Final Report

Quantifying the Impact of Cellular Vehicle-to-everything (C-V2X) on Transportation System Efficiency, Energy and Environment

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16. Abstract

As communication technology develops at a rapid pace, connected vehicles (CVs) can potentially enhance vehicle safety while reducing energy consumption and emissions via data sharing. Many researchers have attempted to quantify the impacts of such CV applications and cellular vehicle-to-everything (C-V2X) communication. Highly efficient information interchange in a CV environment can provide timely data to enhance the transportation system's capacity, and it can support applications that improve vehicle safety and minimize negative impacts on the environment. This study summarizes existing literature on the safety, mobility, and environmental impacts of CV applications; gaps in current CV research; and recommended directions for future CV research. The study investigates a C-V2X eco-routing application that considers the performance of the C-V2X communication technology (mainly packet loss). The performance of the C-V2X communication is dependent on the vehicular traffic density, which is affected by traffic mobility patterns and vehicle routing strategies. As a case study of C-V2X applications, we developed an energy-efficient dynamic routing application using C-V2X Vehicle-to-Infrastructure (V2I) communication technology. Specifically, we developed a Connected Energy-Efficient Dynamic Routing (C-EEDR) application and used it in an integrated vehicular traffic and communication simulator (INTEGRATION). The results demonstrate that the C-EEDR application achieves fuel savings of up to 16.6% and 14.7% in the IDEAL and C-V2X communication cases, respectively, for a peak hour demand on the downtown Los Angeles network considering a 50% level of market penetration of connected vehicles.

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Abstract

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1. Introduction

The American transportation system is growing rapidly, with 276 million registered vehicles, of 4.17 million miles of highways, and 3.23 trillion vehicle miles traveled (VMT) [1]. Because of the large number of vehicles and traffic delays, this gigantic system operates with a significant impact on the environment and traffic safety. According to *Forbes*, every American lost nearly 99 hours in 2019, or an average of $1,377 per person, due to traffic crashes [2].

In addition, at least 38,800 people were killed in motor vehicle collisions [3]. The majority of these crashes were caused by human errors, such as distraction, driver inexperience, drowsiness, or speeding, all of which may be mostly avoided if warnings could be provided to drivers ahead of time. A report released by INRIX found that the economic impact of traffic congestion is both broad and complicated. Congestion cost New York $11 billion dollars, Los Angeles $8.2 billion dollars, and Chicago $7.6 billion dollars in 2019[4]. Safety and efficiency are not the only concerns regarding the traffic system; environmental impact has also become a major issue with the recognition that climate change is caused by human activity. The U.S. Environmental Protection Agency (EPA) published the Inventory of U.S. Greenhouse Gas Emissions and Sinks in April 2021. This annual report summarizes the latest information on U.S. greenhouse gas emission trends from 1990 through 2019 [5]. The report identified the primary sources of greenhouse gas emissions in the U.S. and demonstrated that the transportation sector generated the largest share of greenhouse gas emissions at 29%. The report also mentions that petroleum-based transportation fuel, including gasoline and diesel, is responsible for over 90% of the total transportation sector's fuel consumption. Total transportation emissions increased from 1990 to 2019 due to increased travel demand. In particular, the total vehicle miles traveled (VMT) in the U.S. increased by 48% during that period of time due to population growth, economic growth, urban sprawl, and periods of low fuel prices [6]. The EPA recommends reducing transportation-related emissions by switching to alternative fuel sources; improving fuel efficiency with advanced design, materials, and technologies; improving operating practices; and reducing travel demands.

Connected vehicle (CV) technology enables equipped vehicles to connect with other vehicles, roadway infrastructure, pedestrians, bicycle riders, and other devices through advanced wireless communication to reduce vehicle emissions and improve roadway safety, travel efficiency, and energy efficiency. Not only can CV applications increase throughput and mobility, they may also reduce vehicle crashes by preventing human errors. We expect that CV technology will significantly increase the mobility and safety of the transportation system and reduce greenhouse gas emissions by using advanced technologies and improving transportation operational practices.

Vehicle-to-everything (V2X) technology represents communication between a vehicle and any object that can communicate with the CV. The seven types of vehicle connectivity [7] include vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), vehicle-to-network (V2N), vehicle-to-cloud (V2C), vehicle-to-pedestrian (V2P), vehicle-to-device (V2D), and vehicle-to-grid (V2G). Collectively these are known as V2X. V2I is a communication protocol that bi-directionally communicates information between the vehicle and the road infrastructure. V2V enables equipped vehicles to exchange real-time data with other equipped vehicles. V2N allows vehicles to communicate with the network, including the V2X management system. V2C enables equipped vehicles to offer bi-directional data exchange with the cloud, including digital assistants and the Internet of Things. V2P includes communication with road users, including pedestrians, people using wheelchairs, people riding bicycles, and people using other mobility devices. V2D allows equipped vehicles to exchange information with any smart device such as smartphones, tablets, and other wearable devices. V2G involves communication with the smart electric grid. It should be noted that even though V2X technology includes these seven types of connectivity, most studies have focused on CV applications that are based on V2I and V2V communication.

The goal of the study is (1) to synthesize the literature on the overall impacts of cellular V2X (C-V2X) enabled applications on the transportation system's energy consumption, efficiency, and safety and (2) to assess the environmental effects of a wide deployment of a C-V2X-enabled dynamic routing application using an integrated vehicular traffic and communication simulator (INTEGRATION).

This effort's contributions are as follows: (1) while several studies investigated the benefits of C-V2X enabled applications, these studies focused on individual applications. This is the first effort to systematically summarize the potential efficiency, energy, environmental, and safety benefits of various C-V2X enabled applications and compare their performance. (2) The study identifies shortcomings in current CV research and recommends directions for further research. (3) We developed a fully integrated traffic and C-V2X modeling framework application and used this modeling framework to quantify the system-wide efficiency, energy, and environmental impacts. The developed framework allows us to study and model such complex and challenging systems by capturing the mutual interactions between the communication and transportation systems.

2. Review of Vehicle-to-Everything Enabled Applications

2.1 Overview

There are several studies that have reviewed C-V2X applications. However, none of these studies systematically reviewed and compared the impacts of these C-V2X applications in terms of safety, environment, and mobility. The novelty of this study is that it systematically investigates C-V2X application benefits at the network, freeway, non-signalized, and signalized arterial levels, with and without considering the communication system constraints. Previous C-V2X studies focused on the benefits of single applications without comparing various connected automated vehicle (CAV) applications and test environments.

The potential C-V2X benefits can vary based on the application type, study design, vehicle type, test location or network type, utilized energy/emission model, and market penetration rates (MPRs) of CVs. The conclusions drawn by these previous studies confirmed that, through efficient information exchange between vehicles, infrastructures, networks, devices, and other participating elements, the transportation system can operate more efficiently and with reduced emissions. CVs and C-V2X enabled applications, by providing driving directions, speed advice, and acceleration or deceleration suggestions, can help reduce delays, increase vehicle throughput, reduce greenhouse gas emissions, and improve fuel and energy efficiency, while simultaneously achieving a notable decrease in vehicle crashes. Such benefits can be significant when the MPR of CVs reaches a certain level. Furthermore, not only do CVs benefit from V2X communications, but other non-connected vehicles also benefit from the CVs' improved efficiency, safety, and decreased emissions because the transportation system has more redundancy for non-connected vehicles when CVs use the system more safely and efficiently. Figure 1 provides a graphical illustration of the C-V2X concepts.

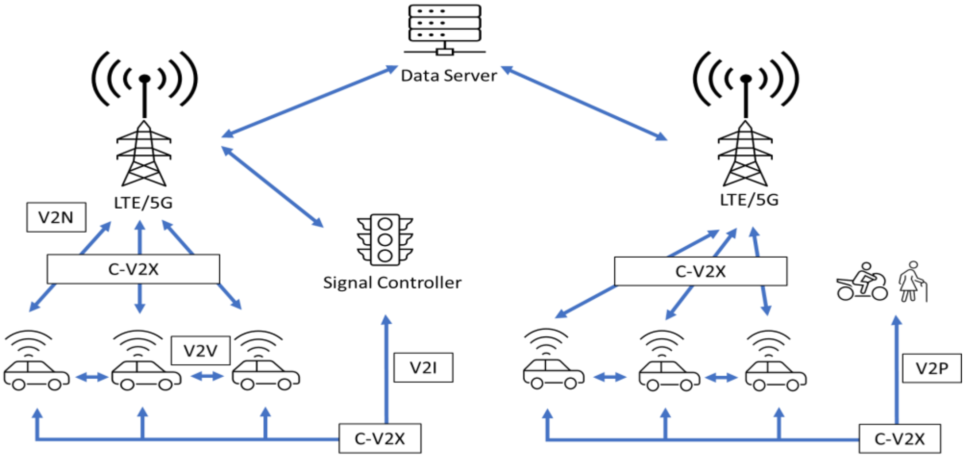

Figure 1. Graphical illustration of C-V2X.

The study categorized previous CV studies into three areas: 1) applications ignoring communication system constraints; 2) applications modeling the mutual dependencies of the transportation and communication systems; and 3) applications considering communication system constraints. In the first category, researchers concentrated on modeling CV application benefits and impacts with the assumption that communication between vehicles and infrastructures is essentially perfect and free of any delays or errors. In addition, researchers assumed the drivers of the CVs fully followed the guidance or suggestions provided by the CV applications. The benefits of CVs typically were maximized in this category of studies. Some of the previous studies evaluated different MPRs for CVs and the interaction of CVs and traditional vehicles. The modeling methodology in this category requires further development to accommodate compound effects generated by imperfections in the communication system. The second category includes research efforts that integrate transportation and communication system modeling in the evaluation of CV applications to account for communication system constraints. There were very few studies available in this category. Because both components of C-V2X—the wireless communication in a big data environment and the technology of connected vehicles—are still in the rapid development stage, researchers have yet to focus on the resulting interaction between these two building blocks. Instead, existing studies mostly concentrate on one of the two fields. Most researchers in this category used traditional communication simulators with implementation support for the dedicated short-range communications (DSRC) and long-term evolution (LTE) C-V2X communication protocols. Although these simulators facilitate performance evaluation for new communication technologies, they lack support for large-scale traffic simulations. Recent work has emphasized the need to provide analytical models for the DSRC and LTE C-V2X communication models to facilitate the simulation of large-scale traffic scenarios and applications. The third category includes research that evaluated applications while considering the communication system constraints. The limited communication bandwidth causes congestion in transmitting signals and data in the CV system, especially during peak demand periods when there are overwhelming data that require transmission. Therefore, the third area focuses on previous studies that accounted for communication system constraints when evaluating the impacts of CV applications.

2.2 Application Evaluations Ignoring Communication System Constraints

Most of the extant literature on CV applications does not consider the communication system constraints on system performance. Specifically, these studies assume that the data related to vehicle locations, vehicle kinematics, infrastructure status, traffic controls, and travelers of all the modes in the transportation network can be transmitted to each agent in the system instantaneously with no loss or delay in data packets. We found that most C-V2X studies tested CV applications in a specific environment. For example, some applications were only tested on uninterrupted freeway sections, while other studies tested their applications only at signalized and/or non-signalized intersections; also, some studies evaluated C-V2X applications for an entire network or at the city level. In this study, we placed C-V2X literature into four categories: network-level applications, freeway applications, signal-free intersection applications, and signalized corridor applications, as described in the following sections. We utilized these categories to compare the benefits of similar C-V2X applications in each category.

2.2.1 Network Applications

This section summarizes the various efforts reported in the literature quantifying the network-wide impacts of CV applications. As summarized in Table 1, we found a limited number of studies focusing on network-wide impacts of CV applications. All studies entailed evaluating these applications in a virtual traffic simulation environment given that actual field implementations are cost prohibitive.

Ahn et al. [8] developed and evaluated an Eco-Cooperative Automated Control (Eco-CAC) system with the purpose of integrating vehicle control strategies with CAV applications. The authors tested their system on a large-scale network in downtown Los Angeles, CA. Testing involved a combination of hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), and internal combustion engine vehicles (ICEVs) in a microscopic traffic simulation environment. The study also examined three different demand (congestion) levels: none, mild, and heavy. Included in the Eco-CAC system were an eco-router; an Eco-

Cooperative Adaptive Cruise Control at Intersections (Eco-CACC-I) controller, also known as green light optimized speed advisory (GLOSA); a speed harmonization (SPD-HARM) controller; and an Eco-Cooperative Adaptive Cruise Control on Uninterrupted flow facilities (Eco-CACC-U) controller, also known as vehicle string control or platooning. According to study findings, the Eco-CAC system reduced fuel consumption by as much as 16.8%, CO2 emissions by up to 16.8%, travel time by up to 21.7%, energy consumption by up to 36.9%, stopped delay by up to 68.7%, and total delay by up to 43.1%. Results also indicated different benefits generated according to vehicle type. For instance, in heavily congested conditions, the Eco-CAC system reduced fuel consumption, total delay, travel time, stopped delay, and CO2 emissions for ICEVs. The benefits of the controllers mostly increased as the CAV MPR increased, although the controllers had a negative effect on ICEV fuel consumption, total delay, stopped delay, travel time, and CO2 emissions for mild or no congestion. For BEVs, the Eco-CAC system improved energy consumption but negatively affected total delay, stopped delays, and travel time for all congestion levels. In addition, the authors tested the Eco-CAC system according to current and projected vehicle composition on the Los Angeles network, with findings indicating effective reductions in fuel and energy consumption, total delay, stopped delay, and travel time for both current and future compositions in heavily congested conditions. Conversely, the study noted different results for different vehicle compositions. Specifically, the authors observed the highest BEV energy consumption savings for the current vehicle composition (36.9%) at a 10% CAV MPR in mild congestion, whereas they observed the highest savings for the future vehicle composition (35.5%) at a 50% CAV MPR with no congestion. Results indicated the developed Eco-CAC system was effective in reducing fuel and energy consumption, total delay, stopped delay, travel time, and CO2 emissions for BEVs, ICEVs, and HEVs for specific scenarios. Additionally, the Eco-CAC systems and controllers' effectiveness depends on traffic conditions, including congestion level, CAV MPR, network configuration, and vehicle composition.

The Netherlands Organization for Applied Science (TNO) investigated various CV use cases. The study reviewed available literature on the environmental impact of CV use cases and the study performed simulation studies using a microscopic emission calculation tool (EnViVer) to quantify the potential environmental impacts of CV applications. EnViVer was developed using the VISSIM traffic microsimulation software and VERSIT+, a vehicle emission simulation tool. The identified mechanisms that were taken into consideration include reduction of trips; reduction and departure time shift; mode shift, reduction of vehicle dynamics, and the powertrain operation. The results showed that an eco-driving technique that reduces vehicle stops is very beneficial, generating a CO2 reduction in the range of 13–45%. An eco-driving technique that reduces deceleration and acceleration shows benefits as well (3–7% improvement). The study found that cooperative adaptive cruise control (CACC) reduces vehicle emissions by 6% compared to ACC [9].

Olia et al. studied the potential impacts of CV applications using PARAMICS. The simulation testbed was a network in northern Toronto. The simulation results showed that CVs were able to navigate through multiple routing options and therefore could save up to 58% in travel time at an MPR of 50% on certain corridors. As for improving safety, the study found that increasing the MPR of CVs can improve the safety index (the probability of incidents) by up to 45%. The Comprehensive Modal Emission Model (CMEM) was used to estimate emission factors. A reduction of 30% in CO2 emissions was identified [10].

In a study by Vahidi et al., the authors reviewed the energy saving potential of CAVs based on first principles of motion and optimal control theory. The study found that connectivity to other vehicles and infrastructure allows better anticipation of upcoming events, such as hills, curves, slow traffic, state of traffic signals, and movement of neighboring vehicles. The review paper concluded that automation allows vehicles to adjust their motion more precisely in anticipation of upcoming events to save energy, and that cooperative driving can further increase a group of vehicles' energy efficiency by allowing them to move in a coordinated manner. The study concluded that CAVs' energy efficient movement could have a harmonizing effect on mixed traffic, leading to additional energy savings for neighboring vehicles [11].

A study by Rahman et al. investigated the safety impact of CVs and lower-level automation (CVLLA) using simulations. Two features of CVLLA were tested: automated braking and lane keeping assistance.

Segment and intersection crash risks were estimated using surrogate safety assessment modeling techniques. The results showed that both CV and CVLLA technology significantly reduced conflict frequency. Higher MPRs of CVs generate higher benefits, where the maximum improvement was found to be at 100% MPR. However, at least 40% MPR is needed to achieve the safety benefits of reduced intersection crash risks and 30% is needed for reduced segment crash risks [12].

Ahn et al. developed a multi-objective eco-routing algorithm (eco- and travel time-optimum routing) for BEVs and ICEVs in a CV environment and investigated the network-wide impacts of the multi-objective Nash optimum (user equilibrium) traffic assignment on a large-scale network. Unlike ICEVs, BEVs are more energy efficient on low-speed arterial trips compared to highway trips. The authors demonstrated that different energy consumption patterns require different eco-routing strategies for ICEVs and BEVs. This study found that single objective eco-routing could significantly reduce BEVs' energy consumption but also significantly increased their average travel time and thus the authors developed a multi-objective routing model (eco- and travel time-routing) to improve both energy and travel time measures. The simulation study found that multi-objective routing could reduce BEVs' energy consumption by 13.5%, 14.2%, 12.9%, and 10.7%, as well as ICEVs' fuel consumption by 0.1%, 4.3%, 3.4%, and 10.6% for "not congested, "slightly congested," "moderately congested," and "highly congested" conditions, respectively. The study also found that multi-objective user equilibrium routing reduced the average vehicle travel time by up to 10.1% compared to the standard user equilibrium traffic assignment for highly congested conditions, producing a solution closer to the system optimum traffic assignment. The study concluded that the multi-objective eco-routing strategy can reduce vehicle fuel/energy consumption effectively with minimum impacts on travel times for both BEVs and ICEVs [13].

In a study conducted by Abdelghaffar et al., a dynamic freeway speed controller based on sliding mode theory was developed and tested. The advantages of the sliding mode control are its simple design, global stability, and robustness that can address the discontinuity of the fundamental diagram due to the capacity drop. SPD-HARM controller was developed in their study to dynamically identify bottlenecks and regulate the speeds of CVs. A decentralized phase split/cycle length controller was used to optimize all traffic signals in the network. The results showed that average travel time was reduced by 12%, total delay was reduced by 21%, and CO2 emissions were reduced by 3.3%. In addition, the authors' results showed that freeways benefit from the controller more than arterials [14].

In summary, we found that the benefits of CV applications were highly dependent on the application type, network settings, MPRs, and test algorithms. There were a limited number of studies focusing on the benefits at a network/system level. More studies concentrated on either freeway only or signalized intersection corridors only.

Table 1. V2X-enabled network applications.

Year, Title	Leading Author, Institute	CV Application	Road type	Topic area	Estimated Benefits	Simulation/ Field Test	Modeling Environment
2021, Evaluating an Eco-Cooperative Automated Control System (Eco-CAC)	Ahn, K – VTTI	Various – Eco-routing, SPD-HARM, Eco-approach and departure, Platooning	Network	Mobility, Environment	Reduced fuel consumption by up to 16.8%, BEV energy consumption by up to 36.9%, travel time by up to 21.7%, total delay by up to 43.1%, stopped delay by up to 68.7%, and CO_2 emissions by up to 16.8%.	Simulation	INTEGRATION, VT-CPFM, VT-CPEM
2020, Environmental Benefits of C-V2X	TNO	Various – CACC, Eco-driving, Intelligent intersection	Arterial and Freeway	Environment	CO_2 reduction in the range of 13-45%.	Simulation	EnViVer (VISSIM and VERSIT+)
2016, Assessing the Potential Impacts of Connected Vehicles: Mobility, Environmental, and Safety Perspectives	Olia, A – McMaster University	Routing and safety	Network	Mobility, Safety, Environment	Reduced travel time by 37%, reduced emissions by 30% and improved safety indicators by 45%.	Simulation	Paramics, CMEM
2018, Energy saving potentials of connected and automated vehicles	Vahidi, A – Clemson	Review paper – Various	Network	Environment	This study summaries the benefits of coordinated and smoother motion of CAVs, in terms of car following, lane changing, and intersection control on energy savings and environment impacts. The authors concluded that from previous literatures, the savings on energy can range from 3% to 20% on varied facilities.	N/A	N/A
2019, Safety benefits of arterials' crash risk under connected and automated vehicles	Rahman, MS – University of Central Florida	Automated braking and lane keeping assistance	Arterial	Safety	Travel time saving between 59% to 84%.	Simulation	VISSM
2021, Multi-objective Eco-Routing Model Development and Evaluation for Battery Electric Vehicles	Ahn, K – VTTI	Eco-Routing	Network	Energy	The multi-objective routing reduced BEV energy consumption up to 14.2% and ICEV fuel consumption up to 10.6%.	Simulation	INTEGRATION, VT-CPFM, VT-CPEM
2020, Development of a Connected Vehicle Dynamic Freeway Variable Speed Controller	Abdelghaffar, H – VTTI	SPD-HARM	Network	Mobility, Environment	12.17% reduction in travel time, 20.67% reduction in total delay, 2.6% fuel consumption saving, CO_2 emission savings of 3.3%	Simulation	INTEGRATION, VT-CPFM

2.2.2 Freeway Applications

Numerous studies have investigated and quantified the impacts of CV-enabled applications on freeway sections, as summarized in Table 2. Some of these studies concentrated on car-following and lane-changing behavior using a basic multi-lane freeway segment without any other complex roadway configurations. Some concentrated on merging or diverging traffic on mainline freeways by analyzing freeway sections with on- and off-ramps. For example, in a study by Jang et al., the authors analyzed crash risks and estimated the safety benefits of the forward hazardous situation warning information presented by a Connected Intelligence Transport System (C-ITS) pre-deployment project for Korean freeways. C-ITS is composed of on-board units, roadside units (RSUs), and a traffic management center. The crash potential index (CPI) was adopted to quantify the crash benefits of CVs. A total of 700 CVs, including 400 buses, 264 trucks, and 36 sports utility vehicles, were instrumented with data acquisition systems and V2X communication devices. The study found that C-ITS reduced the average speed by 10.2% and increased the time-to-collision (TTC) by 5.3%, which significantly improves the safety benefits of the proposed system. In addition, the achievable reduction in the CPI was approximately 20.7% due to the provision of warning information [15].

To study the effectiveness and network communication efficiency of connected (V2V and V2I) vehicular technologies in alerting motorists when they are approaching a hazardous zone, such as using CV technology to recommend a proper speed for travelers going through a low visibility area, Outay et al. compared the performance of V2V and V2I communications in an extensive computer simulation experiment. The authors adapted the iTetris platform for various scenarios—a baseline scenario, a deactivated alert scenario, a V2V cooperative alert scenario, and a V2I alert scenario. The authors also explored, via simulations, whether Cooperative Hazard Awareness and Avoidance systems, based on V2V and V2I communications can potentially contribute towards eco-driving by reducing CO2 emissions. The results revealed that the alerting system based on V2I communication yields better message reception rates and better safety efficiency. The results also showed that the Cooperative Hazard Awareness and Avoidance system can reduce CO2 emissions using SPD-HARM [16].

To explore the impacts of CACC on vehicle fuel efficiency in mixed traffic, Liu et al. conducted analyses at a freeway merge bottleneck. Their results showed that CACC string operation resulted in a maximum of 20% reduction in energy consumption compared to the human driver only case. At a 100% MPR, CACC-equipped vehicles consumed 50% less fuel than ACC vehicles without V2V communication and cooperation. At lower CACC MPRs, the vehicle fuel efficiency could be improved via use of a dedicated CACC lane or by implementing wireless connectivity on the manually driven vehicles. In the case of a CACC MPR of 40%, those strategies brought about a 15% to 19% capacity increase without decreasing vehicle fuel efficiency. The authors' results imply the importance of incorporating the V2V cooperation component into an automated speed control system and highlight the necessity of deploying CACC-specific operation strategies at lower CACC MPRs [17].

A study by Li et al. used simulation coding in MATLAB to test the effectiveness of reducing rear-end collisions in an I2V system that integrated variable speed limit (VSL) and ACC. The results showed that both the surrogate crash risk measures—time exposed time to collision (TET) and time integrated time to collision TIT—were reduced. VSL-only and ACC-only methods had a positive impact in reducing the TET and TIT values (reduced by 53.0 and 58.6% and 59.0 and 65.3%, respectively). The I2V system combined the advantages of both ACC and VSL to achieve the most safety benefits (reduced by 71.5 and 77.3%, respectively) [18].

Table 2. V2X-enabled freeway applications.

Year, Title	Author, Leading institute	CV Application	Roadway Type	Comm. Type	Topic Area	Estimated Benefits	Simulation/ Field Test	Modeling Environment
2020, Identification of safety benefits by inter-vehicle crash risk analysis using connected vehicle systems data on Korean freeways	Jang, J. – Hanyang University	Forward hazardous situation warning system	Freeway	Dedicated Short Range Communications (DSRC) (1 Hz)	Safety	Reduction in the CPI was approximately 20.7 %; TTC increased by 5.3%	Field test	
2019, V2v and V2I communications for traffic safety and CO_2 emission reduction: A performance evaluation	Outay, F. – Zayed University, UAE	Hazardous zone detection and alert system	Freeway	DSRC	Safety, Environment	TTC improved slightly; CO_2 improved by 5%	Simulation	iTetris platform (SUMO)
2020, Freeway vehicle fuel efficiency improvement via cooperative adaptive cruise control	Liu, H. – UC Berkeley	CACC	Freeway	N/A	Mobility, Environment	A maximum of 20% reduction in energy consumption; Up to 49% of capacity increase	Simulation	NGSIM (VT-CPFM+MOVES)
2016, Reducing the risk of rear-end collisions with infrastructure-to-vehicle (I2V) integration of variable speed limit control and adaptive cruise control system	Li, Y. – Southeast University	Variable Speed Limit (VSL) and Adaptive Cruise Control (ACC)	Freeway	N/A	Safety	TET and TIT were reduced by 53% and 58.6% for VSL; 59% and 65.3% for ACC; 71.5% and 77.3% for combined VSL and ACC	Simulation	MATLAB
2018, Longitudinal safety evaluation of connected vehicles' platooning on expressways", Accident Analysis & Prevention	Rahman., M – University of Central Florida	Platooning	Freeway	DSRC of 300 m (1000 feet)	Safety	All five surrogate measures of safety (standard deviation of speed, time exposed time-to-collision TET, time integrated time-to-collision TTT, time exposed rear-end crash risk index, sideswipe crash risk) improved. Managed-lane CV outperformed all-lane CV platooning.	Simulation	VISSIM
2014, Improving traffic operations using real-time optimal lane selection with connected vehicle technology	Jin, Q. – University of California Riverside	Optimal Lane Selection (OLS)	Freeway	N/A	Safety, Environment	Travel time reduced 3.8%; fuel consumption reduced 2.2%; emissions reduced from 1% to 19% depending on the congestion level.	Simulation	SUMO
2016, How to assess the benefits of connected vehicles? A simulation framework for the design of cooperative traffic management strategies	Gueriau M. – Université de Lyon	Advanced Driver Assistance System (ADAS)	Freeway	N/A	Safety, Mobility	Speed decreased with an homogenization of speeds and headways	Simulation	A multi-agent framework embedded with MovSim
2013, Cooperative Highway Traffic Multiagent Modeling and Robustness Assessment of Local Perturbations	Monteil J. – Université de Lyon	Cooperative Car Following	Freeway	N/A	Mobility	With the cooperative traffic, aggressive lane-changing behavior is reduced, and the stability and homogenization of traffic is achieved.	Simulation	OVRV and MOBIL

Year, Title	Author, Leading institute	CV Application	Roadway Type	Comm. Type	Topic Area	Estimated Benefits	Simulation/ Field Test	Modeling Environment
2020, Mobility and energy consumption impacts of cooperative adaptive cruise control vehicle strings on freeway corridors	Liu, H.– UC Berkeley	Platooning	Freeway	N/A	Mobility, Environment	Average mpg of 27 was achieved when MPR is 50%; mobility increased 30% with MPR of 10%.	Simulation	MOVES and VT-CPFM models
2021, Energy and flow effects of optimal automated driving in mixed traffic: Vehicle-in-the-loop experimental results	Ard, T. – Clemson University	CV Car following control with MPC	Freeway	V2Sim	Mobility, Environment	Improvement of 30% in energy economy; increased travel time and headway.	Simulation	Automated driving virtual simulation with a physical vehicle (EGO)
2020, Model-free speed management for a heterogeneous platoon of connected ground vehicles	Weng, Y. – U of Michigan	Eco-CACC	Freeway	N/A	Mobility, Environment	Utility improvement over initial speed is 40% in mobility and 2.2% in fuel economy; utility improvement over desired speed is 18.4% in fuel economy but at the cost of 7.5% mobility.	Simulation	military trucks
2015, Efficient vehicle driving on multi-lane roads using model predictive control under a connected vehicle environment	Kamal, M.A.S. – Gunma University	Model Predictive Control (MPC)	Freeway	N/A	Mobility	6.79% increased velocity and 7.22% fuel economy.	Simulation	MATLAB
2017, Cooperative autonomous driving for traffic congestion avoidance through vehicle-to-vehicle communications	Wang, N. – Fujitsu Laboratories	Altruistic Cooperative Driving (ACD)	Freeway	N/A	Mobility	ACD achieves higher speed efficiency (up to 15%).	Simulation	Traffic simulator implemented in Java
2019, A mixed traffic speed harmonization model with connected autonomous vehicles	Ghiasi, A. – Univerisyt of South Florida	SPD-Harm	Freeway	N/A	Mobility, Environment	Varied benefits from different sensor settings. The savings on throughput, speed STD, fuel consumption, and surrogate safety measures can be up to 1.7%,6.5%,4%, and 17%.	Simulation	VT-Micro
2018, Modeling impacts of cooperative adaptive cruise control on mixed traffic flow in multi-lane freeway facilities	Liu, H. – UC Berkeley	CACC	Freeway	N/A	Mobility	Managed lane (ML) and (vehicle awareness device (VAD) is helpful at low and medium MPR, leading to a capacity improvement ranging from 8% to 23%.	Simulation	NGSIM (VT-CPFM+MOVES)
2021, A Cooperative Platooning Controller for Connected Vehicles	Bichiou, Y. – VTTI	Platooning	Freeway		Mobility, Environment	Travel time, delay, fuel consumption all dropped for connected automated vehicles (CAVs) and non-connected vehicles, with reduction up to 5%, 9.4%, and 8.17%.	Simulation	INTEGRATION

A study by Rahman and Abdel-Aty attempted to evaluate longitudinal safety of CV platoons by comparing the implementation of managed-lane and all-lane CV platoons (for the same MPR) to a non-CV scenario. A high-level control algorithm of CVs in a managed lane was proposed to form platoons with three joining strategies: rear join, front join, and cut-in join. Five surrogate safety measures—standard deviation of speed, TET, TIT, time exposed rear-end crash risk index, and sideswipe crash risk—were utilized as indicators for safety evaluation. The results showed that with CVs, the safety in the studied expressway significantly improved. Managed lane control produced better improvements compared to all-lane control for the same MPR [19].

Jin et al. used micro simulation to evaluate the mobility and environmental benefits of a CV application that involved a real-time optimal lane selection algorithm. On average, the travel time was reduced up to 3.8% and the fuel consumption was reduced by 2.2%. In addition, the reduction in emissions of criteria pollutants, such as CO, HC, NOx and PM2.5, ranged from 1% to 19%, depending on the different congestion levels of the roadway segment [20].

A study conducted by Guériau integrated multi-agent cooperative traffic modeling into the MovSim, a traffic simulator, to model complex interactions between cooperative vehicles and between vehicles and infrastructure. The authors discussed some potentialities of C-ITS for traffic management with the methodological issues following the expansion of such systems. The operational goal of this work was use simulators to develop and validate a decision-making tool tailored to cooperative strategies. The model involved three layers that couple different dynamics to consider information reliability while limiting traffic disturbances, and hence homogenize traffic flow. The results showed that at a 40% to 50% MPR, the proposed connected vehicle environment reduced congestions for the merging traffic from on ramps [21].

Monteil et al. constructed a multi-agent framework using knowledge from traffic theory. Their goal was to develop the modeling bricks of a cooperative auto-adaptive system. A three-layer framework with physical, communication, and trust layers was used to achieve traffic flow homogenization. By modeling trust as a function of distances along with a communication layer and a physical layer, the authors conducted simulations using two lanes of freeway traffic with an entrance flow distribution from US-101 sample data. The results showed that the operation could decrease the speed variance and therefore the likeliness that traffic would fall into local congestion phenomena. Vehicle cooperation can also limit the impact of aggressive drivers (who oppose a global gain in acceleration when making a lane change). An increasing MPR reduces the impact of aggressive lane-changing behaviors, as it increases the traffic stability and homogeneity[22].

A study conducted by Liu et al. examined the impact of CACC string operations on vehicle speed and fuel economy on a 13-mile section of the SR-99 corridor near Sacramento, CA. The authors used simulation to evaluate the performance of the corridor under various CACC MPR scenarios and traffic demand levels. The CACC string operation was also analyzed when a vehicle awareness device (VAD) and CACC managed lane strategies were implemented. The results revealed that the average vehicle speeds increased by 70% when the CACC MPR increased from 0% to 100%. The highest average fuel economy, expressed in miles per gallon (MPG), was achieved under the 50% CACC scenario with an MPG at 27. This was 10% higher than the baseline scenario. However, when the CACC MPR was 50% or higher, the vehicle fuel efficiency only had minor increases. When the CACC MPR reached 100%, the corridor allowed 30% more traffic to enter the network without experiencing reduced average speeds. Results also indicated that the VAD strategy increased the speed by 8% when the CACC MPR was 20% or 40%, while there was a minor decrease in the fuel economy. The managed lane strategy decreased the corridor performance when implemented alone [23].

A study conducted by Ard et al. demonstrated the effectiveness of an anticipative car-following algorithm in reducing energy use of gasoline engine and electric CAVs. Without sacrificing safety and traffic flow, the authors implemented a vehicle-in-the-loop testing environment. Experimental CAVs were driven on a track, interacting with surrounding virtual traffic in real-time. The authors explored the energy savings in microsimulations. Model predictive control handled high level velocity planning and benefited from communicated intentions of a preceding CAV or estimated probable motion of a preceding human driven vehicle. A combination of classical feedback control and data-driven nonlinear feedforward control of pedals achieved acceleration tracking at the low level. The controllers were implemented in a robot operating system and energy was measured via calibrated OBD-II readings. The authors reported energy savings of 30% [24].

A model-free approach was proposed by Weng et al. to incorporate the differences of varied vehicle types and combine the goal of fuel economy and mobility platooning. A utility function was formulated using the Nelder-Mead approach. This approach relies on the communication of instantaneous speed and fuel consumption between vehicles in the platoon with mixed vehicle types. The simulation and experimental results showed that this method was effective in increasing the objective function, with less fuel consumption and higher mobility. However, due to the data-driven nature, convergence required some time [25].

A study conducted by Kamal et al. constructed a model predictive control (MPC) framework to efficiently drive a vehicle on multi-lane roads by enhancing the vehicle's capability in lane change and speed adjustment. MPC uses present state information to predict future behavior through the explicit use of a process model. The results showed that the MPC generated optimal acceleration of the vehicle and the optimal timing to move to the next lane if long term performance gain was anticipated by predicting surrounding traffic [26].

Wang et al. proposed a strategy called Altruistic Cooperative Driving (ACD), where vehicles that are causing congestion should yield the right of way to other vehicles by slowing down or changing lanes. By defining the vehicle driving conditions into maximum, deadlock, and free-run, the strategy changes the deadlock situation into a free-run or maximum to improve overall efficiency. A simulator was generated using Java for a section of multi-lane road. The results showed that the ACD strategy achieved higher speed efficiency with up to 15% improvement and can perform cooperative driving to resolve deadlock conditions in a timely fashion [27].

A study by Ghiasi et al. designed a CAV-based trajectory-smoothing method to control CAVs upstream of a bottleneck to harmonize traffic, improve fuel-efficiency, and reduce environmental impacts. Four steps were adopted: information update, trajectory prediction, shooting heuristic, and damping control. The results showed that the proposed methodology smoothed CAV movements and harmonized the following human-driven vehicles. Improvements were achieved in throughput, speed variations, fuel consumption and surrogate safety measures [28].

Liu et al. conducted a study to model the impacts of CACC on mixed traffic flow on multi-lane freeway facilities. A modeling framework that adopts a new vehicle dispatching model to generate high-volume traffic flow was proposed. The framework also ensures realistic CACC vehicle behaviors. By incorporating new lane changing rules and automated speed control algorithms, the proposed modeling framework could further reproduce traffic flow dynamics under the influence of CACC operation strategies. Case studies on four-lane freeway segments with on- and off-ramps were illustrated, and the results indicated that their proposed modeling framework could improve system mobility for different MPRs. Specifically, at a 60% or lower MPR, managed lane and vehicle awareness devices were helpful and led to a capacity improvement ranging from 8% to 23%. At a 100% MPR, the freeway capacity was 90% higher than the base case [29].

Bichiou et al. proposed an input minimal platooning controller. This controller incorporates various dynamic and kinematic constraints, such as acceleration, velocity, and collision avoidance constraints. The authors tested the controller using a calibrated real network—freeways in downtown Los Angeles—in a simulation environment utilizing the INTEGRATION microscopic simulation software. The results showed that a significant reduction in system-wide travel time, delays, and fuel consumption was achievable. It was also observed that, although the controller only controlled vehicles in the platoon, all the vehicles in the network benefited from the controller [30].

In summary, CV-enabled applications in uninterrupted traffic flow typically regulate car following and lane changing behavior to minimize fuel consumption, maximize throughput, and improve surrogate crash measures, such as the standard deviation of speed, time to collision, etc. The results varied case by case depending on the different applications, congestion levels, and/or MPRs of CVs. In most cases, the percentage of CVs needed to be above a certain level to achieve significant results. The majority of the previous studies used simulation tools to evaluate the effectiveness of the applications, while field tests were rare due to the scarcity of equipped facilities as well as safety concerns.

2.2.3 Signal-free Intersection Applications

Dresner and Stone were the first to introduce the concept of signal-head-free intersection control [31]. In their approach they considered a first-in first-out intersection control mechanism. Mirheli et al. also designed a signal-head-free intersection control logic using a dynamic programming model. The authors used a stochastic look-ahead technique on a Monte Carlo tree search algorithm to determine the near-optimal actions over time to prevent conflicts. By doing so, the model developed by the authors maximized the intersection throughput. The simulation results showed that travel time was significantly reduced at intersections for different demand patterns. Depending on various demand patterns, the improvement ranged between 59% and 84%, compared to intersections controlled by fixed-time and fully-actuated traffic signals [32].

In a similar way, Zohdy et al. developed the intersection CACC system to regulate the flow of traffic proceeding through signal-head free intersections [33-35]. This work was then extended to optimize the flow of traffic proceeding through a roundabout [36]. Work by Elhenawy et al. investigated the use of game theory to optimize vehicle movements through the intersection [37]. Bichiou and Rakha developed a signal-head free offline controller in [38] and extended it to real-time vehicle trajectory optimization considering dynamic constraints to enhance the mobility of intersections. The results showed that the proposed algorithm outperformed other intersection control strategies by not only producing lower delay but also decreasing vehicle fuel consumption and CO2 emissions [39]. In summary, CACC and i-CACC are efficient in decreasing delays and fuel consumptions comparing to conventional signal controls, abandoning the concepts of intersection control by optimizing the scheduling and movement of vehicles traversing an intersection. Table 3 lists the studies for signal-free intersections. The existing studies were mainly conducted in a simulation environment.

Table 3. V2X-enabled signal-free arterial applications.

Year, Title	Author, Leading institute	CV Application	Road Type	Comm. type	Topic Area	Estimated Benefits	Simulation/ Field Test	Modeling Environment
2005, Multiagent Traffic Management: An Improved Intersection Control Mechanism	Dresner, K. – University of Texas, Austin		Arterial	N/A	Mobility	Average trip time for the proposed reservation system is always at the optimum level, comparing to stop sign, traffic signal-controlled intersections, as well as the overpass	Simulation	
2018, Development of a signal-head-free intersection control logic in a fully connected and autonomous vehicle environment	Mirheli, A. – State University of New York at Stony Brook		Arterial	N/A	Mobility	A signal-head-free intersection control logic was developed, and will completely avert incidents and significantly reduce travel time ranging between 59% and 84%.	Simulation	VISSIM
2012, Intersection management for autonomous vehicles using i-CACC	Zohdy, I. – VTTI	CACC, i-CACC	Arterial	N/A	Mobility and Environment	Savings in delay and fuel consumption in the range of 91% and 82% relative to conventional signal control were demonstrated, respectively.	Simulation	INTEGRATION
2012, Game theory algorithm for intersection-based cooperative adaptive cruise control (CACC) systems,	Zohdy, I. – VTTI	CACC	Arterial	N/A	Mobility	The proposed system reduces the total delay relative to a traditional stop control by 35 seconds on average, which corresponds to an approximately 70% reduction in the total delay.	Simulation	
2016, Intersection management via vehicle connectivity: The intersection cooperative adaptive cruise control system concept	Zohdy, I. – VTTI	CACC, i-CACC	Arterial	N/A	Mobility and Environment	Four types of intersection control methods were compared and the results show that the proposed i-CACC system significantly reduces the average intersection delay and fuel consumption level by 90% and 45%, respectively.	Simulation	INTEGRATION
2013, Enhancing Roundabout Operations via Vehicle Connectivity	Zohdy, I. – VTTI	CACC	Arterial	N/A	Mobility and Environment	The proposed system can reduce delay and fuel consumption up to 80% and 40%, respectively.	Simulation	

Year, Title	**Author, Leading institute**	**CV Application**	**Road Type**	**Comm. type**	**Topic Area**	**Estimated Benefits**	**Simulation/ Field Test**	**Modeling Environment**
2015, An intersection game-theory-based traffic control algorithm in a connected vehicle environment,	Elhenawy, M. – VTTI	CACC	Arterial	N/A	Mobility	The proposed algorithm demonstrated reduction in travel time and delay in the range of 49% to 89% compared to an all-way stop sign control.	Simulation	INTEGRATION
2018, Developing an Optimal Intersection Control System for Automated Connected Vehicles	Bichiou, Y. – VTTI	N/A	Arterial	N/A	Mobility and Environment	The model developed in this study optimized the movements of AVs subjected to dynamical constrains and static constrains. The results demonstrate that an 80% reduction in delay is achievable compared with the best of these three intersection control strategies (a roundabout, a stop sign, and a traffic signal-controlled intersection), on average. A 42.5% and 40%, reduction in vehicular fuel consumption and CO_2 emissions, respectively, were achieved as well.	Simulation	INTEGRATION
2019, Real-time optimal intersection control system for automated/cooperative vehicles	Bichiou, Y. – VTTI	N/A	Arterial	N/A	Mobility and Environment	The control system proposed is proved to be effective in achieving 55% reduction in delay compared to roundabout, four-way stop sign, or a traffic signal-controlled intersection. It also yielded a 43% reduction in fuel consumption and CO_2 emissions.	Simulation	INTEGRATION

2.2.4 Signalized Intersection Applications

Numerous studies have attempted to quantify the benefits of V2X enabled applications along signalized roadways as summarized in Table 4. Some of the previous studies tested V2X-enabled applications along arterials with one or more signalized intersections where there are traffic controls that force vehicles to decelerate, stop, and/or accelerate at the onset, during, or at the conclusion of a red indication. By using the data transmitted from other vehicles and infrastructures, the V2X-enabled applications can guide vehicles through intersections with minimum delays, emissions, and without colliding into other vehicles by sharing Signal Phasing and Timing (SPaT) data.

Early work on GLOSA or eco-driving in the vicinity of signalized intersections started with the work of Kamalanathsharma and Rakha [40-43]. The authors introduced a dynamic programming approach to deriving the fuel-optimum vehicle trajectory. Yang et al. extended this work by predicting the queue at the intersection approach [44] and considering multiple signalized intersections in deriving the optimum solution. By varying demand level, MPRs, phase splits and offsets, as well as the distances among the consecutive traffic signals, they concluded that a fuel consumption saving of 13.8% can be achieved given a 100% MPR. Combining higher MPRs with shorter phase lengths produced larger fuel savings. Demand levels, traffic signal offset, and traffic signal spacing all affect the results [45]. Later Almannaa et al. tested the controller in a controlled field environment. Three scenarios were tested: normal driving, driving with a speed advisory, and automated Eco-CACC. The field experiment tested four red indication offset values randomly delivered to drivers along uphill and downhill slopes, totaling 1,563 trips by 32 different participants. The results showed that the proposed Eco-CACC system can reduce fuel consumption significantly; achieving fuel savings of 31% and time savings of 9%. The results also demonstrated that automatic control yields more significant benefits than a human control scenario [46].

A GLOSA system was implemented in a study by Bradaï et al. This system coaches the driver to adapt their vehicle speeds such that the driver can safely proceed through upcoming traffic signals during a green indication. It reduces stop times and unnecessary accelerations in urban traffic situations, thereby saving fuel and reducing CO2 emissions. The results obtained show a significant reduction in CO2 emissions. However, the authors also stated that the results were obtained under specially designed circumstances where the trip length was only 1,500 meters and the experiment environment can be considered as a straight line with no other vehicles [47].

An eco-approach application was designed to provide drivers with recommendations to encourage “green” driving while approaching, passing through, and departing intersections in a study conducted by Xia et al. Both simulation experimentation and field operational testing were carried out to demonstrate the eco-approach application and to quantify its potential fuel and CO2 savings. The results showed that a communication platform based on a 4G/LTE C-V2X network link and cloud-based server infrastructure was effective for this kind of application. It was found that an average of 14% fuel and CO2 savings could be achieved in both the simulation experiment and the field operational testing[48].

A study by Wang et al. developed a cluster-wise cooperative eco-approach and departure (Coop-EAD) application for CAVs to reduce energy consumption and compared its performance to existing Ego-EAD applications. Instead of considering CAVs traveling through signalized intersections one at a time, the authors’ approach strategically coordinates CAVs' maneuvers to form clusters using various operating modes: initial vehicle clustering, intra-cluster sequence optimization, and cluster formation control. The novel Coop-EAD algorithm is applied to the cluster leader, and CAVs in the cluster follow the cluster leader to conduct EAD maneuvers. A preliminary simulation study for a given scenario showed that, compared to an Ego-EAD (speed and location) application, the proposed Coop-EAD application achieves an 11% reduction in energy consumption, up to an 18% reduction in emissions, and a 50% increase in traffic throughput, respectively [49].

In a study conducted by Moser et al., a CACC approach using stochastic linear model predictive control strategies was proposed. Both V2V and V2I communication were assumed to be present. The objective of this approach was to minimize the fuel consumption in a vehicle-following scenario. By means of a conditional Gaussian model, the probability distribution of the upcoming velocity of the preceding vehicle was estimated based on current measurements and upcoming traffic signal timings. The evaluation of the controllers showed a significant reduction in vehicle fuel consumption compared to the predecessor while increasing safety and driving comfortably [50].

A study conducted by Bento et al. designed a novel intersection traffic management system for CAVs. The developed intelligent traffic management (ITM) techniques proved to be successful in reducing the delays and emissions without colliding with each other. The data needed for the ITM system is supported by V2X communication where the vehicle position and speed are exchanged among vehicles and infrastructure. In addition to the savings in CO2 emissions and delays, the authors also found that the improvement is more significant when the traffic is heavier [51].

The study conducted by Wan et al. proposed a speed advisory system (SAS) for pre-timed traffic signals to minimize fuel consumption. They showed that the minimal fuel driving strategy alternates between periods of maximum acceleration, engine shut down, and sometimes constant speed. Instead of using this bang-singular-bang control, they employed a sub-optimal solution with significant improvements in fuel economy. The SAS-equipped vehicles not only improved their own fuel economy, but also benefited other conventional vehicles. A higher MPR generated more fuel savings. The cost in traffic flow and travel time was minimal [52].

A simulation-based case study implemented on a hypothetical four-way single-lane approach intersection under varying congestion conditions showed that the Cooperative Vehicle Intersection Control (CVIC) algorithm significantly improved intersection performance compared to conventional actuated intersection control, with a 99% and 33% reduction in stopped delay and total travel time, respectively. In addition, the CVIC algorithm significantly improved air quality and energy savings: 44% reduction of CO2 and 44% fuel consumption savings [53].

The study by Ho Chaudhuri et al. developed a fuel-efficient control strategy for a group of connected HEVs that considered the congested traffic signals that are common on urban roads. The higher-level controller developed an optimal velocity profile by minimizing the average tractive energy consumption and reducing red light idling. The lower-level controller tracks the velocity profile obtained from the higher-level controller by optimally splitting power between the vehicle engine and the battery using an adaptive equivalent consumption minimization strategy (ECMS). The simulation results showed that using the proposed method, no vehicle had to stop for red lights. ECMS can track the velocity supplied by the higher level controller perfectly and keeps the state of charge of the battery within 1.5% of the initial battery state of charge [54].

Liu et al. designed a cooperative signal control algorithm utilizing CACC datasets and data collected by traditional fixed traffic sensors. The control strategy proved to be effective with mixed traffic as well as 100% CACC traffic. The average vehicle speed and the average vehicle MPG increased by more than 10% and speed increased by 13% when the CACC MPR was 100%, while the speed increased by 36% and MPG improved by more than 34% when the CACC MPR was 40%. Even with a 0% CACC, the proposed method can generate benefits with speed and MPG improvements of 12.5% and 12.2%, respectively [55].

Table 4. V2X-enabled signalized intersection applications.

Year, Title	Author, Leading institute	CV Application	Road Type	Comm. type	Topic Area	Estimated Benefits	Simulation/ Field Test	Modeling Environment
2013, Fuel–Optimal Vehicle Throttle Control: Model Logic and Preliminary Testing	Kamalanathsharma, R. - VTTI	N/A	Arterial	N/A	Environment	The proposed variable throttle model provides significant fuel savings. Additional savings of 37% was observed when the Dijkstra minimum path algorithm was applied and savings of 14% was achieved when using an A-start minimum path finding algorithm.		
2013, Multi-stage dynamic programming algorithm for eco-speed control at traffic signalized intersections	Kamalanathsharma, R. – VTTI	Eco-CACC	Arterial	N/A	Environment	The model proposed by the authors can save fuel consumption by up to 30% in proximity of signalized intersections.	Simulation	INTEGRATION
2014, Leveraging Connected Vehicle Technology and Telematics to Enhance Fuel Efficiency in the Vicinity of Signalized Intersections	Kamalanathsharma, R. – VTTI	Eco-CACC	Arterial	N/A	Environment	The proposed trajectory optimization using a moving horizon dynamic programming approach was calibrated and tested on 30 top-sold vehicles and the results showed saving in fuel consumption ranging from 5% to 30%.	Simulation	
2012, Agent-based modeling of Eco-Cooperative Adaptive Cruise Control systems in the vicinity of intersections	Kamalanathsharma, R. – VTTI	Eco-CACC	Arterial	N/A	Environment	The model proposed by the authors can save fuel consumption by up to 30% in proximity of signalized intersections.	Simulation	INTEGRATION
2016, Eco-Cooperative Adaptive Cruise Control at Signalized Intersections Considering Queue Effects	Yang, H. – VTTI	Eco-CACC	Arterial	N/A	Environment	The results showed that a fuel savings of up to 40% can be achieved with a 10% MPR. Multiple lane approach requires a higher MPR compared to a single lane approach to generate significant results.	Simulation	INTEGRATION
2021, Eco-Driving at Signalized Intersections: A Multiple Signal Optimization Approach	Yang, H. – VTTI	Eco-CACC	Arterial	N/A	Environment	An eco-driving system that computes a fuel-optimized trajectory was proposed. Using SPaT data communicated from downstream, the eco–driving system can produce a reduction of 13.8% in fuel consumption with an MPR of 100%.	Simulation	INTEGRATION
2019, Field implementation and testing of an automated eco-cooperative adaptive cruise control system in the vicinity of signalized intersections.	Almannaa, M. – VTTI	Eco-CACC	Arterial	N/A	Mobility, Environment	Travel time was reduced by 9% (downhill 8.1%, uphill 9.9%) and fuel consumption by 31% (downhill saving 38.4% uphill saving 22.6%).	Simulation and Field Test	INTEGRATION

Year, Title	Author, Leading institute	CV Application	Road Type	Comm. type	Topic Area	Estimated Benefits	Simulation/ Field Test	Modeling Environment
2016, A Green Light Optimal Speed Advisor for Reduced CO 2 Emissions	B. Bradaï – Valeo, France	GLOSA	Arterial	DSRC – V2X	Environment	Cumulative CO_2 emissions for a 1500 m distance travel (max speed 50km/h or 70km/h) decreased by 13%	Field test	Detailed algorithm is not included
2012, Field operational testing of eco–approach technology at a fixed–time signalized intersection	Xia, H. – UC Riverside	Eco-approach and departure	Arterial	CV2X - LTE	Environment	An average of 14% fuel and CO_2 savings can be achieved both for simulation and the field test. Travel time decreased by 0.96%.	Field test, Simulation	Paramics
2018, Cluster-wise cooperative eco-approach and departure application for connected and automated vehicles along signalized arterials	Wang, Z. – UC Riverside	Coop-EAD	Arterial	N/A	Environment	Throughput improved by 50%, energy consumption decreased by 11%, and emissions were reduced up to 20%.	Simulation	MATLAB/Simulink and MOVES
2015, Cooperative adaptive cruise control applying stochastic linear model predictive control strategies	Moser, D. - Institute for Design and Control of Mechatronical Systems at the Johannes Kepler, University of Linz, Austria	CACC	Arterial	N/A	Environment	A CACC control approach was proposed and the fuel consumption in a vehicle–following scenario was minimized.	Simulation	
2019, A study of the environmental impacts of intelligent automated vehicle control at intersections via V2V and V2I communications	Bento, L. – Instituto Politécnico de Leiria	Intelligent Traffic Management techniques	Arterial	N/A	Safety, Environment	The Intelligent Traffic Management techniques reduced the CO_2 emissions significantly, and the benefit increased with the demands	Simulation	INTEGRATION
2016, Optimal speed advisory for connected vehicles in arterial roads and the impact on mixed traffic	Wan, N. – Clemson University	Speed Advisory System	Arterial	N/A	Environment and Mobility	A sub-optimal solution was proposed to avid bang-bang control. Much fewer stops and smoother trajectories were obtained with fewer less consumption	Simulation	Paramics
2012, Development and Evaluation of a Cooperative Vehicle Intersection Control Algorithm Under the Connected Vehicles Environment	Lee, J. – University of Virginia	Cooperative Vehicle Intersection Control (CVIC)	Arterial	N/A	Mobility, Environment	99% and 33% of stop delay and total travel time reductions (comparing to actuated intersection control); 44% reductions of CO 2 and 44% savings of fuel consumption .	Simulation	VISSIM
2016, Hierarchical control strategies for energy management of connected hybrid electric vehicles in urban roads	HomChaudhuri, B. - Clemson University		Arterial	N/A	Environment	Decreased delays significantly by eliminating stops for red lights. The fuel efficiency improved about 50% and CO_2 emission decreased about 40%	Simulation	HEVs

Year, Title	Author, Leading institute	CV Application	Road Type	Comm. type	Topic Area	Estimated Benefits	Simulation/ Field Test	Modeling Environment
2019, Traffic signal control by leveraging Cooperative Adaptive Cruise Control (CACC) vehicle platooning capabilities	Liu, H. – UC Berkeley	CACC - Arterial	Arterial	N/A	Mobility, Environment	Fuel efficiency increased more than 10% and speed increased by 13% when MPR was 100% (36% increase in speed and 34% MPG if MPR was 40%).67% of capacity increase was observed for major approach and 49% was observed for the minor approach.	Simulation	NGSIM/PATH
2015, Real scenario and simulations on GLOSA traffic light system for reduced CO2 emissions, waiting time and travel time	Lebre, Marie–Ange – VALEO, France	GLOSA	Arterial	DSRC	Mobility, Environment	10% reduction in CO_2 when MPR was 100%; 5% reduction in CO_2 and 30% reduction in waiting time was observed (with 40% vehicle MPR and 50% infrastructure MPR).	Field test, Simulation	SUMP
2020, Battery Electric Vehicle Eco-Cooperative Adaptive Cruise Control in the Vicinity of Signalized Intersections	Chen, H. – VTTI	Eco-CACC	Arterial	N/A	Mobility, Environment	A saving of 9.3% in energy consumption and 3.9% in vehicle delays were observed.	Simulation	INTEGRATION
2021, Adaptive Traffic Signal Control: Game-Theoretic Decentralized vs. Centralized Perimeter Control	Elouni, M. – VTTI	Decentralized Nash Bargaining Traffic Controller (DNB)	Arterial	N/A	Mobility, Environment	The reductions, with or without gating, are (in average): travel time between 21% to 41%, in total delay between 40% to 55%, and in emission levels (CO_2) and fuel consumption between 12% to 20%.	Simulation	INTEGRATION
2009, Cooperative Intersection Collision Avoidance System for Violations (CICAS-V) for Prevention of Violation-Based Intersection Crashes	Maile, D. – Mercedes-Benz Research & Development	CICAS-V	Arterial	DSRC	Safety	The system can reliably send out warning messages 100% of the time and therefore prevent crashes from happening.	Field test	

In a study conducted by Lebre et al., a GLOSA system was developed. The results showed that GLOSA could reduce vehicle emissions, waiting time, and travel times. One feature of this study is that it involved real scenario testing. The authors tested the traffic signal with communication devices that transmitted identity, timestamp, location, and phase information. The data were sent to the V2X equipment, which was composed of an IEEE802.11p compliant WiFi router and an antenna mounted to the traffic light through an Ethernet connection. In the case when there was only one vehicle, both the simulation and in-fields test achieved similar savings in CO2 emissions (11% and 13%). When there was more than one vehicle included (only in the simulation), a 5% reduction in CO2 emissions and a 30% reduction in waiting time were observed when the MPR was around 50%. The simulations were conducted with two other networks and the savings in time and CO2 emissions were also significant. For the grid network, a reduction of 10.5% in CO2 emissions and an 80% decrease in waiting time was observed with an MPR of 100%, while for the Valeo shuttle transit route, the reduction in travel time was about 2.05% with 50% vehicle MPR and 50% MPR for infrastructure. The saving increased quickly to 16% when the CAV MPR increased to 50% and 60% for infrastructure [56].

Chen and Rakha developed a connected eco-driving controller for BEVs that helps BEVs traverse signalized intersections by minimizing energy consumption. This controller features multiple realistic constraints, including vehicle acceleration and deceleration behavior, BEV energy consumption behavior, and the intercorrelation of speed, location, signal timing in a CV environment. The results showed that the authors' controller can effectively reduce stop-and-go behavior while at the same time generating a savings of 9.3% in energy consumption and 3.9% in delays [57]. In another study, the same authors developed a HEV Eco-CACC system. The system computes real-time, energy-optimized trajectories for HEVs. Within the system, two models were developed: one HEV energy model to compute the instantaneous fuel consumption and one vehicle dynamics model to capture the relationship between speed, acceleration as well as tractive/resistance forces. The results revealed that on an arterial with three signalized intersections, the proposed system produced a 7.4% reduction in energy consumption, a 5.8% reduction in delay, and a 23% reduction in vehicle stops.

Elouni et al. designed an adaptive traffic signal control system using two methods—game-theoretic decentralized and centralized perimeter control—and compared the performance of both systems. The results showed that the Nash Bargaining (NB) traffic signal controller can prevent congestion from building and improve the performance of the entire network. The NB controller outperforms both gating and non-gating controllers with significant reductions in vehicle travel time, emissions, fuel consumption, and delays. Specifically, the decentralized NB controller led to significant reductions of 21% to 41% in total delay, 40% to 55% in CO2 emission levels, and 12% to 20% fuel consumption, with or without gating [58].

A study by Maile tested a cooperative intersection collision avoidance system using vehicles from five OEMs: Daimler, Ford, GM, Honda and Toyota, among which the GM vehicle contained the full prototype. The intersection at 5th Ave. and El Camino Real in Atherton, CA was used for the testing. Results showed that the system can almost 100% reliably send out warnings and therefore prevent crashes from happening [59].

In summary, V2X-enabled applications in interrupted traffic flow typically involve a speed advisory system where vehicles are advised to go through a traffic signal-controlled intersection to avoid unnecessary deceleration, acceleration or stops. By adjusting the speeds of vehicles upstream of traffic signals, these applications can help vehicles go through the intersection with minimum interruption and fuel consumption. The existing studies were mainly conducted in a simulation environment. Most of them studied conventional ICEVs. Some tested other vehicle types, such as BEVs, trucks, or buses. Existing studies illustrated the promising results of using V2X-enabled applications in terms of improvements in environment, mobility, and safety.

2.3 Modeling Mutual Dependencies of Transportation and Communication Systems

This section briefly describes the work on the modeling of the interdependencies of the transportation and communication systems as it relates to the evaluation of V2X applications, as summarized in Table 5. A well-known framework in this category is Veins, which uses the TraCI interface to integrate a traffic simulator, SUMO, and a communication simulator, OMNET++. TraCI is a messaging standard that applies the Transmission Control Protocol (TCP) connections to share messages across the two simulators. TraCI's advantages include allowing bidirectional coupling of the two simulators. However, a key shortcoming of Veins is that it is unable to model large-scale networks. Veins by default does not support C-V2X mode 4; however, OpenCV2X [60] has extended Veins to support C-V2X modeling. Specifically, OpenCV2X implemented the C-V2X standard in SimuLTE, which is built on top of OMNET++ to support LTE communication [61].

Another integrated simulator was developed which entailed integrating the SUMO traffic and NS-3 communication simulators. The authors extended NS-3 to support C-V2X release 14. The authors did not mention how the integration between NS-3 and SUMO was done, but we assume that they used the TraCI interface as was done in Veins because TraCI is the external interface for SUMO developed by the SUMO authors [62].

In two studies conducted by Elbery et al., the authors developed an integrated simulator, VNetIntSim, which combined the OPNet communication simulator with the INTEGRATION traffic simulator. The integrated framework was used to demonstrate the impact of mobility parameters (traffic stream speed and density) on the communication performance through different applications including the File Transfer Protocol using TCP and Voice over Internet Protocol based on the User Datagram Protocol [63,64].

Hoque et al. attempted to address the scalability problem by parallelizing one or both simulators to speed up the execution time and thus support simulation of large-scale road networks with hundreds of thousands of vehicles. The authors developed an Integrated Distributed Connected Vehicle Simulator (IDCVS) by incorporating hardware-in-the-loop simulation with the integration of SUMO and OMNET++. The authors provided a partitioning heuristic algorithm that partitions the complex traffic network into two sets of partitions: one for SUMO and one for OMNET++. The tool was then used to model DSRC for connected vehicles considering different levels of market penetration [65].

The Vehicular Network Simulator (VNS)—which integrates the traffic simulator DIVERT 2.0 and the communication system simulator, NS-3—falls into the third category of methods. VNS supports the 802.11p communication standard as it was developed before the release of the C-V2X LTE standard. VNS differs from the previous work we discussed in the way that NS-3 and DIVERT are integrated. Since both simulators are developed in the same programming language (C++), they were put into one executable environment instead of having the two executing programs communicating with each other. Although the two simulators share the same execution environment, they still communicate using TCP connections through the network integration module. In VNS, at each simulation time step, the traffic simulator is run first followed by the communication simulator. The communication simulator has node entities that are mapped to the vehicle entities in the traffic simulator. Each node entity has access to its corresponding vehicle entity. One last difference in VNS is the adaptation of the NS-3 network simulator. The authors adapted the implementation of NS-3 to support large-scale simulations. They applied the concept of nearest neighbors and the locality of vehicle position updates by using QuadTrees to accelerate the performance of the NS-3 communication simulator. However, the integrated simulator is still constrained by the computational speed of NS-3 [66].

Table 5. Comparison of integrated traffic and communication simulators.

Year, Title	Author - Institute	Integrated Simulator	Simulation Scale	Network Simulator	Comm. Standard	Vehicle Positions	Simulator Coupling	Spatial Analysis	Modeling Environment
2021, INTEGRATION Large-Scale Modeling Framework of Direct Cellular Vehicle-to-All (C-V2X) Applications	Farag, M – VTTI	INTEGRATION	Large scale	Analytical model	Direct C–V2X	Grid cell and update index	Dynamic interval	Yes	INTEGRATION
2021, VNS: An Integrated Framework for Vehicular Networks Simulation	Fernandes, R. – University of Porto, Portugal	VNS	Large scale	NS-3	DSRC (802.11b)	Quad Tree	Fixed interval	No	DIVERT
2019, OpenCV2X Mode 4 A Simulation Extension for Cellular Vehicular Communication Networks	McCarthy, B – University College Cork Ireland	VEINS	Small scale	OMNET++	IEEE 802.11b	NA	Fixed interval	No	SUMO
2011, Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis	Sommer, C. – University of Erlangen	Open Source C-V2X	Small scale	OMNET++	C-V2X	NA	Fixed interval	No	SUMO
2019, Performance Analysis of C-V2X Mode 4 Communication Introducing an Open–Source C–V2X Simulator	Eckermann, F – TU Dortmund University	Open Source C-V2X	Medium Scale	NS-3	C-V2X	NA	Fixed interval	No	SUMO
2015, VNetIntSim - An Integrated Simulation Platform to Model Transportation and Communication Networks/2015, An Integrated Architecture for Simulation and Modeling of Small- and Medium-Sized Transportation and Communication Networks	Elbery, A – VTTI	VNetIntSim	Medium scale	OPNET	IEEE 82.11g	NA	Fixed interval	No	INTEGRATION
2019, VNetIntSim – An Integrated Simulation Platform to Model Transportation and Communication Networks/2019, Large-Scale Modeling of VANET and Transportation Systems	Elbery, A – VTTI	INTEGRATION	Large scale	Analytical model	DSRC (IEEE 802.11p)	NA	Fixed interval	No	INTEGRATION
2019, Parallel Closed-Loop Connected Vehicle Simulator for Large-Scale Transportation Network Management:	Hoque, M.A. – East Tennessee	IDCVS	Large scale	OMNET++	DSRC (IEEE 802.11p)	NA	Fixed interval	Yes	SUMO

Year, Title	Author - Institute	Integrated Simulator	Simulation Scale	Network Simulator	Comm. Standard	Vehicle Positions	Simulator Coupling	Spatial Analysis	Modeling Environment
Challenges, Issues, and Solution Approaches	State University								

Table 6. Road network architecture and simulation time.

Year, Title	Author – Institute	Road Network	Simulation Time	Number of Vehicles	Execution Time
2021, INTEGRATION Large-Scale Modeling Framework of Direct Cellular Vehicle-to-All (C-V2X) Applications	Farag, M – VTTI	Downtown LA. Area 133 km^2. A total of 1624 nodes, 3556 links, and 457 traffic signals.	1.8 h	145,000 vehicles with a maximum of 30,000 concurrent vehicles	1.5 h
2019, VNetIntSim - An Integrated Simulation Platform to Model Transportation and Communication Networks/2019, Large-Scale Modeling of VANET and Transportation Systems	Elbery, A – VTTI	Downtown LA. Area 133 km^2. 1625 nodes, 3561 links, and 459 traffic signals (42 RSUs).	8.3 h	563,626 vehicles with a maximum of 30,000 concurrent vehicles	8.3 h
2021, VNS: An Integrated Framework for Vehicular Networks Simulation	Fernandes, R. – University of Porto, Portugal	Road network of city of Porto.	40 min	130,000 vehicles with a maximum of 15,000 concurrent vehicles	7 h
2015, VNetIntSim - An Integrated Simulation Platform to Model Transportation and Communication Networks/2015, An Integrated Architecture for Simulation and Modeling of Small- and Medium-Sized Transportation and Communication Networks	Elbery, A – VTTI	An intersection and four zones. Each zone serves as a vehicle origin and destination location. Each road link is 2 km long.	Not reported	3000 vehicles with 180 concurrent vehicles	Not reported
2019, Performance Analysis of C-V2X Mode 4 Communication Introducing an Open-Source C-V2X Simulator	Eckermann, F – TU Dortmund University	A 100 m × 100 m intersection, and an urban Manhattan grid scenario as used by 3GPP (750 m × 1299 m).	30 s	250 vehicles	Not reported
2011, Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis	Sommer, C. – University of Erlangen	A 2700 m six-lane highway section, lane width of 4 m, vehicular speeds of 140 km/h (70 km/h). The inter-vehicle distance of 2.5 s × maximum speed.	Not reported	200 (380) vehicles in the simulation at its most dense stage	Not reported
2019, OpenCV2X Mode 4 A Simulation Extension for Cellular Vehicular Communication Networks	McCarthy, B – University College Cork Ireland	Single-lane Manhattan Grid with intersections spaced 1 km apart. Grid sizes 5 × 5 roads and 16 × 16 roads.	Not reported	30 and 1000 vehicles	Not reported

Elbery and Rakha developed a network simulator that simultaneously models the traffic and communication systems. Unlike the previous work, the communication system abstraction is not a network simulator, but instead is an analytical model, which allows for large-scale modeling of CV applications. The authors developed an analytical communication model for the DSRC Media Access Control layer protocol that estimates the packet drop probability and delay using a Markov chain and a queuing model. They implemented the analytical model in the INTEGRATION microscopic traffic simulator and tested the integrated framework using a dynamic eco-routing application [67,68].

Continuing the work of Elbery and Rakha, Farag et al. developed an integrated C-V2X and traffic simulation framework to simultaneously model the traffic and communication systems and their bi-directional coupling in a large-scale road network. The authors again used the INTEGRATION traffic simulator and an analytical model to implement the communication features of C-V2X and coupled them together in one execution environment. They scaled up the running time by leveraging a spatial index to accelerate the computation time of the communication model and tested it on the downtown Los Angeles network, modeling a total of approximately 145,000 vehicles [69]. In Table 6, we summarize the various parameters associated with the different simulator studies. This includes the different road networks, simulation times, number of vehicles simulated, and execution time for the various CV application simulators.

In summary, developing a fully integrated traffic and communication simulator is essential for the modeling CV applications. Most of the work integrates the two systems using dedicated simulators in the respective fields, which models low level details of both systems but lacks the capability of large-scale simulations. Recent work uses analytical modeling techniques to substitute one of the dedicated simulators for the benefits of scaling to large scale simulations while not significantly sacrificing on the accuracy of the modeling tool.

2.4 Application Evaluations Considering the Communication System Constraints

This section describes how the tools developed in the previous section are used to assess the performance of various CV applications while capturing the mutual interdependencies of the transportation and communication systems.

Schiegg et al. studied the environmental awareness problem of vehicles on the road, which they called incomplete vehicle perception due to the limited range of the vehicle's on-board sensors. They proposed extending the vehicle's perception by sharing the vehicle's information, collected by the vehicle's sensors, with other vehicles on the road using C-V2X communication technology. The service of sharing information within vehicles on the road is called collective perception. The authors proposed an analytical model to evaluate the performance of the service using the C-V2X Mode 4 standard and used an analytical model to model the C-V2X standard. The authors found that the collective perception service enhanced the information when using C-V2X to share sensors' information. They also found that although C-V2X was useful, more enhancement was needed regarding the latency requirements of vehicle safety applications [70].

In the study by Segata et al., the authors studied the performance of the C-V2X communication standard in the context of platooning applications. The authors investigated the impact of the scheduling algorithm for Mode 4 on the platoon formation using several controllers. Findings suggested that although C-V2X performed very well in terms of Packet Delivery Ratio, it did not perform well in terms of packet loss bursts. The authors showed that the packet loss bursts can hinder C-V2X usefulness in safety applications, and claimed that the packet loss bursts are due to the scheduling algorithm and the half-duplex nature of the C-V2X channel (vehicles cannot receive and transmit at the same time) [71].

A study by Rajab and Miucic investigated the performance of the C-V2X communication standard on the performance of two safety applications: Emergency Vehicle Alert and High Beam Assist. The authors modeled the C-V2X communication standard using empirical data from the Crash Avoidance Metrics Partners performance assessment project to create several Packet Error Ratio (PER) curves for different conditions (ideal, medium, and severe). They smoothed the PER curves using splines applied to the empirical data [72].

A truck platoon application was tested in [73] using C-V2X communication. The authors found that the best scenario is to use C-V2X mode 3 in areas covered with LTE-infrastructure and C-V2X mode 4 in areas not covered to get the best benefits from the platoon (i.e., smaller inter-truck gaps). The authors, however, noted that one critical configuration of the C-V2X mode 4 is the re-selection counter, which must be tuned carefully to achieve good performance [73].

Marco et al. developed an open-source framework for testing V2X applications. They evaluated two applications: emergency vehicle (V2V) and area speed advisory (V2I/V2N) using DSRC and C-V2X communication technologies. They showed that the two applications were valuable and did help the emergency vehicle to maintain high speed while crossing intersections (in the V2V case) and decreased the number of collisions in the area of the speed advisory applications (in the V2I/V2N case) [74].

Mouawad et al. tested and evaluated a cooperative collision avoidance V2I application at urban intersections. The vehicles shared their Lidar sensor measurements (local occupancy maps) with RSUs. The RSUs fused all the messages into a global occupancy map and sent it back to all vehicles in range. The authors found that the configuration for the best performance was a message size of 1,685 bytes for global occupancy maps, which led to the lowest obstacle mis-detection rate and a packet generation rate of 10 Hz when the number of vehicles was less than 70 and 5 Hz otherwise [75].

A C-V2I-based system for collision avoidance was introduced and evaluated in a study by Malinverno et al. The authors evaluated the effectiveness of their collision detection algorithm using Cooperative Awareness Messages that were sent by vehicles and pedestrians using C-V2I. It was not clear what the configuration of the communication protocol was, but the authors mentioned that they used SimuLTE-veins for simulating the C-V2I. The authors assumed an MPR of 100% and tested the location of the application server in two settings: the cloud and at the RSU. The results of their algorithm was not affected by the location of the application server [76].

Video-assisted overtaking maneuver application using image processing and video streaming over C-V2X was introduced in a study by Magalhaes et al. The C-V2X enhanced the performance of the application by having low packet-loss and high video quality; however, it affected the latency. The authors used a C-V2X onboard unit with a Cooperative Awareness Messages frequency of 10 Hz, HARQ enabled, and transmission power of 20 dBm with Line-of-sight assumption [77].

A study conducted by 5GAA analyzed the capability of 3GPP LTE-V2X PC5 (LTE side-link) and IEEE 802.11p (DSRC or ITS-G5) in reducing the number of fatalities and serious injuries. The model used the number of crashes as a baseline number and the fraction of signal delivery reliability, effectiveness of receiving alert/warning message, as well as some other ratios to estimate the number of crashes that could be avoided. The results showed that LET-V2X would avoid a greater number of crashes when compared to 802.11p due to a combination of the superior performance of LTE-V2X and the market led conditions that better favor the deployment of LTE-V2X [78].

Rebbeck et al. concluded that C-V2X enhances road safety and traffic efficiency. The base and equitable 5.9 GHz user scenario appeared to the be the most beneficial way to deploy C-V2X considering the cost of upgrading the roadside infrastructure. Additional benefits can be achieved if LTE PC5 communication is integrated in smartphones. The study also concluded that the cost of upgrading the in-vehicle C-ITS system would be significant [79].

Beyrouty et al. evaluated seven bundles of C-ITS services that are mature and are expected to be deployed in the short or medium term, including safety-based V2V services, V2I services that deliver the most benefit on motorways, V2I services mostly appliable in urban areas, services intended to provide information regarding parking, services intended to provide traffic and smart routing information, and V2X vulnerable road user protection services. The authors also assessed policy options considering six key themes: privacy, security, interoperability, compliance assessment, continuity, and enabling conditions. They estimated the savings in avoiding crashes, fuel consumption savings, and emission reductions for different policy options [80].

Using the INTEGRATION simulation tool Elbery and Rakha evaluated the mutual impact of an eco-routing transportation application and the V2I communication system using the 802.11p protocol. They tested the eco-routing application performance using different measures of effectiveness for different CV MPRs and congestion levels. The results of their study showed that reasonable fuel savings were achieved at a low-to-medium MPR. However, at high MPRs and high vehicular traffic congestion levels the eco-routing application performance degraded and caused higher fuel consumption and even a gridlock in the road network. This was because of the sub-optimal routes produced by the eco-routing application caused by the high packet drop rate [81,82]. Alternatively, ignoring the communication system constraints produced benefits that increased as the CV MPR increased. This study clearly demonstrated the need to model the communication system as part of the evaluation of CV applications and demonstrated that without such an integrated modeling framework, erroneous conclusions could be derived.

In summary, V2X-enabled intelligent transportation applications like collective perception, platooning, emergency vehicle alert, area speed advisory, collision avoidance, and video-assisted overtaking maneuvers have been tested in the literature. Despite the promising benefits of V2X technology, there is still more room for enhancement, specifically from the latency perspective.

2.5 Open Research Direction for C-V2X Applications

This study reviewed numerous research efforts that attempted to quantify the effects of various CV applications on the transportation system's mobility, safety, and the environment. As such, we have derived the following conclusions based on the literature review:

1. CV applications are highly efficient in improving the transportation system's mobility and safety and minimizing vehicle emissions and fuel consumption levels. Assuming perfect wireless communication among the different components of the CV environment, the mobility, safety, and environmental impacts typically increase as the CV MPR increases.
2. CVs' MPR is a critical factor affecting the performance of CV applications. A minimum MPR was recommended in many studies to reach a significant level of savings in travel time, delays, and emissions. Depending on the types and features of the different applications, the minimum MPR varies from 10% to 40%.
3. The benefits of CV applications generally increase with the increase of MPR if communication constraints are not explicitly accounted for. The benefits, however, do not follow a linear relationship with the MPR. Some applications start to show effects once a minimum number of CVs are in the traffic flow, but the benefits flatten out after the MPR reaches a certain level. Some applications do not generate benefits until a certain MPR level is attained; however, as benefits increase accordingly with the increasing percentage of CVs in the traffic flow.
4. Most of the previous research efforts treated communication among various parts of the system as latency- and/or error-free, assuming the C-V2X data are accepted and applied by all users without any errors. This assumption should be modified in future research. Due to the delays in signal transmission, bandwidth, and varied levels of acceptance and cooperation by travelers in the system, the benefits will be lower in real-world situations. The benefits in the real world need to be estimated accordingly to account for limitations in the communication system and ensure accuracy.
5. A unique study of an eco-routing application showed that a minimum MPR of about 10% was needed to achieve benefits, with the benefits peaking at a CV MPR of 30–40%. Higher MPRs overloaded the 802.11p communication system, and at an MPR of 75%, the application produced gridlock because of the loss and latency in the packet transmission. This finding is unique because it demonstrates the importance of including the communication system constraints in the modeling of CV applications.
6. Most previous research efforts were based on microscopic simulations. Very few studies tested CV technologies in the field given the high cost of such testing. Even in those cases with field testing, the testbed typically was a closed environment involving a small sample of CVs (no more than 10), thus not overloading the communication system.
7. The benefits of CV applications vary based on the application type, study design, vehicle type, test location or network type, roadway condition, and utilized energy/emission model. The differences might also be caused by different modeling algorithms, modeling assumptions, or model parameter settings.

3. Development and Evaluation of a Cellular Vehicle-to-Everything Enabled Energy-Efficient Dynamic Routing Application

3.1 Overview

By providing real-time, highly reliable, and actionable information flows, cellular vehicle-to-everything (C-V2X) seeks to redefine transportation by enabling better informed decisions. C-V2X can enhance road safety, increase traffic flow efficiency, reduce vehicular environmental impacts, and provide travelers with valuable new communication services.

C-V2X will serve as the platform for V2X, providing 360º non-line-of-sight awareness and a higher level of predictability for enhanced road safety and autonomous driving. C-V2X systems are based on the widely deployed 3GPP LTE cellular specifications [83]. Future communication models will take advantage of newer 5G technology to add features and improve data rates and latency.

In this study, we will assess the environmental effects of a wide deployment of a C-V2X-enabled dynamic routing application. More specifically, we attempt to quantitatively determine how specific C-V2X-enabled applications can reduce CO_2 emissions and fuel consumption. This analysis will help various stakeholders improve their understanding of the societal benefits of C-V2X, and thereby accelerate the deployment of C-V2X across the US. Further, this study will investigate the impact of C-V2X communication on the performance of transportation applications.

The proposed methodology entails developing and using a microscopic integrated traffic and C-V2X simulation tool to quantify the network-wide efficiency and environmental impacts of a Connected Energy-Efficient Dynamic Routing (C-EEDR) application. The C-EEDR application is an ITS application that attempts to minimize the vehicle's fuel consumption levels, by routing vehicles through the most environmentally friendly routes. It utilizes connected vehicle technology to collect real-time fuel consumption information from probe vehicles to compute the best routes. The C-EEDR navigation system assumes the capability of some vehicles (known as sensor vehicles or probe vehicles) to compute the fuel consumption on each traversed road segment and report the computed fuel consumption and the associated road segments to the cloud. The optimal routes are calculated at the cloud and reported back to all the connected vehicles.

3.2 Energy-Efficient Dynamic Routing Algorithm

The routing application determines the best route the vehicles should take based on a predefined criterion (travel time, distance, or fuel consumption). It is of high importance to decrease fuel and energy consumption in the transportation sector. Energy-efficient routing can find a route that reduces vehicle fuel consumption cost. Fixed routing calculates the best routes based on the given road segments' cost. The costs used in the fixed routing algorithm could be historical data on the average cost of using the specified road network or the cost of travelling the network with the free flow speed. The traffic mobility patterns are very dynamic and thus require adaptive or dynamic routing algorithms. An important step in dynamic routing is to obtain the real-time periodically updated cost of travelling on a road segment. This requires the vehicles to be able to identify which road segment it is on at any point in time and to be able to communicate the cost of travelling on a road segment. At each of the update intervals, the costs are collected, the routing algorithm is run again using the updated costs, and new routes are produced. The traffic will be assigned to the new routes if their costs are better than the old routes.

The routing problem can be modeled as a shortest path problem and is solved in this study using the Dijkstra algorithm [84]. The Dijkstra algorithm is applied periodically with the current road segments' costs collected from the probe vehicles. To prevent the frequent change of routes (oscillating routes), a traffic assignment algorithm is utilized. The routing algorithm produces the top five best routes. The traffic is randomly distributed between these five routes. Then, the update period is divided into five sub-periods. At each of these sub-periods, the recent costs of the road segments are collected and used to update the current costs. Then, the routes are recalculated using the recently updated costs. In this way, at each updated sub-period, only one fifth of the traffic demand will be updated with the new routes. Another factor that prevents the frequent change of routes is that vehicles do not change their routes unless the new route's cost is better than the old route's cost with a predefined threshold.

The fuel consumption of a road segment can be calculated using simplified macroscopic analytical or data-driven models using the average speed on the road segment. A microscopic approach is to use the second-by-second speed and acceleration to calculate the fuel consumption of each vehicle. The microscopic approach provides more accurate calculation but with more computation steps. We adopted the Virginia Tech Comprehensive Power-based Fuel Consumption Model (VT-CPFM) [85] microscopic model to calculate the second-by-second fuel consumption of each vehicle. The details of the fuel consumption model are described in the next section. We used the average fuel consumption of the vehicles that traversed the road segment as a representative of the cost of the fuel consumption on that road segment.

The study used the Virginia Tech Comprehensive Power-based fuel consumption (VT-CPFM) model to estimate the instantaneous fuel consumption rate of ICEVs. The VT-CPFM was selected due to its simplicity, accuracy, and ease of calibration [86]. The selected fuel model utilizes instantaneous power as an input variable and can be easily calibrated using publicly available fuel economy data (e.g., Environmental Protection Agency [EPA]-published city and highway gas mileage). Thus, the calibration of model parameters does not require gathering any vehicle-specific field data. The VT-CPFM is formulated in *Eq.* 1.

$$FC(t) = \begin{cases} a_0 + a_1 P(t) + a_2 P(t)^2 & \forall\, P(t) \geq 0 \\ a_0 & \forall\, P(t) < 0 \end{cases} \qquad \text{Eq. 1}$$

where α_0, α_1, and α_2 are the model parameters that can be calibrated for a particular vehicle using publicly available vehicle specification information from the manufacturer, and the details of calibration steps can be found in [86]; *P(t)* is the instantaneous total power (kW); $a(t)$ is the acceleration at instant t, which can be calculated by consecutive time speed values; $v(t)$ is the velocity at instant t, and $R(t)$ is the resistance force on the vehicle.

The Virginia Tech Comprehensive Power-based EV Energy consumption Model (VT-CPEM) was selected to estimate BEV energy consumption levels [87]. The VT-CPEM model is a microscopic, power-based BEV energy model developed to estimate the instantaneous energy consumption of BEVs. The model uses instantaneous speed, acceleration, and grade information as input variables. The outputs of the model are the energy consumption (kWh/km), the instantaneous power consumed (kW), the instantaneous energy regenerated (kW), and the final state of charge of the electric battery (%). VT-CPEM has a simple structure that allows it to be implemented into other modeling tools, including microscopic traffic simulation models and in-vehicle/smartphone applications for real-time eco-driving and eco-routing. One of the major advantages of VT-CPEM is that it captures instantaneous braking energy regeneration, which is not available in most EV energy models. The model estimates the power at the wheels using *Eq.* 2.

$$P_W(t) = \left(ma(t) + mg \cdot \cos(\theta) \cdot \frac{C_r}{1000}(c_1 v(t) + c_2) + \frac{1}{2}\rho_{Air} A_f C_D v^2(t) + mg \cdot \sin(\theta) \right) \cdot v(t) \qquad \text{Eq. 2}$$

Here m is the vehicle mass, $a(t) = dv(t)/dt$ is the acceleration of the vehicle in m/s^2 ($a(t)$ takes negative values when the vehicle decelerates), g (m/s^2) is the gravitational acceleration, θ is the road grade, C_r, c_1, and c_2 are the rolling resistance parameters that vary as a function of the road surface type, road condition, and vehicle tire type. ρ_{Air} (kg/m^3) is the air mass density, A_f(m^2) is the frontal area of the vehicle, C_D is the aerodynamic drag coefficient of the vehicle, and $v(t)$ is the vehicle speed in m/s [88-90].

3.3 Energy-Efficient Dynamic Routing using IDEAL Communication

In this section, we describe the logic of the C-EEDR application in the context of the INTEGRATION [91], since we used it in our simulations for the evaluation. The INTEGRATION software is an agent-based microscopic traffic assignment and simulation software. It is capable of simulating large-scale traffic road networks at a time granularity of 0.1 s. This high time-resolution allows detailed analyses of many traffic theory phenomena, such as acceleration, deceleration, lane-changing, and car following behavior. It computes several measures of performance, including delay, stops, fuel consumption, hydrocarbon, carbon monoxide, carbon dioxide, and nitrous oxide emissions, and the crash risk for 14 crash types.

INTEGRATION, by default, models the C-EEDR application assuming IDEAL connectivity, i.e., all messages transmitted are received without loss or delay. This assumption simplifies the modeling process from the traffic engineering perspectives and provides an upper bound of the expected benefits of the application. The C-EEDR application is developed as a feedback system that assumes the vehicles are connected and equipped with GPS. Moreover, a vehicle is assumed to be capable of calculating the fuel consumption for each road segment it traverses and communicating this information to the central server. In INTEGRATION, the fuel consumption and emission rates of each vehicle are calculated every second, based on instantaneous speed and acceleration.

Each vehicle accumulates this fuel consumption rate on each road segment it travels on. Then, whenever the vehicle exits that road segment, it updates the road segment's cost. Based on the IDEAL communication assumption, these updates are promptly added to the routing information at the central server in the cloud. The vehicle route is a sequence of connected road segments. Thus, if a route R_i consists of k road segments, the total route fuel consumption cost F_{R_i} is the summation of the fuel consumption of the constituting road segments, as expressed in the following equation:

$$F_{R_i}(t) = \sum_{j=1}^{k} F_{s_j}(t) \qquad \text{Eq. 3}$$

where F_{s_j} is the fuel consumption on the road segment S_j at time t.

Initially, F_{s_j} is computed based on the free-flow speed. Then, this value is updated based on updates from probe vehicles. Based on the IDEAL communication assumption, whenever a vehicle exits a road segment S_j, INTEGRATION uses the reported vehicle's fuel consumption F_v on this road segment to update the road segment's cost S_j. It uses a smoothing factor α, as shown in Eq. 4; a typical value of α in INTEGRATION is 0.2.

$$F_{s_j}(t+1) = (1-\alpha).\, F_{s_j}(t) + \alpha.\, F_v \qquad \text{Eq. 4}$$

where F_v is the estimated fuel consumption of vehicle v on the road segment S_j. The fuel consumption cost is communicated to the central server when the vehicle leaves the road segment. Then, the routing algorithm uses all the communicated road segments costs to update the current ones using Eq. 4.

3.4 Energy-Efficient Dynamic Routing using C-V2X Communication

In this section, we describe the changes to the C-EEDR application to accommodate the limitations of using the realistic communication system. First, we describe the communication model used, then how this model is implemented in the INTEGRATION simulation tool.

We used cellular vehicle-to-everything (C-V2X) 4G LTE-V communication technology to model the communication system. We used a realistic communication simulation model of the C-V2X communication technology and integrated it with the traffic simulator INTEGRATION [2].

We used Packet Reception Ratio (PRR) curves provided from a communication company [92]. The PRR is the probability that a packet will be received by a vehicle using V2V/V2I C-V2X communication at a specific distance and density of vehicles. The company used its proprietary analysis to produce PRR curves at different distances (0 to 760 m with step 10 m) and vehicle densities (60 to 1200 vehicles with step 60 vehicles). Figure 2 shows the PRR curves produced, which represent a realistic approximation to the real world, as the company's simulator, used to produce the PRR curves, has been calibrated with the real word measurement data [92]. The curves were generated for vehicles moving on a highway with line of sight (i.e., no buildings or obstacles preventing sight). There is a PRR curve for each density index. The density values represent the number of vehicles around the receiving vehicle within 500 m. The x-axis represents the distance between the transmitting and receiving vehicles. The y-axis represents the probability that the transmitted packet will be received. As can be observed in Figure 2, as the density of the vehicles increases, the PRR decreases even at the same distance. The same behavior is observed with the distance, where the PRR value decreases as the distance increases.

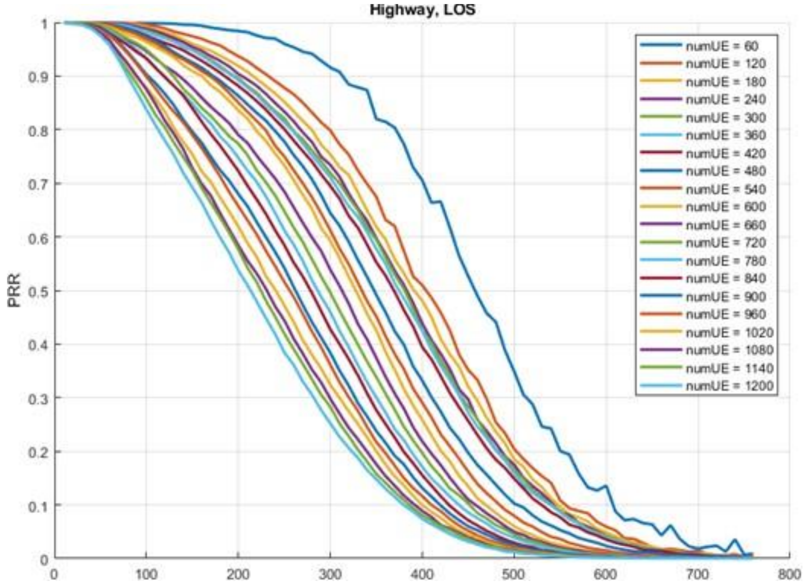

Figure 2. PRR of C-V2X communication data generated using a proprietary simulation software.

To use these curves in our simulation tool, we could look up a 76 × 10 × 20 table of PRR values at a specific density and distance. If the required density or distance does not exist, then we can use the nearest values and interpolate for the required values. A faster approach is to fit a curve to those values. We fitted the PRR curves with 2 polynomial functions and an exponential function to come up with a formula that produces a PRR value given any distance between the receiving and the transmitting vehicles, as well as any number of vehicles around the receiving vehicle. Eq. 5 shows the function used to fit the PRR curves. A two-step fitting process was performed to fit the PRR data.

$$PRR = \frac{1}{\frac{a_1}{a_2 * \exp\left(\frac{density}{a_3}\right)} + poly_7(density) * \exp \frac{distance}{poly_8(density)}} \qquad \text{Eq. 5}$$

where a1, a2, a3 are parameters calibrated using curve fitting, poly7 and poly8 are two polynomial functions of the 7th and 8th degrees, respectively. The variables' density is the vehicular density and distance is the distance between the transmitting and the receiving vehicles. Eq. 6 shows the polynomial function used to calculate poly7 and poly8 with n equal 7 and 8, respectively.

$$poly_n(density) = \sum_{j=0}^{n} p_i * density^i \qquad \text{Eq. 6}$$

where p_i are the polynomial coefficients and are calculated using curve fitting.

First, we fitted the PRR data (PRR vs. Distance) using an exponential three-parameters function. This fitting step was conducted for each density value (i.e., we had 20 × 3 parameters). Using the fitted function, we can obtain the PRR value for any distance between 0 and 760 meters. Second, we used an exponential, 7th degree polynomial, and 8th degree polynomial functions to fit the three-parameter data produced from the first step. Using these fitted functions, we obtain the corresponding three parameters for any density value (between 60 to 1200 vehicles). Combining all four fitted functions, we obtain the function shown in Eq. 5. Figure 3 shows the resulting fitted curves using the PRR data and Eq. 5. We can observe that the fitted PRR curves demonstrate the same behavior as the original data.

There are many advantages of using PRR data in this way. First, the data were produced from a communication network simulator that was calibrated using real-world connected vehicles data, thus providing the most high fidelity and accurate data. Second, this approach allows for running large-scale simulations of hundreds of thousands of vehicles in city-scale road networks in an efficient and reasonable time. This is in contrast to the other approach of using a communication network simulator, where the simulation time is very long due to the huge computation time of the communication network simulators, as it runs at the scale of milliseconds with a high level of detail. Similarly, using an analytical communication model can save a huge amount of time but lack the high fidelity and accurate results that are produced by a communication network simulator. Thus, our approach combines the advantages of both worlds: the high fidelity of the communication network simulators and the large scale and scalability of the analytical models.

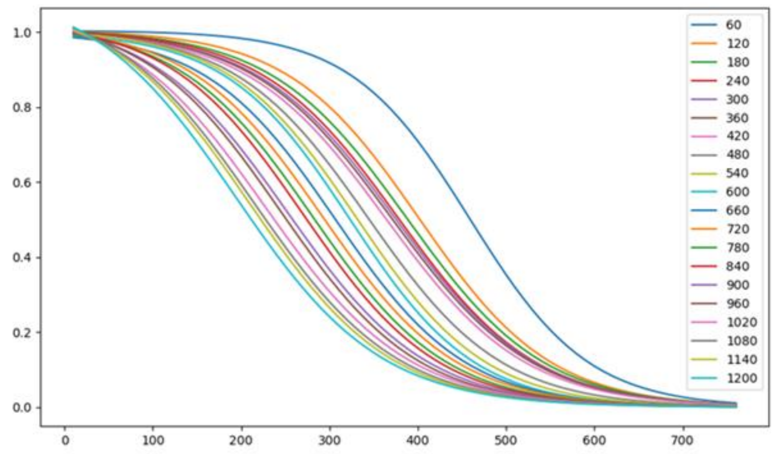

Figure 3. PRR of C-V2X communication fitted the data in Figure 2.

During each time step in the simulation, the traffic simulator efficiently utilizes a spatial index data structure to identify, for each transmitting vehicle, the set of receiving vehicles and their corresponding distances, and the vehicle density around each receiving vehicle. Using these two pieces of information, we used the PRR Eq. 5 to compute the PRR value for each transmitting–receiving vehicle pair. We then draw a random value (0-1), and if the PRR value is bigger than the random value, then the message that contains the fuel consumption cost will be delivered. Otherwise, the message will be lost.

For the C-EEDR application to work correctly, the road segment's fuel consumption cost needs to be communicated to a central server. Using C-V2X Vehicle-to-Infrastructure (V2I) technology, every vehicle that leaves a road segment transmits its fuel consumption cost on the road segment to the nearest Road-Side Unit (RSU) if there is one. We assume that the RSUs can deliver the information to the central server (using fiber or wireless wide area connectivity). One important factor for the C-EEDR application is the placement of the RSUs. We chose to place the RSUs at the traffic signals to minimize the infrastructure cost. We modeled the problem of choosing the subset of the traffic signals as a set cover problem [93] and used a greedy algorithm to find the minimum number of traffic signals that maximize the coverage of all the traffic signals in the road network within a 500m communication range. By placing the RSUs at the selected traffic signals, we guarantee that most of the road network will be covered by the RSUs and thus most of the vehicles will be able to transmit their information to the central server through one of these RSUs during their trip anywhere in the road network.

3.5 C-V2X Energy-Efficient Dynamic Routing Simulation Model Development

The downtown area in the city of Los Angeles (LA), shown in Figure 4, is used for the simulation and evaluation. The red points and surrounding circles are the RSU locations and their communication ranges, which are used in communication modeling. This road network is about 133 km^2. It has 1625 road network nodes, 3561 road links, and 459 traffic signals. The road network's vehicle traffic demand was calibrated based on the vehicle count data from loop detectors in the same area. These data are collected from multiple sources, as described in detail in [94]. This traffic demand represents the morning peak hour in the downtown area of the city of LA, which continues for 1 h from 7:00 a.m. to 8:00 a.m. The demand runs for one hour. However, we run the simulation for two hours to give the vehicles enough time to finish their trips and leave the road network. The total number of vehicles that are simulated is approximately 144,000 vehicles.

After applying the greedy algorithm on the set of traffic signals, 126 traffic signals were chosen by the algorithm to cover all the 459 traffic signals. We assume RSUs will be installed at the traffic signals controlling these intersections. This algorithm does not guarantee coverage of the whole road network. However, it covers the maximum number of signalized intersections with a minimum number of RSUs.

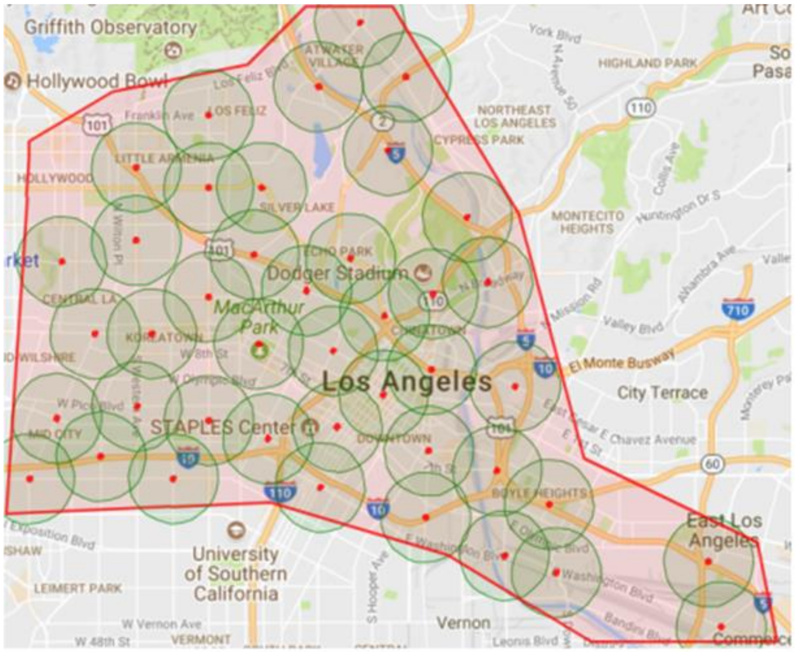

Figure 4. Los Angeles simulation model.

3.6 C-V2X Energy-Efficient Dynamic Routing Simulation Results

To study the impact of different traffic origin-destination demand (OD) levels, the calibrated traffic rates are multiplied by OD Scaling Factors (ODSFs) ranging from 0.25 through 1.0 at a 0.25 increment, which produces four traffic demand levels (0.25,0.50,0.75,1). For each of these four traffic demand levels, we used nine different market penetration rates of the probe-connected vehicles (1, 2, 5, 10, 20, 25, 50, 75, 100). Thus, we ran 36 scenarios using the IDEAL communication configuration, and then reran the same 36 scenarios with the realistic C-V2X V2I communication modeling. The next subsections present and analyze the results at the different traffic demand levels.

We evaluate the C-EEDR application using the IDEAL and C-V2X communication using the following measures: the average fuel consumption, the average travel time, and the average stop delay per vehicle.

3.6.1 Traffic Demand Scale 1

The full traffic demand produced 143,815 vehicles during the first hour of the simulation. Figure 5 compares the fuel consumption of the C-EEDR application using IDEAL and C-V2X communication and contrasts them against the fuel consumption without using the C-EEDR application (base). The base fuel consumption is the average fuel consumption of all the vehicles that travelled through the road network based on the Frank-Wolfe user-equilibrium traffic assignment for the entire simulation period. The C-EEDR application helped decrease fuel consumption with increasing market penetration rates in general. As more of the vehicles are connected and act as probe vehicles, more information is collected, and thus more accurate routing decisions are made. The C-V2X C-EEDR application behavior follows the same behavior as the IDEAL C-EEDR application with slightly higher fuel consumption due to the loss of information from the communication system. The fuel consumption increases at higher market penetration rates (> 75%).

The average travel time and the average stopped delay exhibited a similar behavior as the fuel consumption up to a certain market penetration rate. At the beginning, the travel time decreased as the market penetration rate increased until it reached 25%, and after that, the travel time and stopped delay increased as the market penetration rate increased. The C-V2X showed the same behavior as the IDEAL C-EEDR application, as shown in Figure 6 and Figure 7.

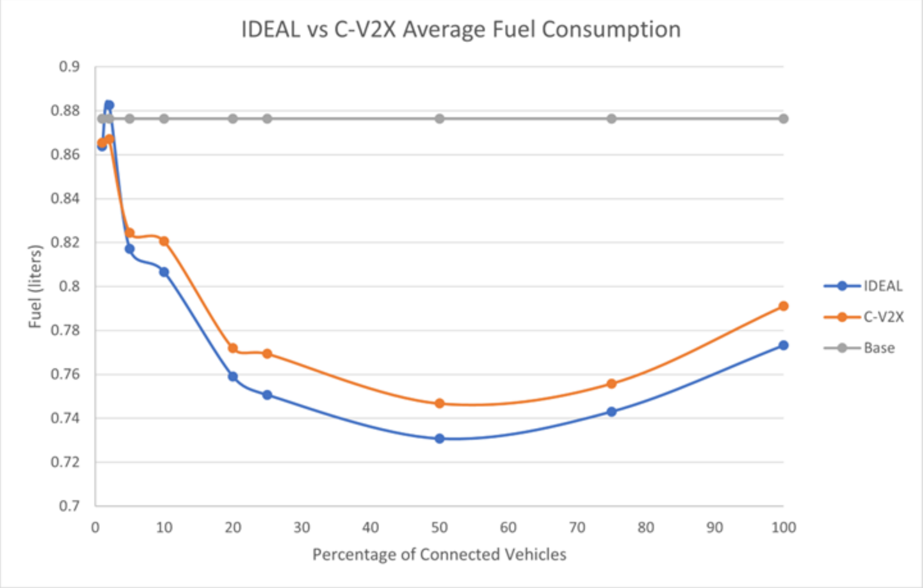

Figure 5. Average network-wide Fuel consumption of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 1.

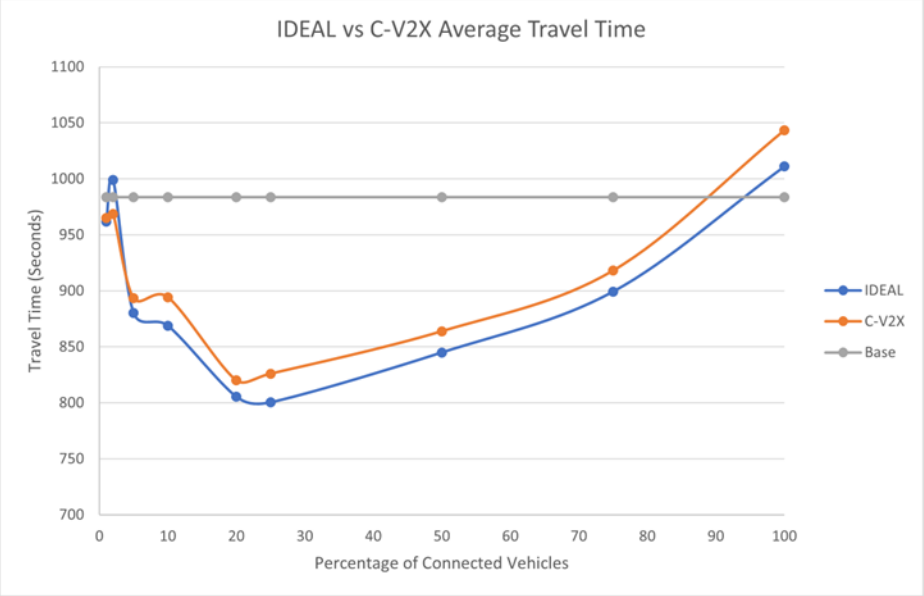

Figure 6. Average network-wide Travel Time of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 1.

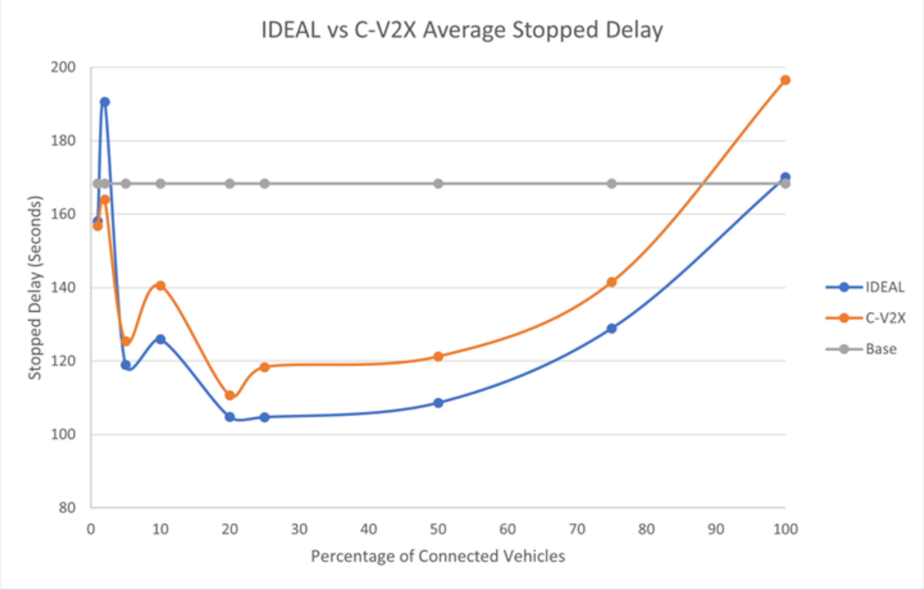

Figure 7. Average network-wide Stopped Delay of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 1.

An expected behavior of the C-EEDR application is that when we decrease the average system-wide fuel consumption, we may increase the average travel time and the stopped delay.

It is worth noting that the C-V2X-enabled C-EEDR does not follow the same pattern as the IDEAL C-EEDR with market penetration rates below 10%. This could be due to the limited information collected by the system, which affects the quality of the routing decisions.

We ran the two-tailed Student's t-Test (p-values ranged between [0.17–0.82]) between the IDEAL-based C-EEDR and C-V2X-based C-EEDR applications and found that there was no statistically significant difference between the corresponding travel time, stopped delay, or market penetration rates less than 25% at a significance level of 0.05. For market penetration rates 25% and higher, there was a statistically significant difference between the IDEAL-based C-EEDR and C-V2X-based C-EEDR applications for the corresponding travel time, stopped delay, and the fuel consumption between the mean of the 10 different seed runs. Table 7 shows the percentage change in the fuel consumption, travel time, and stopped delay between the C-V2X and IDEAL-based C-EEDR applications and their corresponding p-value. The degradation in performance was less than 3.5% for fuel consumption and travel time and reached 15.6% for the stopped delay.

Table 7. The percentage change between the C-V2X and IDEAL-based C-EEDR applications performance in terms of travel time (TT), stopped delay (SD) and fuel consumption.

MPR (%)	TT (%)	SD (%)	FC (%)
1	−0.33 (0.88)	0.84 (0.91)	−0.18 (0.88)
2	3.03 (0.21)	13.95 (0.1)	1.76 (0.18)
5	−1.5 (0.21)	−5.37 (0.25)	−0.9 (0.19)
10	−2.94 (0.08)	−11.6 (0.11)	−1.73 (0.08)
20	−1.82 (0.12)	−5.66 (0.34)	−1.69 (0.02)
25	−3.2 (0.01)	−13.06 (0.01)	−2.49 (0)
50	−2.25 (0)	−11.65 (0)	−2.19 (0)
75	−2.1 (0.01)	−9.81 (0)	−1.72 (0)
100	−3.21 (0)	−15.63 (0)	−2.31 (0)

Although there was a statistical significance between the performance of the C-V2X- based and the IDEAL-based C-EEDR applications at market penetration rates of 25% and higher, we still achieved fuel savings in both cases at all MPR levels. This result confirms the effect of the communication system on the traffic system performance and of the mutual interaction between both systems.

3.6.2 Traffic Demand Scale of 0.75

The traffic demand at 75% produced 107,960 vehicles during the first hour of the simulation. The C-EEDR application decreased the average system-wide fuel consumption, as shown in Figure 8. We observe the same behavior: as the market penetration rate increases, fuel consumption decreases. However, the average travel time, as shown in Figure 9, did increase as the market penetration rate grew, even more than the travel time of the base case. The same behavior is noticed in the case of stopped delay, as shown in Figure 10.

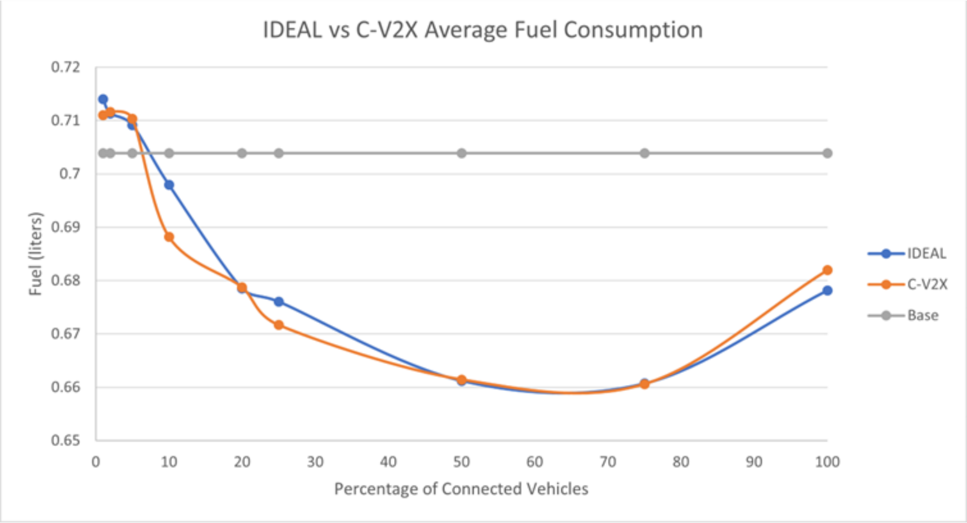

Figure 8. Average network-wide Fuel consumption of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 0.75.

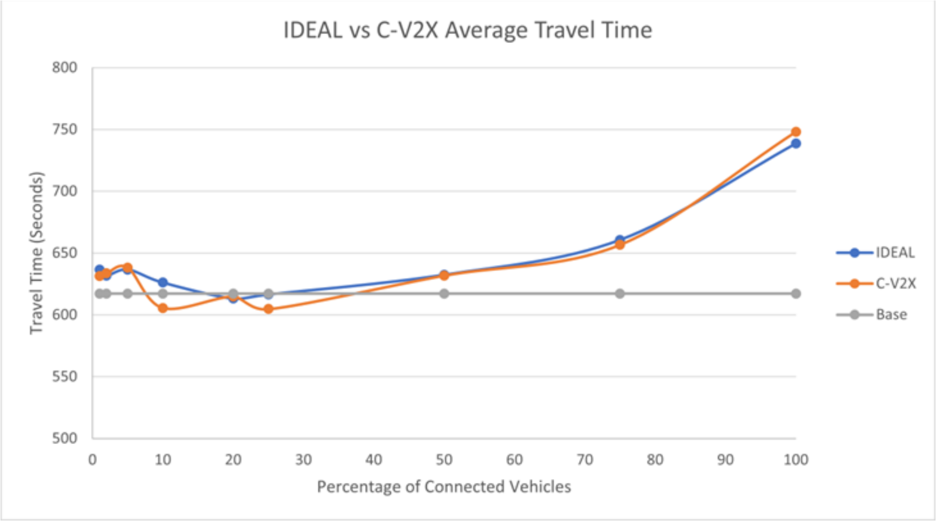

Figure 9. Average network-wide Travel Time of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 0.75.

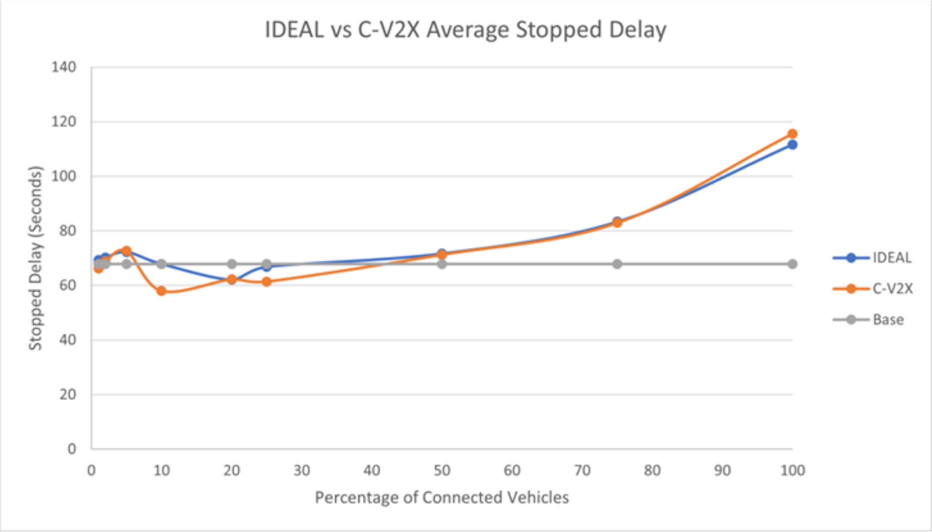

Figure 10. Average network-wide Stopped Delay of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 0.75.

The behavior of the C-V2X and IDEAL C-EEDR applications are similar at market penetration rates larger than 25% in all the evaluation measures. At market penetration rates less than 25%, the lack of information (due to the low percentage of probe vehicles and packets loss) plays a major role in the quality of the decisions of the C-V2X-based C-EEDR application. We ran the two-tailed t-test (p-values ranged between [0.17–0.92]) between the IDEAL-based C-EEDR and C-V2X-based C-EEDR applications and found that there was no statistically significant difference between the corresponding travel time, stopped delay, and the fuel consumption between the means of the 10 different seeds for each of the 9 market penetration rates at a significance level of 0.05.

3.6.3 Traffic Demand Scale of 0.5

A 50% traffic demand produced 70,721 vehicles during the first hour of the simulation. The C-EEDR application decreased the fuel consumption with the increase in the market penetration rate, as shown in Figure 11. Here, we noticed that the C-EEDR application maintained the same behavior (decreasing fuel consumption) even at a full market penetration rate (in contrast with the previous two traffic demand levels).

However, the system-wide travel time increased as the market penetration rate increased even at low market penetration rates, as shown in Figure 12. The same behavior is noticed in stopped delay too, as shown in Figure 13.

We ran the two-tailed t-test (*p*-values ranged between [0.15–0.86]) between the IDEAL- based C-EEDR and C-V2X-based C-EEDR applications and found that there was no statistically significant difference between the corresponding travel time, stopped delay, and the fuel consumption between the means of the 10 different seeds for each of the 9 market penetration rates at a significance level of 0.05.

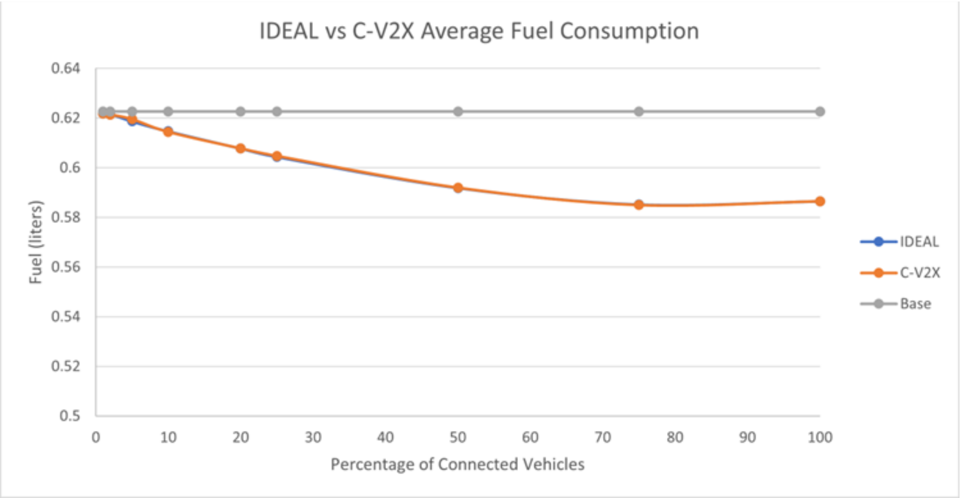

Figure 11. Average network-wide Fuel consumption of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 0.5.

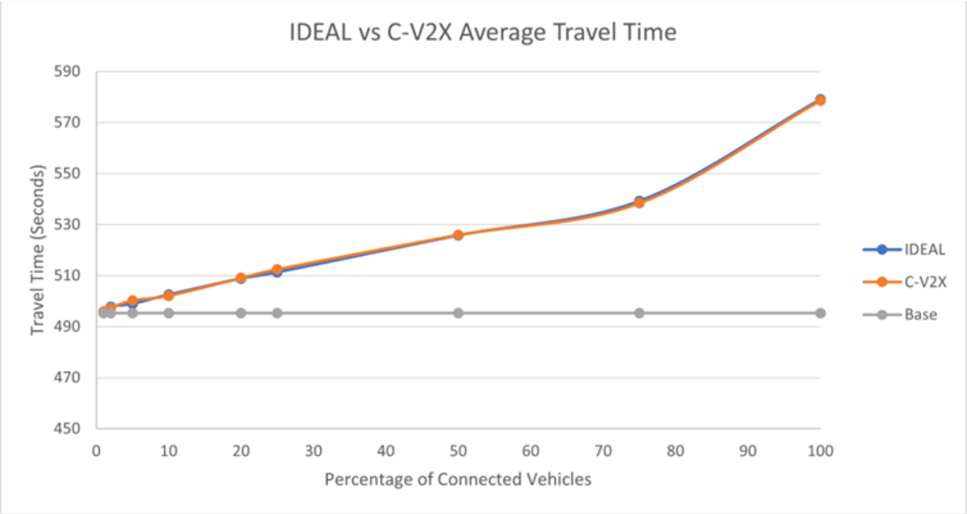

Figure 12. Average network-wide Travel Time of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 0.5.

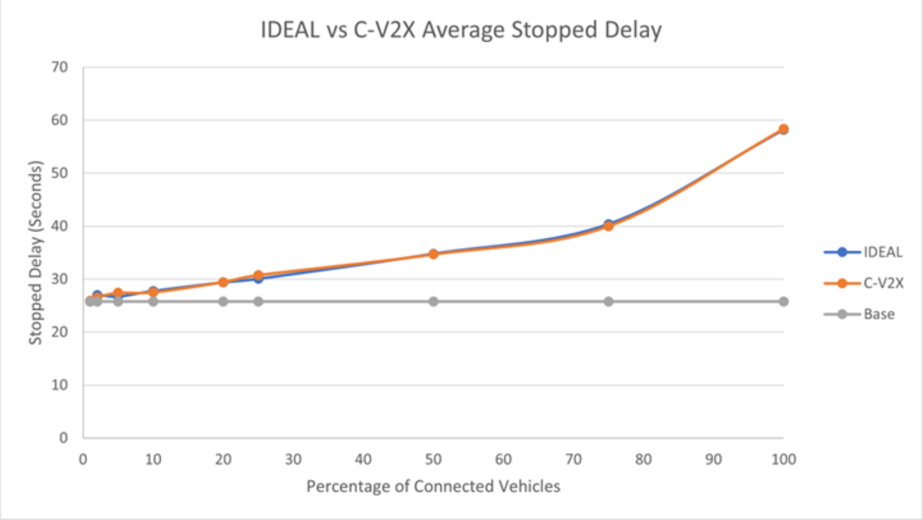

Figure 13. Average network-wide Stopped Delay of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 0.5.

3.6.4 Traffic Demand Scale of 0.25

The 25% traffic demand produced 34,449 vehicles during the first hour of the simulation. As expected, the C-V2X and IDEAL C-EEDR applications demonstrated the same behavior, as previous traffic demands in terms of the fuel consumption, travel time, and stopped delay, as shown in Figure 14, Figure 15, and Figure 16, respectively.

With low and medium traffic demands (25%, 50%, and 75%) levels, the C-EEDR application exhibits the normal behavior where decreasing the system-wide fuel consumption leads to increasing the system-wide travel time and stopped delay. However, at a high traffic demand level (100% case), the C-EEDR application not only decreased the system-wide fuel consumption but also managed to decrease the system-wide travel time and stopped delay in almost all of the market penetration rates except for the 100% one.

We ran the two-tailed t-test (p-values ranged between [0.18–0.96]) between the IDEAL-based C-EEDR and C-V2X-based C-EEDR applications and found that there was no statistically significant difference between the corresponding travel time, stopped delay, and fuel consumption of the means of the 10 different seeds for each of the 9 market penetration rates at a significance level of 0.05.

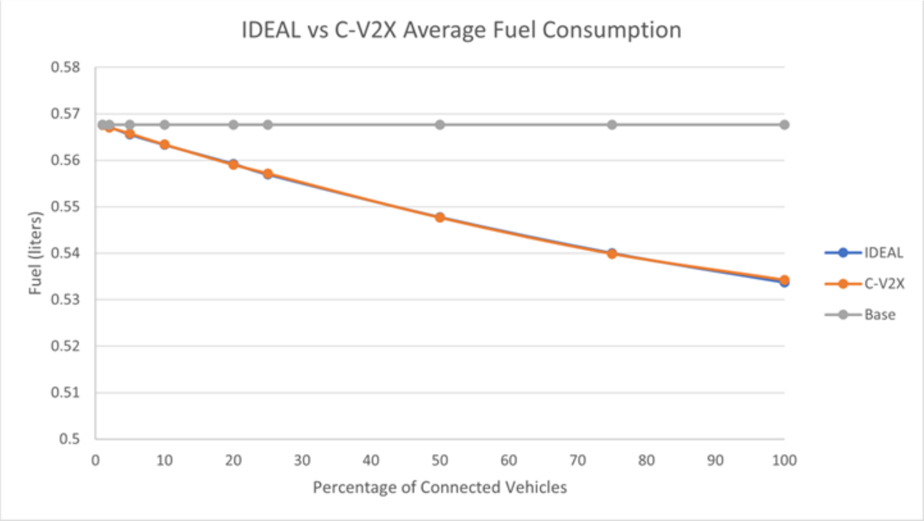

Figure 14. Average network-wide Fuel consumption of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 0.25.

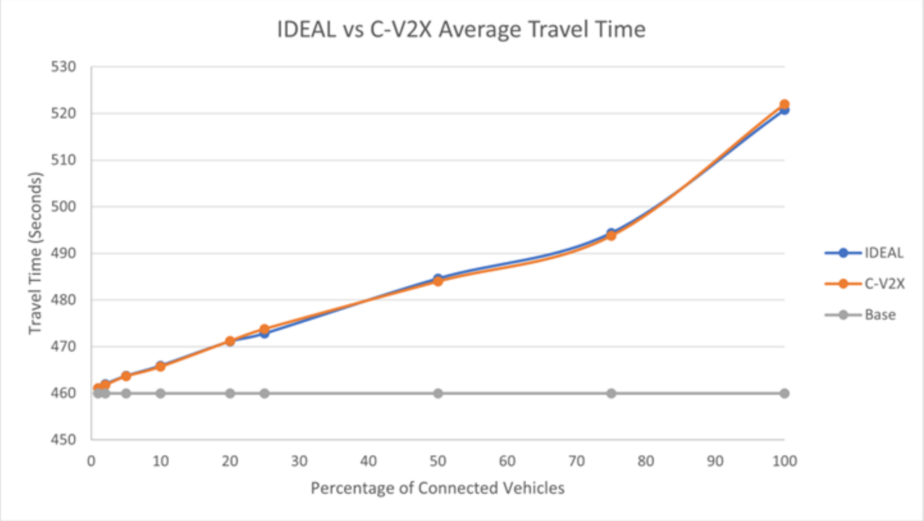

Figure 15. Average network-wide Travel Time of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 0.25.

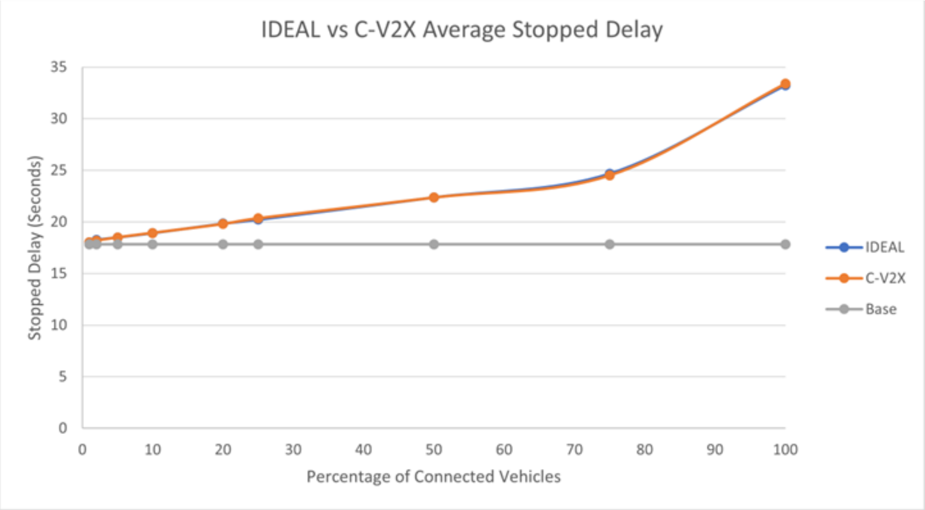

Figure 16. Average network-wide Stopped Delay of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with traffic demand of scale factor 0.25.

3.6.5 Fuel Saving

The maximum fuel savings were achieved (as expected) at 100% traffic demand with 18% savings at a 50% market penetration rate. At 75% traffic demand, the maximum fuel savings were 5% at a 75% market penetration rate. The maximum savings at 50% and 25% traffic demands were 6% at the 100% market penetration rate. Figure 17 shows the fuel savings for each of the four traffic demand levels at different market penetration rates.

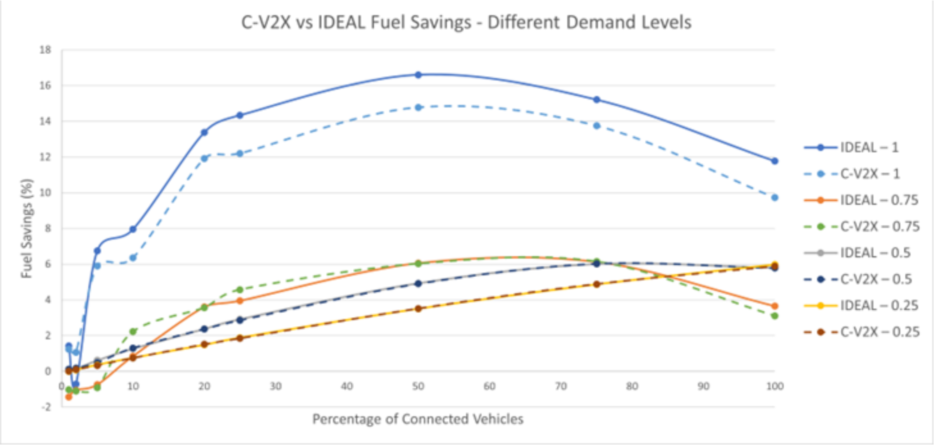

Figure 17. Average network-wide Fuel Savings of Energy-Efficient dynamic routing application using IDEAL and C-V2X communication on LA road network with different traffic demand scale factors.

3.6.6 C-V2X Communication Performance

To understand the behavior of the C-V2X C-EEDR application, we investigated the performance of the C-V2X communication system. We measured the average PRR value during the whole simulation in each simulation we ran. Figure 18 shows the PRR values at different market penetration rates for the four traffic demand levels (25, 50, 75, and 100%, respectively).

There are two observations to note here. First, as the traffic demand increases, the performance of the C-V2X communication system decreases. This is clear as the PRR value decreases with the different traffic demand levels at the same market penetration rate. Second, as the market penetration rate increases, the performance of the C-V2X communication system decreases. It is clear that as more connected probe vehicles enter the system, the traffic density increases and the traffic system becomes more congested, and, consequently, the communication system becomes more congested, which leads to more lost packets.

The C-V2X communication protocol provides reliability to the C-EEDR application with a minimum of 70% of the messages delivered in the case of 100% traffic demand and 100% market penetration and 80% of the messages received in the case of the 25% and 100% market penetration rate.

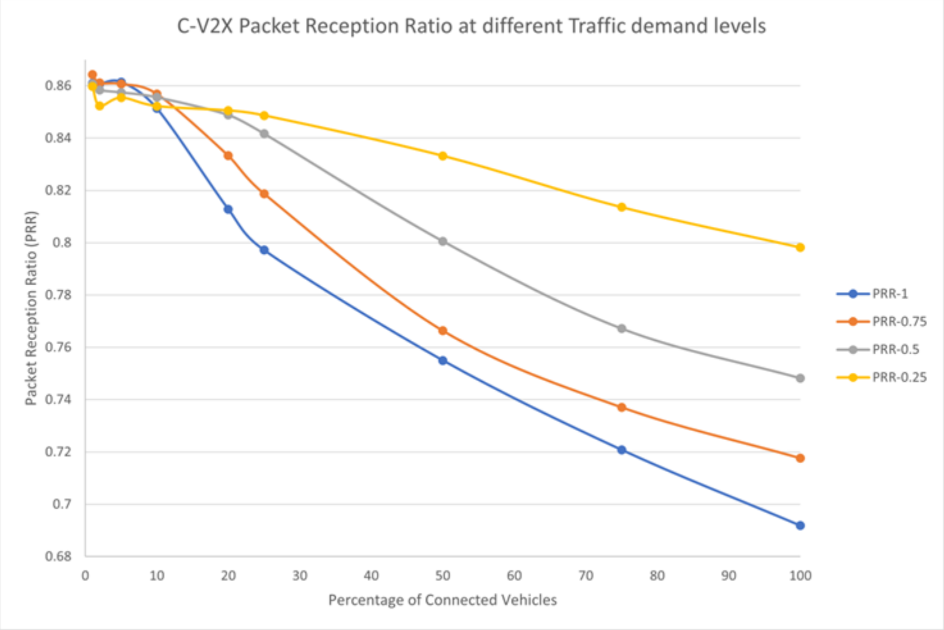

Figure 18. Average Packet Reception Ratio using C-V2X-based Energy-Efficient dynamic routing application in LA road network with different traffic demand scale factors.

4. Findings and Conclusions

The impacts of CV applications in previous studies have been based on assumptions in one field or another where the efficiency is perfect and/or with zero obstacles. This is not true in the real world. A realistic direction for further research into C-V2X is to incorporate the likely uncertainty in both systems, such as the effects of failures in the process of communication, the propagation of traffic flows where a bottleneck may move backwards or congestion may spill back and sideways to other locations in a road network, delays in responding to traffic congestion and traffic controls, mixed traffic with varied percentages of connected and regular vehicles, and many other dynamic characteristics of the transportation and communication systems.

Based on the findings of previous research, we recommend the following research directions:

1. Further research is needed to develop C-V2X application protocols that can define minimum modeling requirements. This could include variables like vehicle type, test location or network configuration, roadway congestion level, and market penetration levels.
2. Modeling tools that capture the interdependence of transportation and communication systems are critical to the assessment of CV applications. Further research is needed to develop scalable modeling tools that provide a good abstraction of the communication and transportation systems.
3. Validation of simulation-dominant studies using high fidelity modeling tools or real-world empirical data is needed.
4. Further work is needed to quantify the impact of varied MPRs and C-V2X applications using these integrated modeling tools to identify the most effective parameters and identify bottlenecks in the communication system.
5. The large-scale system-wide impact of C-V2X applications up to the country level should be investigated to support a transportation policy decision making process.

This study also studied the impact of C-V2X communication technology on the performance of an Energy-Efficient Dynamic Routing application. We leveraged a communication dataset to model the C-V2X communication system. The data were used to calibrate a general function that produces the Packet Reception Ratio (PRR) using the distances between the transmitting and receiving vehicles and the vehicle density in the vicinity of the receiving vehicle within the communication range. We incorporated the communication model in the INTEGRATION microscopic traffic simulator, which supports large-scale traffic simulations. The existing IDEAL C-EEDR application was modified to incorporate our C-V2X model and account for the C-V2X communication constraints (mainly packet losses). The C-EEDR application was evaluated using the IDEAL communication setting (default implementation without packet loss) and using the C-V2X communication model. The simulations were run on the Los Angeles (LA) downtown large-scale road network considering four traffic demand levels and nine market penetration rates. We also compared the performance of the C-EEDR application to the base case where the application is not enabled. The base case used the Frank–Wolf user equilibrium method for routing the vehicles in the road network.

The simulation results demonstrated that the C-V2X-based C-EEDR application followed the same behavior as the IDEAL-based C-EEDR application with a slight decrease in benefits. The results demonstrate that the C-EEDR application achieves a fuel savings of up to 16.6% and 14.7% in the IDEAL and C-V2X communication cases, respectively, for a peak hour demand on the downtown Los Angeles network considering a 50% level of connected vehicle market penetration. The results demonstrate that the fuel savings increase with the increasing levels of market penetration at lower traffic demand levels (25% and 50% of the peak demand). At higher traffic demand levels (75% and 100%), the fuel savings increase as market penetration levels increase, with maximum benefits at a 50% market penetration rate. Although the communication system is affected by the high density of vehicles at high traffic demand levels (75% and 100% the peak demand), the C-EEDR application manages to perform reliably, producing system-wide fuel consumption savings. The C-EEDR application achieves fuel savings of 15.2% and 11.7% for the IDEAL communication and 14% and 9% for the C-V2X communication at 75% and 100% market penetration rates, respectively. Finally, the study demonstrates that the C-V2X communication constraints only affect the performance of the C-EEDR application at the full demand level when the market penetration of the connected vehicles exceeds 25%. This degradation, however, is minimal (less than a 2.5% reduction in fuel savings).

The C-V2X communication protocol demonstrated a reliable performance that allowed the C-EEDR application to achieve benefits even in the highest traffic demand levels (100%) and at full market penetration rates (100%) in contrast to previous studies, where the traffic system failed due to the failure of the underlying communication system used on highly congested transportation networks.

The results demonstrate the importance of the C-EEDR application when applied in highly congested road networks, where the application managed to achieve savings not only in fuel consumption but also in the average system-wide travel time and the stopped delay.

Appendix A

Abbreviations

5G - the 5th generation mobile network
ACC - Adaptive Cruise Control
BEV - Battery Electric Vehicle
CACC - Cooperative Adaptive Cruise Control
C-EEDR - Connected Energy-Efficient Dynamic Routing
C-ITS - Cooperative Intelligent Transport System
Coop-EAD - Cooperative Eco-Approach and Departure
CPI - Crash Potential Index
CV - Connected Vehicle
C-V2X - Cellular Vehicle-to-Everything
CVIC - Cooperative Vehicle Intersection Control
CVLLA - CVs and lower-level automation
DSRC - Dedicated Short-Range Communication
ECMS - Adaptive Equivalent Consumption Minimization Strategy
Eco-CAC - Eco-Cooperative Automated Control
Eco-CACC - Eco-Cooperative Adaptive Cruise Control
EPA - Environmental Protection Agency
GLOSA - Green Light Optimal Speed Advisory
HEV - Hybrid Electric Vehicle
ICEV - Internal Combustion Engine Vehicle
IDCVS - Integrated Distributed Connected Vehicle Simulator
ITM - Intelligent Traffic Management
MPR - Market Penetration Rate
NB - Nash Bargaining
PER - Packet Error Ratio
RSU – Roadside Unit
SAS - Speed Advisory System
SPD-HARM – Speed Harmonization
TCP - Transmission Control Protocol
TET - Time Exposed Time to Collision
TIT - Time Integrated Time to Collision
TNO - Netherlands Organization for Applied Science
TTC - Time-to-Collision
V2C - Vehicle-to-Cloud Communication
V2D - Vehicle-to-Device Communication
V2G - Vehicle-to-Grid Communication
V2N - Vehicle-to-Network Communication
V2P - Vehicle-to-Pedestrian Communication
V2V - Vehicle-to-Infrastructure Communication
V2X - Vehicle-to-Everything Communication
VMT - Vehicle Miles Traveled
VNS - Vehicular Network Simulator
VSL - Variable Speed Limit

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