to inaccurate simulation results. Hence, there is a need to research how to account for mobile obstacles in signal propagation models, even in less dense traffic conditions.
- Vehicles equipped with wireless communication capabilities may not be restricted to using only a single communication protocol. There is the possibility of a single equipped vehicle having the capability to use multiple communication protocols (e.g., DSRC, WiFi, LTE, 5G,

and others) depending on a variety of factors. There is a need to understand how vehicles or onboard applications equipped with multiple wireless communication protocols can switch between these protocols depending on what protocol is available and how the handoffs between them may affect wireless-based traffic management and safety applications. This will provide insights on the interoperability between these wireless communication protocols and how the handoffs between them may affect wireless-based traffic management and safety applications. In addition to investigating handoff between different wireless communication protocols, it is also important to research how different protocols can be integrated for use in single traffic management and safety applications to complement each other and minimize some of the individual weaknesses such as limited range, latency, and others.

1 Introduction

1.1 Background

In recent years, the deployment of wireless communication technologies in transportation systems has gained momentum due to their potential to enhance safety, efficiency, and mobility. Vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-everything (V2X) communication systems enable real-time data exchange, enabling vehicles to communicate with each other and with the surrounding infrastructure. This communication facilitates the implementation of new advanced traffic management and safety applications or improvements to existing applications. These include cooperative collision warning systems, truck platooning, speed harmonization, intelligent traffic signal control, curve speed warning and others.

As vehicles become more connected and autonomous, and their penetration rates on roadways increases, transportation agencies will have to leverage their wireless connectivity capabilities to develop effective traffic management and safety applications. To determine which applications to implement, transportation agencies will need to develop, test, and evaluate numerous potential strategies using analysis, modeling, and simulation (AMS) techniques, prior to selecting the most effective applications for implementation. Conducting such analysis requires accurate modeling and simulation of wireless communications among vehicles and between vehicles and infrastructure. However, there appears to be limited information on how transportation agencies can incorporate wireless communications into their traditional modeling and simulation activities. Some of the key questions of interest to the Federal Highway Administration (FHWA) and transportation stakeholders include:

- How are wireless communications currently modeled in traffic simulators?
- What are the key characteristics or operational constraints of wireless communications and how are they modeled in traffic simulators?
- What are the key challenges and gaps in modeling wireless communications in traffic simulators?
- What is the best approach for modeling wireless communications in traffic simulators?
- What are the research and development needs on modeling wireless communications in traffic simulators?

This white paper seeks to addresses these key questions on incorporating wireless communication models into traffic simulation frameworks. Through a comprehensive examination of the subject, this white paper seeks to advance the understanding of modeling wireless communications in traffic simulators by documenting the current state of practice, and providing insights on limitations, challenges, gaps and research needs.

The remaining sections of this chapter provides overviews of analysis, modeling, and simulation, especially with regards to traffic simulation; and wireless communications. In addition, the purpose and scope of this effort, and how chapters are organized in this document are also presented in this chapter.

1.2 Analysis, Modeling, and Simulation Overview

Analysis, modeling, and simulation (AMS) is a core competency in the field of transportation engineering, enabling engineers to safely test strategies and technologies prior to field deployment. Practitioners can iteratively test hypotheses, assess impacts, and select optimal strategies and alternatives. Decision makers can make more informed investment decisions. AMS can be a critical element in decision-making in an increasingly complex, dynamic transportation system, particularly with new questions arising regarding the impact of the emerging technologies on the surface transportation system.

AMS tools include less complicated tools used for quick project evaluations (e.g., Sketch planning tools, Highway capacity software), traffic analysis tools used by states and local transportation agencies in project development (e.g., Microscopic traffic simulation tools), much more complicated tools for proof-of-concept projects (e.g., Hardware-in-the-Loop testing of connected automated vehicle applications) and others. The next section takes a deeper dive into traffic simulation models since it is an essential piece of this white paper.

1.3 Traffic Simulation Models

Traffic simulation is a virtual representation of interactions between elements of a transportation system (i.e., vehicles, pedestrians, roadway, traffic control, etc.) that allows transportation agencies to effectively plan and manage traffic operations. Traffic simulation models can be used to evaluate a wide range of operational strategies or roadway modifications at individual locations or across an entire network. The disaggregate approach used by simulation models allows them to more precisely and quantitatively capture the effects of advanced operational strategies at an individual vehicle level that other, lower-sensitivity methods are poorly designed to handle [1]. The three key types of traffic simulation models are briefly described in the following subsections.

Microscopic Traffic Simulation Models simulate the movement of individual vehicles based on car-following and lane-changing theories, with each vehicle assigned a destination, vehicle type, and driver type. They require significant computational time and storage, which may limit the network size and the number of simulation runs that can be completed in a given timeframe [2]. With the appropriate computational and storage capabilities, microscopic traffic simulation models can be developed for geographic sizes as large as urban areas and cities. Examples of microscopic traffic simulation tools include PTV Vissim, Aimsun, CORSIM, TransModeler, SUMO, etc.

Macroscopic Simulation Models simulate traffic flow based on deterministic relationships of flow, speed, and density, focusing on aggregate speed/volume and demand/capacity relationships. They have fewer computational demand requirements than microscopic simulation tools, but they do not provide as much detail in analyzing transportation improvements [2]. Macroscopic simulation models are usually developed for large areas such as cities and regions. Examples of macroscopic simulation tools include Visum, TransCAD, TRANSYT-7F, etc.

Mesoscopic Simulation Models describe traffic facilities at a higher level of resolution compared with macroscopic models, but the behavior and interactions of vehicles exhibit a lower level of fidelity compared with microscopic models. Movement of vehicles in mesoscopic models is governed by the average speed on the travel link, similar to what happens in macroscopic traffic simulation models. Mesoscopic simulation models aim to fill the gaps between the aggregate-level approach of macroscopic models and the individual interactions of microscopic models [3]. Mesoscopic simulation has discretized descriptions of each individual vehicles Origin/Destination and route Choice, same as in the microscopic simulations. Movement of vehicle in a link is handled by flow dynamic relationships similar to macroscopic simulation. The result is that two events are discretized per vehicle, link entry time and link exit time. Compared with microscopic models, mesoscopic models can provide significant savings in modeling time and efforts, especially when analyzing large area networks, without unduly compromising the accuracy of results [4]. Mesoscopic simulation models can be developed for all geographic sizes ranging from singular routes to corridors, grid networks, cities, etc. Examples of mesoscopic simulation tools include Dynasmart, Dynus T, Dynameq, etc.

1.4 Wireless Communications

Wireless communication involves the transmission and reception of information between two points separated by a distance, without using any connection like wires or cables. Wireless communication does not require any physical medium but propagates signal through space. Since signal transmission through space requires no guidance, the medium used in wireless communication can be referred to as Unguided Medium. In contrast with wired communication where cables are used, the transmission and reception of signals is accomplished through Antennas. Antennas are electrical devices that transform the electrical signals to radio signals in the form of Electromagnetic (EM) Waves and vice versa. These Electromagnetic Waves propagates through space. Hence, both transmitter and receiver consist of an antenna [5].

Within the context of transportation, the utility of wireless communication lies in its ability to enable transmission and reception of messages among vehicles, between vehicles and surrounding roadway infrastructure, and between vehicles and mobile devices of travelers. The messages could be Basic Safety Messages (BSM) as specified by SAE J2735, Signal Phase and Time (SPaT) messages, Traveler Information Messages (TIMs), Probe Vehicle Data messages, Signal Request Messages (SRM), Signal Status Messages (SSM), Collision Avoidance warnings, and numerous other types of messages.

The transmission and reception of above-mentioned messages can be achieved through different types of wireless communication channels or protocols. These include Dedicated Short-Range Communication (DSRC), Cellular V2X technology (e.g., 5G), Bluetooth, Wi-Fi, and others. Each communication protocol has its strengths and limitations in terms of reception range, latency, signal packet loss ratio, etc. In addition, all the wireless communication protocols may be subject to interference, distortion, noise, and scattering at varying degrees.

To simulate wireless communication network protocols, a network simulator is needed. A network simulator is simply a discrete event-driven network simulation tool used for studying the dynamic nature of communication networks [6]. Network simulators can be used to evaluate the performance and other characteristics of wireless communications. Examples of network simulators include Network Simulator-2 (NS2), Network Simulator-3 (NS3), OMNET++, QualNet, Colosseum, etc. [7]. Brief review of a few network simulators/emulators is provided below.

Network Simulator -3 (NS-3) is a discrete-event network simulator. Conceptually, the simulator keeps track of a number of events that are scheduled to execute at a specified simulation time. The job of the simulator is to execute the events in sequential time order. Once the completion of an event occurs, the simulator will move to the next event (or will exit if there are no more events in the event queue) [8]. The NS-3 simulator was developed from scratch addressing the shortcomings of ns-2, which included scalability, outdated code design, and difficulties in using the simulator. The components required when simulating vehicular communication scenario include the definition of nodes and mobility features (i.e., vehicles, RSUs, Traffic Lights, etc.), network devices (e.g., WiFi, WAVE, LTE), network routing (IPV4/6, Broadcast, routing protocols), and ITS applications. NS-3 contains propagation loss models (e.g., ITUR1411, LogDistance, etc.), and propagation delay models (i.e., constant speed or random) that enables the simulation of real-world vehicle communication scenarios [9]. The NS-3 network simulator is a free open-source tool and is written in C++. The NS-3 simulator can be used to simulate large-scale wireless communication networks through techniques such as parallel programming and distributed topologies [10].

OMNET++ is an extensible, modular, component-based C++ simulation library and framework which also includes an integrated development and a graphical runtime environment. Domain-specific functionality (support for simulation of communication networks, queuing networks, performance evaluation, etc.) is provided by model frameworks, developed as independent projects [11]. OMNeT++ provides a generic component architecture that allows users to map concepts such as network devices, protocols or the wireless channel into model components. Components (modules) are programmed in C++, then assembled into larger components and models using a high-level language [12]. The main components of OMNET++ are Simulation kernel library (C++); The NED topology description language; Simulation IDE based on the Eclipse platform; Interactive simulation runtime GUI (Qtenv); Command-line interface for simulation execution (Cmdenv); Utilities (makefile creation tool, etc.). OMNET++ uses signal propagation loss models ranging from simple models like Free Space Path Loss to more complex ones like Rician and Rayleigh fading to model signal propagation features of wireless networks. In addition, the Constant Speed Propagation model is used to model signal propagation delays. OMNET++ is a free open-sourced tool written in C++ and can be used to model large-scale wireless communication networks through parallel batch processing to reduce simulation times [13].

Colosseum is an open-access and publicly available large-scale wireless testbed for experimental research via virtualized and softwarized waveforms and protocol stacks on a fully programmable, “white-box” platform. Through 256 state-of-the-art software-defined radios and a massive channel emulator core, Colosseum can model virtually any scenario, enabling the design, development and testing of solutions at scale in a variety of deployments and channel conditions [14]. Colosseum is regarded as the world’s largest wireless network emulator with hardware in-the-loop—as a platform that is for the first time available to the research community. With its 256 SDRs and 128 remotely-accessible compute nodes and GPUs, Colosseum provides the capabilities to test full-protocol stack solutions at scale with real hardware devices and in emulated—yet realistic—environments with complex channel interactions (e.g., path loss, fading, multipath). Currently, Colosseum can support scenarios in areas of size 1 km by 1km with omnidirectional transmissions. Efforts are underway to extend capability to support areas of size 100 km by 100 km [15].

Qualnet is a network simulation tool that enables the evaluation of on-the-move communication networks by mimicking the behavior of a physical communications network. It uses a network digital twin to digitally represent the entire network, the various protocol layers, radios, antennas, and devices. QualNet employs state of the art Parallel Discrete Event Simulation (PDES) algorithms designed to leverage multi-core and parallel processors to dramatically increase the event processing rate and hence simulation execution speeds to run high-fidelity simulations of large networks at faster than real-time speeds [16]. QualNet is a commercial version of GloMoSim that runs on all common platforms (Linux, Windows, Solaris, OS X) and is specialized in simulating all kind of wireless applications..It is ultra high-fidelity network simulation software that predicts wireless, wired and mixed-platform network and networking device performance [17].

1.5 Purpose

The purpose of this white paper is to examine the various methodologies and approaches for modeling wireless communications in a traffic simulator. It investigates the state of practice and research, highlighting the different simulation frameworks and tools available for modeling wireless communication systems in traffic simulators. Ultimately, this white paper seeks to equip the FHWA with a comprehensive overview of the existing approaches for modeling wireless communication in traffic simulators, identify gaps and needs, and suggest future trends to potentially inform FHWA’s research and development planning activities in the modeling of wireless communication in traffic simulators.

1.6 Scope of Document

Although there are three key types of traffic simulation models as described in the “Traffic Simulation Models” section, this white paper focuses only on modeling wireless communications in microscopic traffic simulation models. Subsequent use of “traffic simulation” or “traffic simulation models” in this white paper refers specifically to microscopic traffic simulation models. In terms of wireless communication protocols, this white paper seeks to understand how different protocols are modeled in traffic simulations. Hence, a broad number of wireless communication protocols applicable to transportation are covered. Finally, information presented in this white paper on the modeling of wireless communication in traffic simulations is not limited by the size of study area. Literature regarding all sizes of study areas (i.e., singular routes, corridors, or grid network) are considered for review.

1.7 Report Organization

The remainder of this white paper is organized as follows:

- Chapter 2 presents a summary of the literature review of existing methodologies and approaches to modeling wireless communications in traffic simulation models.
- Chapter 3 presents the key challenges and research gaps in modeling wireless communications in traffic simulations models.
- Chapter 4 summarizes the conclusions, including responses to the key questions and project recommendations to address research and development needs.

2 Literature Review

This chapter presents an overview of the methodologies and approaches used in the modeling of wireless communication in traffic simulation models obtained through the review of publicly available literature. The initial approach was to search for literature that directly dealt with the subject matter. However, this yielded little to no results. Subsequently, a new approach that focused on searching for literature on simulating connected vehicles (CVs) and Connected Automated Vehicles (CAVs) applications was employed. Since CVs and CAVs rely on wireless connectivity, information on how wireless communications is modeled in traffic simulation models was obtained.

In all, three key approaches for modeling wireless communications in traffic simulations were identified. These include:

- Modeling efforts that modify driver behavior parameters to simulate impacts of information exchanged through wireless communication channels.
- Modeling efforts that integrate traffic simulators and wireless network simulators.
- Hardware-in-the-Loop simulation efforts.

In the following sections, sample research has been presented for illustrative purposes, recognizing that this literature review is by no means an exhaustive representation of the body of literature in this field.

2.1 Modeling Efforts that Modify Driver Behavior Parameters

This section presents a summary review of a modeling approach that does not explicitly model wireless communications in traffic simulations. Instead, assumptions are made with regards to impacts of information exchanged through wireless communication on driver behavior. The driver behavior is expected to change because of the assumption that information will be delivered to vehicles at a specific time and place (i.e., no randomness) or under predefined set of travel conditions (i.e., random process based on probabilities). Consequently, driver behavior parameters (e.g., acceleration/deceleration rates, driver reaction times, gaps, etc.) are modified based on these assumptions to estimate overall impacts on a transportation network. The key strength of this approach is that it is very simple and can be used for high level order of magnitude planning analysis. However, simulation model results from this approach may not be accurate due to inaccurate driver behavior assumptions and the assumption of perfect wireless communication (i.e., no dropped messages, no message transmission delays, etc.). The studies identified can be divided into two distinct approaches based on how the driver behavior parameters are modified: (i) Simple adjustment of driver behavior parameters and (ii)

Developing new driver behavior models. Brief descriptions of each approach are presented below.

2.1.1 Simple Adjustment of Driver Behavior Parameters

In this approach, simple adjustment of driver behavior is done to simulate wireless communication. This approach was illustrated in [18, 19, 20, 21, 22]. Chiara et al, 2008 [18] studied the impact of inter-vehicle communication systems on road safety through a simplified model that evaluates the potential reduction in crash risk with improved driver response time. The study proposed a risk index (RI) method to assess the effectiveness of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication in enhancing road safety. The Gipp's car-following model within AIMSUN, is adopted to evaluate maximum following vehicle speeds in acceleration and deceleration scenarios, using dynamic rules to establish a risk index (RI) based on a simplified crash situation where a collision occurs if the time needed for the following vehicle to stop is greater than or equal to its time to reach the leading vehicle. The car-following model was implemented in MS Excel with Visual Basic code. A leading vehicle's deceleration triggers an emergency broadcast of a warning message (i.e. a stopped vehicle ahead) to nearby vehicles and infrastructure, allowing following vehicles to react synchronously and directly to the leading vehicle's action, ensuring timely response. It was expected that the introduction of V2V and V2I communication systems would reduce driver perception and reaction time, leading to a reduction in the total time required for following vehicles to come to a stop. Subsequently, driver response times were reduced for the scenario where V2V and V2I were active. Simulation (consisting of 5 vehicles) results demonstrated that the use of V2V and V2I systems consistently leads to an RI of less than 1, indicating a reduced risk of longitudinal collisions.

2.1.2 Development of New Driver Behavior Models

In this approach, new driver behavior models were developed based on assumed benefits of wireless communications and field data. Authors in [23, 24, 25, 26] adopted this approach in modeling wireless communication in traffic simulation. For example, Songchitruksa et al 2016 [23] proposed a framework for incorporating realistic driver behaviors into a microscopic traffic simulation for AV/CV applications using VISSIM. To demonstrate the framework, the authors conducted a case study of a simulation evaluation of cooperative adaptive cruise control (CACC). The simulated network scenarios consisted of traffic volumes ranging from 2500 to 4000 vehicles per hour. As part of the framework, a new car-following model which was based on a previous model validated by field data such as vehicular speed, acceleration, deceleration, headways, and clearance was developed. This model basically has two modes: speed control mode and gap control mode. Speed control mode is activated when the car is in free flow, and there is no leader, or the leader is more than 120 m from the ego vehicle. This mode is to address situations when ego vehicles have no immediate leader. In this mode, the objective of the ego vehicle is to reach its desired speed. The second mode is gap control mode. This mode is activated when the distance between the ego vehicle and the leader is less than 100 m. This gap control mode is activated in close following situations, and in this mode, the ego vehicle takes into account the spacing between it and the lead vehicle and their relative speed to take control decisions. Researchers assigned the CACC-equipped vehicles (which formed platoons of up to a maximum of 10 vehicles) a desired time gap based on a random number generated from a normal distribution with a mean of 2 seconds and a standard deviation of 0.4 seconds. The deceleration limit of the original mode (−2 m/s2) was replaced with a lower limit (−3.4 m/s2), so the CACC-equipped vehicles were able to handle sudden stop conditions. In addition, a new lane change model was developed for CACC-equipped vehicles with main purpose of promoting platoon formation.

To join a platoon, a CACC-equipped vehicle has to follow another CACC-equipped vehicle for at least 10 s. The followers in a platoon are assigned a desired time gap from a distribution and once in a platooning state, following vehicles must receive the leader's data (i.e., location, speed, acceleration, etc.) wirelessly to continue in a platoon. The wireless reception is through the Nakagami probabilistic distribution. Wireless data reception was considered poor when the transmission power (which is measured as the maximum distance to which the data can be transmitted) was low and considered high/good when the transmission power was high. A full wireless signal propagation was not modeled. The case study shows that new driver behavior models based on wireless connectivity field deployment data can be successfully used in simulations to evaluate the benefits of AV/CV applications such as CACC with respect to their mobility, safety, and environmental performance.

The FHWA with partner institutions developed customized functions for CV and weather features using VISSIM. A Wyoming case study evaluated three CV-enabled weather-responsive management strategies (WRMS), including traveler information messages (TIM), CV-based variable speed limits (VSL), and snowplow pre-positioning along the 402-mile I–80 corridor through the southern part of the State. The evaluation was done using a framework consisting of a VISSIM Network module, a simulation Manager module, and an application programming interface (API) module that determines driver behavior under the CV application scenarios. The API module is a program that determines driving behavior by customized programs for corresponding parameters in different CV applications. An external driver model is implemented through a dynamic linked library (DLL) interface. This substitutes the built-in Vissim driving behavior with a fully user-defined behavior for vehicles. The external driver model incorporated assumed benefits of wireless communication (e.g., increased situational awareness and driver response time) into its development. Vissim passes the current state of a vehicle and its surrounding traffic to the DLL, the DLL computes and determines the succeeding behavior of the vehicle as specified by an algorithm, and the DLL passes the updated state of the vehicle back to Vissim for the next simulation step. This feature allows the user to model (and test) various CV applications. For example, in modeling the CV-based VSL, driver behavior parameters such as speed distribution, look-ahead distances, and other behavioral parameters were varied to mimic the communication of dynamic real-time regulatory and advisory speed limits under three weather scenarios (normal, snowy, and severe). In addition, VISSIM's Wiedemann 99 model parameters were calibrated [27].

2.2 Modeling Efforts that Integrate Traffic and Wireless Network Simulators

This section presents summary review of an integrated modeling approach that couples both traffic and network simulators to run concurrently in real-time and facilitates exchange of information between the two simulators. The key strength of this approach is that wireless communication of messages is not assumed to be perfect. Consequently, wireless communication protocols are explicitly modeled to account for issues such as packet loss, interference, signal attenuation, etc. Due to the integration of traffic and wireless network simulations, this approach is relatively complex and requires more computing resources. The studies identified can be divided into three distinct approaches based on how the co-simulation is set up: (i) Traffic simulator API is used to develop wireless communication model, (ii) Traffic simulator and communications network simulator coupled using an interface/conversion tool, and (iii) Traffic simulator with built-in network simulator. Brief description of each approach is presented below.

2.2.1 Traffic Simulator API for Wireless Connectivity Model Development

In this approach, the API capabilities of traffic simulation tools are used to develop wireless connectivity or communications model to facilitate exchange of messages or data. This enables V2X and CAV applications to be modeled and evaluated. In 2021, Rahka et al. [28] developed a dynamic and integrated traffic and direct cellular V2X modeling tool on a large scale. They achieved this by integrating an analytical C-V2X model into the INTEGRATION traffic microsimulation model in real-time, creating a comprehensive dynamic connected vehicle modeling tool. The integrated model consisted of four components: a vehicle position database, the C-V2X communication standard, a communication operator, and a communication application. For the vehicle position database, traffic simulators track vehicle positions over fixed time intervals throughout the simulation. To facilitate the communication application's identification of candidate vehicles within range for V2V pairing, actual distances between vehicles on the road network were considered. A grid cell approach was used to build a spatial index, optimizing range queries and update operations. The integrated traffic simulator enabled the use of different communication messages/applications such as the Basic Safety Messages, left-turn assist, intersection movement assist. The Packet Delivery Ratio (PDR) was computed based on these positions to determine packet reception or dropping. This PDR calculation recurred every 100 ms, generating a random number for comparison. Packets were received if the random number was less than or equal to PDR; otherwise, they were dropped. Simulating a total traffic demand of 145,000 vehicles with a peak of 30,000 concurrent vehicles, the model was tested across different demand levels and 100% CV penetration rates. The model operated faster than real-time on a regular Windows operating system personal computer, producing spatiotemporal PDR estimates. The strength of this approach is that it enables the large-scale testing of Direct C-V2X enabled applications. However, using analytical models to abstract communication systems is not as accurate as network simulators.

Mei Bing et al. [29] integrated AIMSUN, a traffic network simulation tool, with a Python module for wireless communication simulation. Their study assessed the impact of vehicle-to-vehicle wireless communication on vehicle dynamics in response to an incident in a small network. The focus was on control strategies such as dynamic route diversion (DRD) and variable speed limits (VSL). The simulated vehicles were assumed to be equipped with an onboard equipment that enables them to identify the vehicles' locations, collect operations data of the vehicles, and communicate with other similarly equipped vehicles. The onboard equipment also receives en-route traffic information (e.g., incidents), which is used to update their travel plans. The Python module which interacts with the Aimsun simulator gathers data from equipped vehicles via the API. This data includes both static vehicle information (ID, type) and dynamic operational information (collection time, position, speed). Data collection occurs at a 1-second interval and is then analyzed by the onboard equipment at specific intervals to identify typical traffic conditions. The onboard equipment collects multiple sequential instant speeds on a given road segment, which are subsequently averaged for comparison with the typical speed, providing a more stable measure of vehicle operations. If the average instant speed falls below a predefined threshold, indicating atypical condition, an alarm message is triggered, incorporating vehicle details, condition time and location, experienced typical speed, message age, and path alignment. These messages are sent promptly through the ad hoc wireless network. Using an all direction single-hop broadcasting, equipped vehicles within the transmission range (250m) of the host equipped vehicle receive the message and assess whether an identical copy already resides in their message box. If not, they accept and store the message; otherwise, they reject it. Using a small portion of a street network, a total of about 1900 trips were modeled and simulated. Results showed that a significant portion of equipped vehicles responded positively to control strategies, with around 20-25% considering route diversion and about 21% adjusting speed for VSL-only scenario. Combining VSL with DRD reduced speed adjustments to 12% due to some drivers opting for diversion over speed adjustments, suggesting that the model effectively responds to a range of control strategies.

VISSIM offers an interface for modeling Connected and Autonomous Vehicle (CAV) behavior. The COM Application Programming Interface (API) grants access to VISSIM data, enabling adjustments in driving behaviors and vehicle movements. It supports various programming languages and allows both reading and writing of specific simulation parameters. For instance, while parameters like acceleration and headway are only readable, desired speed and desired lane parameters are both readable and writable. However, the COM API doesn't provide direct control over CAV lateral movements; it only allows lane changes managed by VISSIM. The COM API: offers improved scalability and flexibility over the internal modeling capability in VISSIM. Developers can design functions in COM that enable CAVs to receive information from the infrastructure or other CAVs based on specific conditions, such as vehicles within a designated radius. Nonetheless, the COM API cannot directly control longitudinal and lateral movement; it offers limited options for adjusting behavioral parameters in VISSIM. This doesn't allow for accurate and realistic presentation of acceleration. Thus, unless a trajectory considers realistic acceleration, its advised that the use of COM API be used cautiously [27].

2.2.2 Co-Simulation of Traffic and Network Simulators Using an Interface/Conversion Tool

In this approach, two separate traffic and communications network simulators are integrated through an interface/conversion tool to enable concurrent simulation of both the transportation network and communication protocols [30, 31, 32]. Petrov et al, 2021 [30], developed a framework which couples VISSIM traffic simulation and OMNeT++ communication networks simulation in real time, enabling an assessment of the relationship between a communication reliability and transport service quality. The framework has two interfaces in VISSIM and OMNeT++ exchanging data via a shared folder. VISSIM's interface updates entity parameters based on previous OMNeT++ communication status, conducts traffic simulation modules, and compiles VISSIM entities' attributes. After each simulating step updated parameters are computed. VISSIM generates a file of these entities and updated attributes. On the other hand, the OMNeT++ interface consists of three modules: VissimMobilityManager, responsible for managing OMNeT++ nodes' positions and synchronization with VISSIM; VissimMobility, updating node positions and visual representation; and Communication Network ReliabilityEvaluator, collecting communication statistics. The generated output file with VISSIM entity IDs and positions, is used by the VissimMobilityManager to synchronize with OMNeT++. OMNeT++ nodes are managed by Active VISSIM Entities (AVE) and Active OMNeT++ Nodes (AON) vectors. AVE initializes with VISSIM entity IDs, creating OMNeT++ objects. AON entries not in AVE are removed, and positions are updated. OMNeT++ then simulates data transmissions and logs parameters. VissimMobilityManager creates a file with VISSIM entity communication status, pausing OMNeT++ until a new input file is created for the next simulation period. To illustrate the functionality and practicality of the framework, a demonstration scenario was set up, where a dense network of connected vehicles (CVs) transmits messages (including speed, location and planned route to the intersection) to a Roadside Unit (RSU). This was achieved through simulating a four-leg intersection governed by an adaptive traffic control algorithm that utilizes data from the connected vehicles received by the RSU. The likelihood of communication errors increases as the distance between CVs and RSUs grows due to electromagnetic interference and signal attenuation, and even at shorter ranges, there's a possibility of errors arising from co-channel interference.

Similarly, Liu et al [33] integrated SUMO and NS-3 to develop vehicular Ad Hoc Networks to demonstrate the ability of the wireless protocol to send data packets at crossroads (intersections) and in congested traffic scenarios. The data packets contained information such as vehicle’s coordinate, vehicle’s speed, route ID, origin and destination. The simulation framework was developed by establishing a feedback loop between the SUMO traffic simulator and the NS-3 network simulator. This loop is achieved through TCP protocol communication, with NS3 controlling SUMO's time frame and requesting vehicle positions from SUMO every millisecond. The interaction is enabled by, a Traffic Control Interface (TraCI), and facilitated by a TraciClient that connects NS3 and SUMO. The TraciClient manages communication between the two platforms, ensuring synchronized time and consistent object positioning. The framework uses a simplified data transfer system, synchronizes simulation time, and optimizes data exchange by requesting attributes incrementally. To validate the feasibility of the co-simulation of

SUMO and NS3, a network consisting of 120 vehicles was modeled. After simulation, NS-3 instructs SUMO to change vehicle routes. The result showed that most vehicles could receive data packets with a packets reception rate of approximately 97.5%.

The FHWA is currently developing an integrated tool under the CARMA everything-in-the-loop (XiL) project which leverages the developed cooperative driving automation (CDA) simulation framework to establish a comprehensive CDA simulation environment. Specifically, it focuses on realizing software-in-the-loop (SIL) simulation through the integration of an AV simulator and a traffic simulator. The system comprises core components including tools from the FHWA-developed CARMA suite, integrated with MOSAIC, SUMO, Cars Learning to Act (CARLA) and NS-3. The project aims to construct the co-simulation platform, integrating CARLA and SUMO, linking CARMA Platform with CARLA to enable sensor and interaction simulations among CARMA-equipped virtual vehicles, and embedding the NS-3 communication simulator with DSRC and cellular vehicle-to-everything (C-V2X) capabilities. Subsequently, the significant CARMA Streets component will be assimilated into the platform, introducing previously unavailable co-simulation capabilities. Once completed and validated, this cost-effective co-simulation tool will be made publicly accessible to support CDA algorithm and application development, evaluation, and adaptation, enabling CARMA Platform utilization for CDA research [34]. The framework is shown in Figure 1.

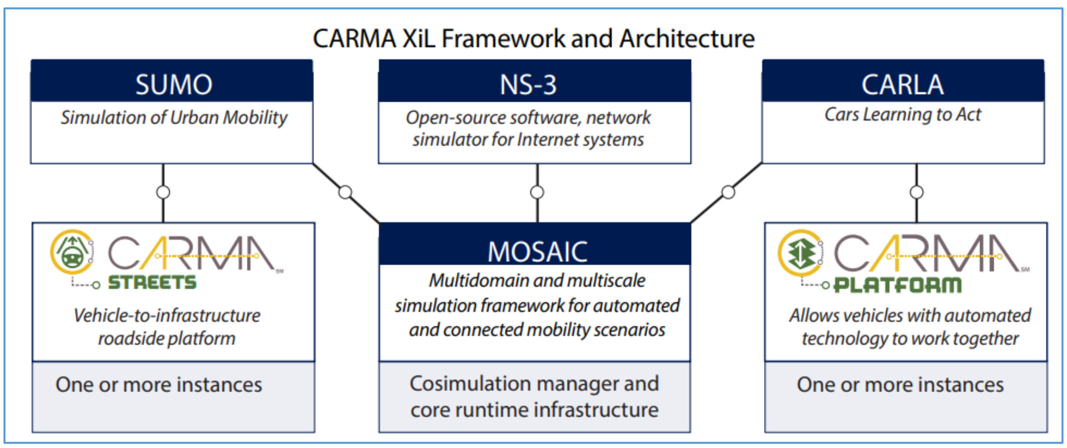

Figure 1: CARMA XiL Components (Source: FHWA)

2.2.3 Traffic Simulator with Built-In Network Simulator

Aimsun Next V2X Software Development Kit (SDK) included in Aimsun Next 22 and later versions facilitates the simulation and analysis of Vehicle-to-Everything (V2X) communications, including Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) interactions. It provides a framework for creating and studying various aspects of connected vehicle systems in a simulated environment. To model V2X communication in using the V2X SDK in Aimsun, the analyst begins by creating the essential components of the V2X system which include defining the message type that vehicles and roadside units (RSU) will exchange, and the specifying the communication protocols used for transmitting messages, such as IEEE 802.11p or LTE.

Parameters like latency, range, and packet loss are configured. The onboard units (OBU) are then configured by linking them to specific vehicle types and determining their connections to channels and message types. Additionally, RSUs are configured by defining their locations, communication channels, and the message types they use. If needed, a Traffic Management Center (TMC) that aggregates information from RSUs and controls the traffic network based on the received data is defined. The simulation scenarios are then set-up by defining traffic and communication parameters, including traffic flows, vehicle actions, and communication interactions. These parameters can be fine-tuned by adjusting vehicle, environment, and vehicle-infrastructure interaction settings. Various metrics including response time, collision avoidance, congestion reduction, and overall system performance etc. are then obtained after simulation runs [35].

2.3 Hardware in the Loop Simulation Efforts

In Ma et al, 2018 [36] the authors showcased the utilization of hardware-in-the-loop (HIL) testing techniques to assess connected and automated vehicle (CAV) applications, focusing on vehicle-to-infrastructure (V2I) scenarios. The HIL testing setup included the integration of several software and hardware elements, including a real-time controllable physical CAV, a traffic signal controller, V2I communication devices, and the VISSIM traffic simulator. The communication protocol employed was DSRC. The developed HIL system was employed to evaluate a CAV Queue warning application that examines CAV interactions with traffic signals and other vehicles at intersections. The algorithm of the queue warning systems generates recommended speed profiles based on the vehicle's status, signal phase and timing (SPaT), downstream queue length, and system constraints and parameters (e.g., maximum acceleration and deceleration). The results showed a reduction in fuel consumption when employing the queue warning application system, though it did not delve into wireless communication performance measures like latency. Similar approach was adopted in [37, 38, 39].

2.4 Key Findings

This section documents the key findings based on the review of existing literature on modeling wireless communications in traffic simulations.

- **DSRC and Cellular V2X wireless communication protocols were the most modeled protocols among the literature reviewed**. Although, some of the literature reviewed did not specify which wireless communication protocol was being modeled, DSRC and Cellular V2X were the most modeled protocols among the remaining literature.
- **Accuracy of wireless communication models (e.g., signal propagation and interference models) were not reported in the literature**. Unlike in traffic simulations where transportation network calibration results are reported, wireless communication models developed and simulated in all the literature reviewed did not provide any information on how these models truly represent real-world conditions.

- **The number of vehicles modeled appears to decrease as the complexity of wireless communication models increase**. In simulations where wireless communication is not explicitly modeled, or the chosen model is overly simplified the number of modeled vehicles appear to be high compared to when more sophisticated communication models that account for a lot of factors are used. For example, in simulations where APIs were used to develop simple communication models, as high as 30,000 vehicles were modeled. In contrast, when a traffic simulator was coupled with a communications network simulator, only 120 vehicles were simulated. This appears consistent as the most comprehensive network emulator, Colosseum, can simulate only 256 equipped vehicle radios [40].
- **Limited computing resources can hinder realistic modeling of wireless communications in traffic simulation models**. Realistic modeling of wireless communications in traffic simulations requires adequate computing resources to ensure that all the models truly represent real-world conditions. However, this may introduce computational limitation issues. To mitigate this, most of the reviewed research efforts implemented simulation runtime optimization techniques such as skipping portions of the simulation that has no useful data to the applications being simulated.
- **Incorporation of wireless communication model has been tested in wide variety of AMS tools**. Per literature reviewed, wide range of AMS tools have been used to conduct research on wireless communications modeling. These range from analytical tools that were built from the scratch to more popular microscopic traffic simulation tools such as Vissim, AIMSUN, SUMO and Paramics.
- **Research efforts that adjusted driver behavior parameters or developed new parameters assumed perfect and reliable wireless communications**. As a result, wireless communication issues such as data loss, drops in connectivity, signal interference, and others were not accounted for.
- **Most research efforts did not account for mobile obstacles such as moving vehicles in their signal propagation models**. Most of the signal propagation models adequately accounted for static objects such as buildings but failed to account for interference from other moving vehicles in the traffic stream, especially during dense vehicle traffic.
- **Most of the research efforts reviewed were not conducted by or on behalf of state and local transportation agencies**. Instead, most of the reviewed literature on modeling wireless communications in traffic simulations were conducted by universities and research institutions.

2.5 Trends in Modeling Wireless Communications in Traffic Simulators

Per the literature reviewed, the following trends in modeling wireless communications in traffic simulations were identified.

- **Relatively old research efforts targeted simple adjustment of driver behavior model parameters**. On the contrary, most recent literature focuses on coupling traffic and network simulators for concurrent simulation and real-time exchange of data.

- **Relatively old research efforts focused on incorporating DSRC into traffic simulation models**. In contrast, most recent literature rather focuses on how to model Cellular V2X technologies such as 5G in traffic simulators.
- **Traditional microsimulation tools are beginning to incorporate wireless communication modeling as a built-in capability.** AIMSUN's V2X software development kit enables the simulation of V2X communications network to accurately reproduce the transmission of every packet of data, to model the channel contention, the data encapsulation in routing and connection protocols, and to model the electromagnetic effects of the urban landscape on transmission. If the default V2X communication model does not satisfy the communication protocol being modeled, then the design of the V2X SDK allows the default V2X components to be substituted with user supplied components and API code written to provide the capability required for the study.

2.6 Comparison of different modeling approaches

The literature review assessed three approaches for modeling wireless communications in traffic simulators. The following section synthesizes the strengths and weaknesses of each approach for comparison.

Incorporating assumed impacts of wireless communication in driver behavior models

Strengths:

- Models that simply modify driver behavior based on assumed impacts of wireless communication are easy to build and simulate.
- Can be used for high level order of magnitude planning analysis.
- Some driver behavior models leverage equipped vehicle field data and provide a means to assess transportation impacts of wireless communication.
- Extensive computing resources are not required.

Weaknesses:

- Simulation results from models that simply adjust driver behavior parameters may not be accurate due to inaccurate assumptions of the impacts of wireless communication on driver behavior.
- Models that simply modify driver behavior parameters as well as models that leverage equipped vehicle field data do not explicitly wireless communication and its associated challenges (e.g., packet loss, interference, multipath effects, etc.).
- The accuracy of models that are built using equipped vehicle field data are limited to the specific real-world scenarios that generated the field data.

Integrating traffic simulators and wireless network simulators

Strengths:

- Integrating a traffic simulator with a network simulator allows for a more realistic modeling of wireless communication.
- Explicitly modeling wireless communications enables the determination of the feasibility and limits of effectiveness of CV/CAV applications.
- Simulation modeling results based on this approach are likely to be more accurate than simply adjusting driver behavior parameters.

Weaknesses:

- Coupled simulation tend to be computationally intensive, especially when dealing with many vehicles and complex wireless network models.
- Integrating two separate simulation tools can be technically challenging and may require additional software coding skills and training.
- Calibration results of the wireless communication models is often not reported per literature reviewed.

Hardware-in-the-Loop

Strengths:

- HIL simulation allows for the realistic interaction between physical hardware components (such as vehicles) and the wireless communication system. This enables a more accurate representation of real-world scenarios.
- Simulation results from this approach are likely to be more accurate compared to other approaches that simply modify driving behavior parameters.

Weaknesses:

- HIL simulators may be limited in terms of scalability.
- The complexity and cost of setting up a large-scale simulation with numerous vehicles and wireless devices can be challenging.
- Integrating various components (traffic simulators, hardware, control systems) in a HIL setup can be technically complex.

3 Key Challenges and Research Gaps in Modeling Wireless Communications

This chapter summarizes the key challenges and research gaps in the modeling of wireless communications in traffic simulations, based on the review and synthesis of existing publicly available literature. A challenge as used in this document refers to the difficulties encountered when modeling wireless communications in traffic simulations. In contrast, a gap is a topic or area of interest which hasn't been well studied and will require further research to understand and gain insights.

3.1 Key Challenges

The following issues were identified as key challenges in modeling wireless communications in traffic simulations.

- **Cost and computational requirements limits the level of detail when modeling wireless communications in traffic simulations**. Wireless communications modeling involves several individual models such as signal propagation models, network models, interference models, and others. Therefore, a realistic model of a vehicular communications environment can be very slow. Even with position updates and message generation frequency set to low values (1s both) and using moderately powerful simulation computer, the run of 2400 simulation seconds can take up to one day of the CPU time, i.e. 24 hours, to finish [30]. Hence, there is a need for techniques to optimize simulation run time.
- **Building/Running an interface/conversion tool between traffic and communication network simulators requires considerable amount of time and expertise**. To couple traffic and network simulators, there is a need for a conduit through which the two simulators can exchange data. In an offline environment (i.e., one of the simulators is running a time) conversion tools are used to convert vehicle positions obtained via traffic simulators to trace files that are usable by the wireless network simulator. In this scenario, the information exchange is unidirectional (i.e., from traffic simulator to network simulator). Examples of conversion tools include TraceExporter, MObility model generation for VEhicular networks (MOVE), and TraNSlite. In online coupling (i.e., both traffic and network simulators running at the same time), traffic and network simulators are combined with the help of an interface tool interlinking them in a bi-directional way. This ensures that information is exchanged in both directions in real-time. Examples of interface tools include Traffic Control Interface (TraCI), Traffic and Network Simulation (TraNS), Vehicle in network simulation (Veins) [41]. Using these conversion and interface tools requires training and specialized skills. In instances where already existing conversion/interface tools don't work for a particular combination of traffic and network simulators, new conversion/interface tools would have to be built.

- **Lack of field data to calibrate signal propagation and interference models for different wireless communication protocols**. Accurate wireless communication models relies on realistic representation of the network environment, including how signal is propagated and the level of interference experienced. Modeling signal propagation and interference for different wireless protocols (e.g., DSRC, 5G, LTE, etc.) requires accurate and adequate field data to build and test these models. Such data may not be readily available to most stakeholders. Consequently, resulting signal propagation models built with limited data may not adequately represent the real-world.
- **Lack of trained and skill personnel to develop and incorporate wireless communications into traffic simulations limits adoption by agencies**. Modeling wireless communications in traffic simulations requires additional skillsets and training. Whether a communications model is being built using a traffic simulator's API or traffic simulators and network simulators are being coupled, the technical and computing skills required may not be readily available in many transportation agencies. This may be a hinderance to widespread adoption of traffic management and safety applications enabled by wireless communications.

3.2 Research Gaps

Per the literature review, the following research gaps on modeling wireless communications were identified.

- **There are no benchmarks or standards on the accuracy of wireless communication models**. Almost every literature reviewed talks about the development and incorporation of a realistic wireless communication models (i.e., signal propagation models, network models, interference models, and others) in their integrated traffic-network communication simulations. However, there is no means of deducing whether the presented models truly represent real-world conditions. Hence, there is a need for common benchmarks to evaluate the accuracies of these models. Such benchmarks will improve the confidence of transportation stakeholders in improvement estimates generated by these simulation models.
- **Realistic modeling of mobile obstacles in signal propagation models is lacking**. Signal propagation models that aim to realistically model the complex environment surrounding the communicating vehicles, must account for both static objects (e.g., buildings, overpasses, hills), as well as mobile objects (other vehicles on the road) [42]. Per the literature reviewed, most network simulators have models to account for static obstacles. On the contrary, mobile obstacles such as vehicles on the road are sometimes not accounted for in the signal propagation models used in traffic simulations. This may lead to inaccurate simulation results. Hence, there is a need to always account for mobile obstacles in signal propagation models, even in less dense traffic conditions.
- **There is lack of information on how to simulate handoff between different wireless data transmission protocols and its resulting impacts on the transportation network**. In a heterogeneous network environment, there are plethora of wireless communication protocols including DSRC, WiFi, LTE, 5G, and others. There is a need to understand the how vehicles or onboard applications equipped with multiple wireless communication

protocols can switch between these protocols depending on what protocol is available and how the handoffs between them may affect wireless-based traffic management and safety applications. For example, in a Forward Collision Warning scenario, the lead vehicle is equipped with both DSRC and LTE while the following vehicle is equipped with only LTE communication protocol. If the lead vehicle stops abruptly, it would have to send a forward collision warning to the following vehicle through LTE by switching from DSRC to LTE communication protocol (i.e., assuming it was initially transmitting information through DSRC) to avoid a rear-end crash. There is a need to understand how these types of handoffs impact the mobility and safety of a transportation network.

- **There is lack of information on the effectiveness of hybrid wireless communication environment**. The different wireless communication protocols such as DSRC, 5G, LTE, satellite and others have their strengths and weaknesses. In a hybrid environment where two or more different wireless communication protocols are integrated for one or more applications, they will complement each other and minimize some of the individual weaknesses such as limited range, latency, and others. There is a need to research the feasibility of a hybrid wireless communication environment and its impact on traffic management and safety applications and the overall transportation network.
- **There is general lack of guidance on how to model wireless communications in traffic simulation models**. Per the literature reviewed, researchers are devising creative ways to incorporate wireless communication models in traffic simulators to help assess effectiveness of wireless-based traffic management and safety applications. However, it was noted that most of these efforts are led by universities and research institutions. There was little to no information about state and local transportation agencies championing the modeling of wireless communication in traffic simulations. This may be due to lack of guidance on how to carry out such tasks. Hence, there is a need for guidance on how to model wireless communications in traffic simulations.

4 Conclusions and Future Research

This chapter summarizes findings of the literature review conducted on modeling wireless communication in traffic simulations and identifies research needs on this topic. The findings presented here are direct responses to the key questions introduced in Chapter 1. In addition, potential projects to address identified needs are also presented.

4.1 Responses to Key Questions

Per literature review conducted, below are the responses to the key questions that this effort sought to answer.

How are wireless communications currently modeled in traffic simulators?

Modeling wireless communications in traffic simulators has evolved from assuming ubiquitous and perfect transmission of messages to drivers/vehicles) to integrating traffic and communications network simulators through appropriate interfaces/conversion tools to simulate impacts of wireless-based V2X/CAV applications. In an offline environment (i.e., one of the simulators is running a time), conversion tools are used to convert vehicle positions obtained via traffic simulators to trace files that are usable by the wireless network simulator. In this scenario, the information exchange is unidirectional (i.e., from traffic simulator to network simulator). Examples of conversion tools include TraceExporter, MObility model generation for VEhicular networks (MOVE), and TraNSlite. In online coupling (i.e., both traffic and network simulators running at the same time), traffic and network simulators are combined with the help of an interface tool interlinking them in a bi-directional way. This ensures that information is exchanged in both directions in real-time. Examples of interface tools include Traffic Control Interface (TraCI), Traffic and Network Simulation (TraNS), Vehicle in network simulation (Veins) [40]. In some research efforts, the APIs of traffic simulators are used to develop wireless communication models that enables V2V and V2I/I2V interactions. Finally, some traffic simulators have built-in network simulators to facilitate V2V and V2I/I2V interactions. In such traffic simulators, network parameters like latency, range, and packet loss can be specified and tested.

What are the key characteristics or operational constraints of wireless communications and how are they modeled in traffic simulators?

The key characteristics of wireless communications mostly mentioned in the literature review includes signal propagation effects, obstacles, line of sight issues, density of nodes, signal attenuation (i.e., loss of signal strength), packet loss (i.e., transmitted data packets fail to reach receiver), multipath effects (i.e., signal being emitted from a transmitter is directed to the receiver through multiple paths, leading to signal deterioration), interference, refraction (i.e., signal passing through a medium with a different density, causing direction of signal to change), reflection (i.e., signal bounces back to transmitter), diffraction (i.e., the bending and spreading around of a signal when it encounters an obstruction), and range (i.e., longest distance from transmitter to receiver while maintaining sufficient signal strength) . Per the literature reviewed, these characteristics are accounted for in the signal propagation and wireless communication models. However, the reviewed literature does not provide detailed description of how these models are built and calibrated.

What are the key challenges and gaps in modeling wireless communications in traffic simulators?

The challenges and gaps in modeling wireless communications in traffic simulations identified through the literature review are presented in Chapter 4.

What is the best approach for modeling wireless communications in traffic simulators?

While there is no best approach mentioned in the literature reviewed, coupling traffic and communication network simulators appears to be the most used approach for modeling wireless communications in traffic simulations. This includes (i) integrating individual traffic and communication network simulators (e.g., VISSIM and OMNeT++); (ii) using traffic simulator API to develop a wireless communication model; and (iii) using traffic simulators that have built-in network simulators.

What are the research and development needs on modeling wireless communications in traffic simulators?

The research and development needs on modeling wireless communications in traffic simulations are presented in the next section.

4.2 Future Research and Development Needs

To increase confidence in simulation model outputs to assess the impacts of wireless technology-based traffic management applications, there is a need for realistic modeling of the wireless communication component. Currently, there are no benchmarks or standards on the accuracy of wireless communication models. As a result, there may be numerous communication models used in traffic simulations that do not have realistic and technically acceptable assumptions. Hence, there is a need for common benchmarks and standards to evaluate the accuracies of communication models used in traffic simulation models.

One key characteristic of wireless communication modeling that needs to be carefully considered is how to realistically account for the impacts of mobile obstacles during signal propagation. Signal propagation models that aim to realistically model the complex environment surrounding the communicating vehicles, must account for both static objects (e.g., buildings, overpasses, hills), as well as mobile objects (other vehicles on the road). While most network simulators have models to account for static obstacles, mobile obstacles such as vehicles on the road are sometimes not accounted for in signal propagation models used in traffic simulations. This may lead to inaccurate simulation results. Hence, there is a need to research how to account for mobile obstacles in signal propagation models, even in less dense traffic conditions.

Vehicles equipped with wireless communication capabilities may not be restricted to using only a single communication protocol. There is the possibility of a single equipped vehicle having the capability to use multiple communication protocols (e.g., DSRC, WiFi, LTE, 5G, and others) depending on a variety of factors. There is a need to understand how vehicles or onboard applications equipped with multiple wireless communication protocols can switch between these protocols depending on what protocol is available and how the handoffs between them may affect wireless-based traffic management and safety applications. This will provide insights on the interoperability between these wireless communication protocols and how the handoffs between them may affect wireless-based traffic management and safety applications. In addition to investigating handoff between different wireless communication protocols, it is also important to research how different protocols can be integrated for use in single traffic management and safety applications to complement each other and minimize some of the individual weaknesses such as limited range, latency, and others.

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