Final Report

Investigating the Effect of Connected Vehicles (CV) Route Guidance on Mobility and Equity

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16. Abstract

Traffic congestion is a serious and increasing national problem, especially for urban commuters. Providing accurate real-time traffic information is a key tool to reduce congestion. Recent studies have shown that connected vehicles (CVs) can help improve traffic mobility and safety while saving energy and reducing emissions. The research initially evaluates the gradual deployment of CVs and their effect on mobility, energy consumption, and the amount of pollutants. Then, our research investigates the CV guidance system as an emerging form of dynamic route guidance. This research develops and calibrates a microscopic traffic simulation model to replicate the fairly realistic behavior of such vehicles in the traffic simulation environment. Unlike the majority of prior studies that used hypothetical study areas with simple networks, this study develops a real-world medium urban road network. Different penetration rates of CVs (0%-100%) are developed, and the system-wide effects of CV-equipped vehicles with route guidance features on mobility and equity are analyzed. The results showed that as the market penetration rate (MPR) of CVs increases, traffic parameters (e.g., total delay time), total emissions, and average travel time of re-routing paths decreases. In order to find the effects of new traffic reduction policies for mass public transportation systems, dynamic CV bus lanes were suggested. The results showed that increasing the service time of a dynamic CV bus lane may improve average travel time for CV buses, but it negatively affects the average travel time of non-CV and CV cars. Finally, a network-wide average travel time analysis is proposed. Based on the proposed methodology, 85% MPR was determined as a critical breakpoint of the network-wide weighted average travel time chart. The results of network-wide equity analysis highlighted that, as the MPR of CVs increases, the percentage of critical breakpoint decreases, and that point shifts to the left of the chart.

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ABSTRACT

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1. INTRODUCTION

Traffic congestion and safety have been major concerns for government organizations for a long time. According to 2020 Census Bureau statistics, the average commute time to work was estimated to be 53.2 minutes, assuming one round trip (1), and the historical data reflects that from 1990 to 2017, the average daily commute in the United States has increased from 49.35 to 55.62 minutes (1). Due to the increasing number of cars in the United States, 276.5 million registered in 2019 (2), and the high percentage of hours lost in traffic due to congestion, 99 hours in 2019 (3), new technologies such as dynamic route guidance could potentially shorten commute times and improve congestion problems. Earlier research suggested that route guidance technology, especially dynamic route guidance, can improve traffic congestion better than static routing technology (4).

The emergence of Connected Vehicle (CV) technology provided the proverbial light at the end of the tunnel by solving the traffic congestion problem. Previous studies before the advent of CV technologies showed a close relationship between driver behavior and mobility (5, 6) along with safety (7-9), providing significant evidence that these relationships are affected by route guidance technology. Along these lines, it has been established that most of the crashes in the urban traffic environment are directly or indirectly caused by anger and aggressive driving behavior in response to extended travel time and congestion (4, 10, 11). In 2019, a total of 36,096 fatalities occurred in the U.S. (47). Distracted driving, drunk driving, speeding, running red lights and stop signs, reckless driving, fatigue, and aggressive driving are the most important causes of accidents. One solution to diminish the number of crashes will be using connected vehicles (CVs). Connected vehicle technology is a fast-growing concept aiming to develop a fully connected transportation system that enables data exchange among vehicles, infrastructure, and mobile devices to improve mobility, safety, and environmental impacts. One of the CV applications is route guidance, based on vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-smart terminal (V2T) technologies. The dynamic route guidance algorithm of the CV application facilitates real-time traffic information in routing choice. It receives information through V2V and V2I technologies faster than the traditional system, and the driver can be informed immediately about a shorter routing option. It helps the driver select the best substitute path when the road becomes congested. The more vehicles and infrastructures are equipped with CV technologies, the more effective the route guidance will be. The CV-equipped drivers will experience a shorter travel time due to more updated knowledge of routes' conditions.

On the other hand, traditional route guidance is slower to detect an incident or congestion to offer rerouting information. Increasing the amount of CVs will enable users to share more data, and more accurate information will reduce travel time. Additionally, the V2T communication technology of the CVs will provide information to a traffic control center faster than the conventional system, which in turn will result in more frequent warnings and updates on Dynamic Message Signs (DMSs) for the non-CV users. Several studies have been conducted on the CV route guidance algorithms and the effectiveness of the system (12-15), but only a few have been done on mobility and equity.

According to the literature, different predictions have been presented regarding the market penetration rate of CVs in the U.S. Bansal and Kockelman (16) mentioned it was 9.33% in 2016 and expected to reach 27.66% in 2020 and 98% by the year 2030. The U.S. Census Bureau predicted it at roughly 97% in 2035 (17). Connected vehicles have the potential to transform travel patterns through the creation of a safe, interoperable wireless communications network – a system that includes cars, buses, trucks, trains, traffic signals, smartphones, and other devices. Enhancing the number of CVs on the roads will result in safety, mobility, environmental, and socioeconomic benefits. It is worth noting that combinations of V2I safety and road weather applications are effective in reducing crashes (safety benefits). Combinations of V2I applications are effective in prioritizing signal timing and reducing travel time and overall delay (mobility benefits). V2I applications have potential congestion and lane management capabilities and can reduce fuel consumption and emissions (environmental benefits). Regarding the socio-economic benefits of CVs, a 2015 Intelligent Transportation Society of America study examined existing research to estimate the comprehensive costs of a crash and the number of crashes that four connected vehicle safety applications may prevent. The study concluded that the applications could result in $178.8 billion in societal benefits annually if deployed across the entire U.S. vehicle fleet. This includes tangible economic benefits such as avoided medical care costs and productivity losses, as well as intangible benefits such as reductions in quality of life as a result of a motor vehicle crash (18).

However, CVs and other advanced technologies will likely exclude low-income families, who will find them unaffordable and miss out on their benefits. Additionally, these technologies may not be suitable for people with mobility challenges, travelers with disabilities (mobility-impaired, color-blind, hearing-impaired, etc.,) and seniors. Therefore, these technologies may exacerbate existing barriers and increase inequality. Policymakers must not only consider how to deploy these technologies safely in a timely manner but also how to use them to improve the lives of those who need them most.

1.1. Problem Statement

A few studies applied different types of microsimulation software to model CV technologies in a hypothetical network. Microsimulation is a software-based technique widely used in traffic and Intelligent Transportation Systems (ITS)-related studies that allows researchers to test, design, and conduct sensitivity analysis for CV technologies. The most commonly used microsimulation software packages were VISSIM (19), CORSIM (20, 21) and PARAMICS (22, 23) along with major integrations such as VISSIM and NS-2 (24), and AIMSUN and Qualnet (25). The TSS company, the provider of AIMSUN software, recently added a V2X module to this software. The V2X Software Development Kit (SDK) is designed to allow a modeler access to the core V2X framework in AIMSUN Next to implement connected vehicles within a simulation. CVs are able to exchange information about their location and activity. By aggregating this information, a vehicle is able to infer the pattern of the traffic around it and amend its own behavior accordingly (26). Researchers who applied these packages concluded that there was a significant decrease in travel time for CVs due to V2V and V2I technologies (13-15). The information shared by CVs includes vehicle positions, speeds, travel times, weather conditions, and incidents. These are conveyed to the traffic center through Roadside Units (RSUs), allowing traffic center operators to update DMSs with real-time information in addition to disseminating this information to other CV-equipped vehicles in the system. Unequipped drivers directly benefit from CV technologies through DMS messages and reduced sizes of backups. Some mobile technologies such as Waze (based on crowdsourcing) allow users to disseminate information but are highly distracting as they engage the driver's attention (brain, eyes, and hands). Accordingly, the CV route guidance technology will eliminate the driver's engagement and interaction while driving and help drivers navigate in a better way. Other research also suggested that the route guidance technology of CVs can potentially improve mobility and traffic safety in various conditions such as work zones (27).

The main focus of the research (27) was to evaluate the potential benefits of developing and deploying a Vehicle-to-Vehicle communication system (V2V) to improve safety around work zones. Microsimulation traffic modeling was employed in this research to precisely model and implement a Connected Vehicle Environment. Researchers, e.g., (15), investigated the benefits of the route guidance technology of CVs when an incident happens. Their research concentrated on assessing the benefits of V2V communication in high-incident cases resulting from extreme conditions, such as adverse weather conditions. The results of intensive experimentation showed an overall improved network performance and reduced incident occurrence rate. The reduction in path travel time not only benefitted V2V-enabled vehicles but all vehicles. Although V2V-enabled vehicles exhibited significant reductions in their path travel time, their counterparts without V2V also had pronounced reductions in their path travel time as a result of fewer slow V2V vehicles traveling on their path. Researchers, e.g., (28), presented the impact of connected vehicles on the effectiveness of VSL (Variable Speed Limit) on a freeway bottleneck section by using a microscopic simulation model. Simulation experimental results showed that a CV-powered VSL improves the traffic congestion conditions by up to 7% to 12%, depending on CV market penetration rates. Last but not least, researchers, e.g., (29), investigated significant factors of CVs' average lane speed. The results indicated that the LSM (Lane Speed Monitoring) application benefits the individual user even under a low market penetration rate. Moreover, vehicles equipped with the application demonstrate up to 11% average speed improvement. According to the aforementioned studies, an increase in the number of CVs on the network will decrease the average travel time. In this study, we will evaluate the range of changes, the accuracy of this statement, and whether increasing the number of CVs will improve other traffic parameters.

1.2. Goal

This study uses a realistic small urban road network in the microsimulation platform to assess the effectiveness of CV dynamic routing guidance. A microscopic traffic simulation model is developed to simulate the driving behavior of CV guidance with various penetration rates of CVs under various traffic conditions. The findings from this research provide insight into the impacts of the gradual deployment of CVs on mobility and equity, which helps planners develop public policies or regulations based on the suggested results in this research. It also assists transportation agencies to equip roads with an optimum number of RSUs to take advantage of their capabilities in incident detection and congestion relief. Additionally, the study provides recommendations regarding after-market packages to be used for low-income non-CV vehicle owners, as well as information dissemination methods to accommodate mobility-challenged travelers in CVs. Consequently, the study considers different levels of market penetration of CVs (0%-100%) to evaluate and analyze the system-wide effect of CV route guidance technology on mobility and equity. It is worth mentioning that the study does not evaluate the route guidance technologies and algorithms since the focus is on how such technology affects equity and mobility.

2. LITERATURE REVIEW

Traffic congestion has become one of the most pressing concerns for transportation engineers. In the U.S., the total cost of lost productivity due to congestion was nearly $87 billion in 2018 (30). Various types of efforts have been made to control traffic congestion, one of which is providing travelers with real-time traffic information. Connected Vehicles (CVs) technologies can improve traffic mobility by sharing real-time traffic information. At the top of vehicular communication systems is the vehicle to everything (V2X) communication. The concept of a “connected car” is not new to the automotive industry; however, the technology to make it possible, as well as the necessary communication standards, was not available until a few years ago. There are 7 types of vehicle connectivity encompassing V2X communications (31):

- Vehicle to network (V2N)
- Vehicle to infrastructure (V2I)
- Vehicle to vehicle (V2V)
- Vehicle to cloud (V2C)
- Vehicle to pedestrian (V2P)
- Vehicle to device (V2D), and
- Vehicle to grid (V2G)

Vehicle to vehicle (V2V) is a connected vehicle technology that can share information to ensure smooth traffic mobility and safety. This interchange is done wirelessly via dedicated short-range communication (DSRC) frequencies, the same used in V2I communications. Thanks to V2V, vehicles can share their speed, location, and heading, as well as any other relevant information, giving the system a 360-degree representation of its surroundings. Since V2V communications were conceived as a mesh network, each vehicle becomes a node that can capture, send, and retransmit signals. Since V2V is an integral part of V2X and V2N, nodes also include smart traffic signals, road sensors, and other V2I components.

The CV guidance system can provide dynamic route guidance. CVs’ sharing of travel information can be used as an input for dynamic route guidance to minimize travel time and increase mobility and equity. In a network, when connected vehicles share information about the traffic conditions, drivers can avoid congested routes and divert to less congested ones to reduce their travel time. In addition, drivers selecting an alternative route may help habitual drivers improve their travel time as well. This will not only serve for better mobility but will also help address the “vertical equity” concept in transportation, which proposes dividing users into different groups based on demographic criteria. Vertical equity is the idea that people with higher incomes should take on a greater share of the responsibility for paying for public services.

The following literature review is divided into four sections to follow previous studies on Route Guidance, CV Route Guidance for Mobility and Safety, Traffic Simulation of CVs, and Equity in Transportation.

2.1. Route Guidance

The route guidance system (RGS) is considered an effective way to alleviate traffic congestion by providing navigational assistance to new or regular drivers for the decision-making process along with increasing the level of service of the highway, local and arterial roads (31). The routing application in the navigation system calculates the shortest distance and minimum travel time between any origin and destination at any time and conveys the options to the drivers to help them make better routing decisions. Indeed, RGSs use macroscopic approaches to generate flow-level route guidance and provide homogeneous guidance to all drivers who belong to the same flow, which may simply shift the ongoing congestion from one point to another (32).

Two major routing options are static and dynamic route guidance systems. The static routing algorithm is less accurate in calculating optimal route (OR) and travel time (TT) as it is restricted in receiving real-time traffic information, such as congestion, incidents, etc., for updating the route choice. The relevant shortest routing algorithms applied in earlier studies were the Bellman-Ford (33), Dijkstra (34), a bidirectional (35), and a heuristic algorithm (36). Dijkstra is one of the most commonly used algorithms. The great advantage of Dijkstra is that it discovers the whole network, and it is quite simple, but its disadvantage is having too many time-consuming steps.

On the other hand, “the dynamic route guidance method” obtains real-time traffic information and updates route choice, providing more accurate TT and OR. One example of dynamic route guidance is the location-based system developed by the Korea Highway Cooperation (KHC) for mobile phone users of the country. The proposed system demonstrated how to use historical and real-time data in predicting link TT for the near future (37). An intuitive encoding scheme was used to solve the shortest route problem in a dynamic network, but that did not demonstrate satisfactory performance in the first-in-first-out (FIFO) property. However, the results indicate that the dynamic route guidance A* algorithm is suitable for the route guidance difficulty in a FIFO dynamic network, the dynamic route guidance Q-learning algorithm is suitable in a steady non-FIFO dynamic network, and the dynamic route guidance genetic algorithm is suitable in a vertiginous non-FIFO dynamic network (38).

In the past 20 years, dynamic traffic models (DTMs) have been recommended by different researchers to manage the urban traffic network and help users better navigate the transportation network. (39) suggested a DTM that could identify the route choice behavior of the users and at the same time consider different topological grades of the network, and suggested that the scale-free network could bear a more substantial capacity of traffic flow than a random network. The study also identified that between the two types of route guidance systems, the dynamic system is more efficient in solving the congestion problem than the static system because it can receive real-time information and avoid congestion situations at the cost of computation complexity. In another instance, (40) concentrated on several simulations on the basis of symmetry models, implemented in practical cases to streamline vehicle density and reduce traffic congestion. Their research highlighted that the car network and the blocked route have been improved by technical implementations such as dynamic rerouting or the elements of modern road infrastructure. Furthermore, the simulations were made on the propagation of traffic and the occurrence of congestion depending on the density of cars and the established graphic model, thus obtaining defining elements through which traffic congestion can be dispelled.

Regarding the dynamic route guidance system, there are two traditional centralized and decentralized classifications. The specifics of a centralized dynamic route guidance system include communication and information sharing between vehicles and traffic information centers to provide reliable TT and OR information. The decentralized one operates within the vehicle unit and provides routing options based on estimated link TT. Investigation of the centralized route guidance system architecture was conducted by the Bell-Northern Telecommunication Research Center, where the optimum routes were selected based on probabilities (41). In a centralized route guidance system architecture, different subsystems work with each other to find the best shortest path. Examples of subsystems are:

- "passive system," which provides responses for trip legs, a routing engine (with PT stops and timetable), a list of exchange points (with global ID), and a gazetteer (with names and geolocations),
- "client system," which provides the GUI to the end-use and sends a Trip Request to the active system with origin and destination information,
- "active system," which forwards this request to the distributing system, and
- "distributing system," which splits the journey planning request into pieces; it sends the request for trip legs to the passive systems and creates trip composition.

In another study, systems' optimal logic was applied in a centralized architecture to provide real-time route guidance within a congested road network (42). The study performed a comparative analysis to gauge the performance of the distributed control structure against a benchmark scenario of the time-dependent system-optimal logic in a centralized architecture. The assessment was conducted under various scenarios of different incident links, durations, and severity. The findings of the simulation-based experiments indicated that the distributed scheme is more robust than the centralized time-dependent scheme under incident conditions.

Besides that, the decentralized system was investigated in an urban network through feedback from a decentralized optimal traffic control method (43). Another study proposed a decentralized route guidance algorithm that successfully responded to small amounts of network stochastically, as well as congestion caused by incidents, and illustrated the potential of tuning the parameters of the algorithm with real-time traffic conditions through intelligent vehicle technologies (44). In their research, an algorithm was implemented and tested on a small sample network in which both guided and unguided drivers could be modeled.

2.2. Connected Vehicle Route Guidance for Mobility and Safety

A U.S. Census Bureau 2021 report highlighted that in 2006, the average travel time nationwide for one-way trips was 25 minutes. The increase of about 2.6 minutes between 2006 and 2019 represents an increase of about 10% over 14 years. The longest average travel times were associated with various forms of public transportation. For example, workers who traveled to work by bus had an average one-way commute time of 46.6 minutes (45).

Earlier research suggested that route guidance technology, especially dynamic route guidance technology which works better than a static version, can improve the congestion scenario (4). They conducted a questionnaire survey of 171 English drivers and investigated the relationships between trait aggressiveness, self-reported driving violations, and perceptions of the commission of driving violations by others, using the extended violation scale of the Manchester Driver Behavior Questionnaire (DBQ). The results of this research showed that those who scored high on anger and hostility were also more likely to have been involved in a road traffic accident.

The relationship between driving behavior and mobility was studied by (46) that is affected by route guidance technologies. They evaluated the potential effects of route guidance under a CV environment on an urban traffic network in terms of traffic mobility and safety, using microsimulation and driving behavior that was modeled through aggressiveness and awareness of drivers. Simulation results showed that the market penetration level of connected vehicles has little impact on the mobility and safety of the road network. A shorter updating interval was shown to be likely to lead to better mobility, while the safety of the road network is likely to decline under the assumptions embraced in the simulation.

In 2019, a total of 33,244 fatal crashes took place on U.S. roadways (47). This resulted in 11 deaths per 100,000 people and 1.11 deaths per 100 million miles traveled. A set of research outputs revealed that almost all the crashes took place in the urban traffic environment and were directly or indirectly caused by angry and aggressive driving behavior that was a corresponding response or temporary emotional outbreak due to extended travel time and traffic congestion (4, 10, 11, 48). Although driving assistance technologies have improved traffic safety, equal importance should be given to driver behavior as well (48-50). Thus, it is necessary to evaluate the effectiveness of dynamic route guidance technology in a connected vehicle environment.

The definition of a Connected Vehicle (CV) refers to vehicles equipped with devices (e.g., On-Board Unit - OBU) that connect with other vehicle devices, networks, and infrastructures outside the vehicles such as Roadside Units (RSUs), Transportation Management Center (TMC), etc. Definitions of these parts are:

- The OBU provides the receiver and transmitter in a vehicle, with the proportion of vehicles equipped with each type of OBU defined in the vehicle type. Each OBU is capable of using one or more channels to receive one or more message types on each channel.
- The RSU is the "I" component of the Vehicle to Infrastructure (V2I) communications network. An RSU has a physical location, connections to road network nodes, a set of channels it can use, and a set of message types it can transmit and receive. It may also communicate with a traffic management center (TMC). RSU is a physical device, which communicates through the same channels as the vehicle OBUs and exchanges the same messages, but is anchored at a specific location and has a defined range of communication. Communications are received from vehicles equipped with a compatible OBU that are currently within the RSU's defined area. The RSUs may also exchange data with a TMC on a different channel type. Depending on range

and connectivity, vehicles then form ad-hoc VANETs based on a common channel. There are different types of RSUs on the market.

- The Traffic Management Center integrates the data from multiple RSUs and initiates coordinated signal control and traffic management actions. It communicates to the RSUs via a separate channel type which may now be based on wired links or dedicated radio channels through a local area network or the internet to share traffic and vehicle information.

Earlier studies identified that mobility depends not only on the route guidance but also on the information update interval of CVs (46). The CV technology is proliferating in the transportation system, aiming to improve mobility and road safety through the rapid development and gradual deployment of such vehicles. OBUs and RSUs communicate using a dedicated short-range communication (DSRC) technology that is more secure and faster than Wi-Fi, which provides communication without interaction. Recently another technology called long-term evolution (LTE) wireless communication system has become available, although DSRC has been the established one in the transportation sector. Types of information shared by both technologies are the vehicles' position, velocity, origin/destination, trajectory, and travel time, etc. (13).

Meanwhile, V2V and V2I technologies are assumed to reduce fatalities and accidents, increase road safety and decrease travel time for better mobility (46). The U.S. Department of Transportation referred to V2V as a crash avoidance technology, which relies on communication of information between nearby vehicles to potentially warn drivers about dangerous situations that could lead to a crash. For example, V2V could warn a driver that a vehicle up ahead is braking and they need to slow down, or let a driver know that it's not safe to proceed through an intersection because another car yet unseen by the driver is quickly approaching. It is worth noting that in this process DSRC can enable a number of safety "applications" that help drivers with different aspects of driving, such as warning about stopped vehicles in the road ahead, vehicles speeding unexpectedly through intersections, vehicles in blind spots, etc.

Previous studies before the innovation of CV technologies showed a close relationship between driver behavior and mobility (5, 6) along with safety (7-9). Other research also suggested that the route guidance technology of CVs can potentially improve mobility and traffic safety in various conditions such as work zones (27, 51), incidents (15), intersection operation efficiency (52), and average lane speed (29). Significant factors of CV technologies are the rate of market penetration with regular traffic and the interval rate of information dissemination. The market penetration rate of CVs in the U.S. was 9.33% in 2016, and that is predicted to reach 27.66% in 2020 and approximately 98% by the year 2030 (53, 54). According to the Mobility Market Outlook report, 79.86% of passenger cars sold in 2020 are connected (53). Vehicles well-equipped with technology can provide real-time traffic and on-ground information to other CVs and Traffic Management Centers (TMCs). Indeed, V2V communication's ability to wirelessly exchange information about the speed and position of surrounding vehicles shows great promise in helping to avoid crashes, easing traffic congestion, and improving the environment. But the considerable benefits can only be achieved when all vehicles can communicate with each other. Whenever these conditions are met, CVs can gain the required up-to-date information in a shorter time interval. This issue will quickly provide updated route guidance to users and reduce the overall travel time along with congestion for both CV and non-CV users.

2.3. Traffic Simulation of CVs

The number of connected vehicles will increase over time. This raises associated questions such as how many CVs will deploy from time to time, what will be the rate of mixing with conventional traffic, how will complexities be incorporated, etc. Previous studies applied multiple equilibrium behaviors (i.e., mixed User-Equilibrium -UE for CVs and Stochastic User-Equilibrium assignment -SUE for non-CVs) along with a sensitivity analysis to estimate the impact of different market penetration levels of CVs in various environments (6, 56, 57). In recent times, microsimulation studies were conducted in different environments, weather, road networks, and traffic levels to evaluate the impact and performance of CVs.

Software-based microsimulation has been used recently to evaluate the feasibility and effectiveness of various approaches to improve mobility in advanced transportation systems. PARAMICS set adverse weather conditions, along with incidents in the simulation environment, and identified the positive impact of CV deployment in reducing network travel time within a moderate to high level of traffic congestion (15). The safety aspect associated with different levels of market penetration of CVs was studied in 2016, and the result showed that less than 40% of market penetration of CVs provided a safer traffic network in special road conditions such as a work zone to maintain the standard mobility (51). In 2014, the authors also had focused on micro-modeling and quantitatively assessing the potential impacts of CVs on mobility, safety, and the environment under non-recurrent congestion scenarios, such as incidents, lane closures, and construction work zones. The results of their simulation indicated that CVs have the potential to 1) improve travel times by 37%, 2) reduce CO2 emissions by 30%, and 3) improve safety, as measured by Time to Collision (TTC), by 45%.

Through microsimulation, a Lane Speed Monitoring (LSM) application based on V2V communication was proposed to identify in-lane real-time vehicle status (29). This application takes advantage of Basic Safety Messages (BSM), transmitted from equipped vehicles via dedicated short-range communication (DSRC), to estimate the real-time traffic states at the lane level. It then recommends the optimal lane selection to the driver. Results indicated that the LSM application benefits the individual user even under a low market penetration rate. Vehicles equipped with the application demonstrate an average speed improvement of up to 11%.

Other researchers evaluated the potentialities of the CV to increase mobility and traffic safety and reduce greenhouse gas emissions. The results demonstrated the effectiveness of CVs in improving all three aspects and provided quantitative results on how the market penetration rates proportionally affect the traffic network’s performance. Besides the impact of CV technologies in the traffic system, (58) also considered information that updates time intervals. The developed API providing vehicle trajectory and conflict prediction messages could improve traffic safety all over the network. In general, with a 0% to 50% market penetration rate, travel time experienced a 37%

enhancement, but when the market penetration rate increased to 60%, average travel time began to decrease.

Several types of research have been conducted to identify and evaluate the positive impact of CV technologies on enhancing mobility and safety, but none have concentrated on quantifying these benefits under a realistic environment (13). The researchers developed both analytical and simulation models to study the market penetration (MP) effect and connection range (CR) of CVs in a traffic network. Their research showed that critical MP is sensitive to CR and vice versa, and reasonable MP and CR of CVs can reduce average travel time by 20% (54). Their research presented an integrated multi-agent approach, coupled with percolation theory and network science, to measure the mobility impacts (i.e., mean travel time of the system) of a CV network at varying levels of market penetration rate. The results of their research showed that:

(1) Percolation phase transition phenomenon is a function of both market penetration and communication range;
(2) Percolation phase transitions in both mobility and a CV network are highly correlated;
(3) The application can reduce the average travel time of the system by up to 20% with reasonable market penetration and communication range;
(4) Critical market penetration is sensitive to communication range, and vice versa;
(5) At least 70% of the CVs on the network were shown in the same cluster for mobility benefits to appear; and
(6) For high levels of MP or CR, a low probability of connectivity does not dramatically change the mean travel time.

Mobility performance was measured by the Average Trip Time (ATT) and Average Vehicle Trip Speed (AVS) along with a surrogate measure, the Time-To-Collision involved Incident Rate (TTC-IR), which was used to assess safety (59). Their observations revealed that as CV market penetration increased from 0% to 50%, ATTs decreased, while the opposite was true for non-CVs. In addition, according to the simulation and its assumptions detailed in their paper, a shorter updating interval is likely to lead to better mobility, while the safety of the road network is likely to decline. By contrast, the simulation also showed that a longer updating interval is likely to lead to better safety and decreased mobility.

The researchers like (65) used a VISSIM micro-simulator for various route guidance strategies of CVs and considered factors such as market penetration of connected vehicles, congestion levels, updating intervals of route guidance information, and drivers' compliance rates. The study used a hypothetical road network with 21 signalized intersections, four stop-controlled intersections, freeways, major and minor corridors, and two major incidents with different occurrence times and durations. The sensitivity analysis of different route guidance strategies was conducted with factors such as market penetration of CVs, congestion levels of a road, and compliance rates. The results showed improved travel time compared with the base scenario, and route guidance significantly reduced travel time over the no-guidance case. Among four route guidance strategies, the weighted average link travel time-based guidance performed the best.

In other research regarding the benefits of microsimulation of CVs, a self-developed API was used in PARAMICS to model vehicle-to-infrastructure. The authors considered only V2I communication protocols, not V2V, and the results showed that a higher penetration rate of CVs was beneficial for collecting vehicle data such as location, route, and travel time (60). These simulation results showed the sensitivity of probe data collection to communication range, market penetration, number of active roadside communication units (RSUs), interval between snapshots, and snapshot buffer size. Impacts on link travel time estimates are also presented. These results clearly demonstrated the utility of the simulator in conducting evaluations and sensitivity analyses for scenarios that would be difficult to execute in existing test beds.

A study to mitigate nonrecurring congestion due to incidents using V2V communication in PARAMICS was conducted by (15). Researchers developed two APIs, one that created an incident and another that transmitted that information to equipped vehicles to improve awareness and decrease aggressive driving in the incident zone. The authors considered different market penetration rates of CVs and assumed that informed drivers are more aware and less aggressive. In response to the information disseminated, drivers of V2V-equipped vehicles were modeled to exhibit increased awareness and decreased aggressiveness when approaching the road hazard location. In addition, these drivers received timely updates of the network travel time and, as a consequence, could make more informed route choices. The results of intensive experimentation showed an overall improved network performance and reduced incident occurrence rate. It is worth noting that the reduction in path travel time not only benefitted V2V-enabled vehicles but all vehicles.

Multiple studies also identified that real-time information provision increases drivers' awareness and decreases aggressiveness (61, 62). Commuters' route choice behavior in response to traveler information systems was addressed by (61). The simulation results supported the notions that commuters' decisions to divert to alternate routes are influenced by their socio-economic characteristics, the degree of familiarity with network conditions, and the expectation of improved travel time that exceeds a certain delay threshold associated with each commuter. As well, the results showed improvements of 4%-7% in network speeds; 5%-8% in network delays; 7%-11% in stop time per vehicle, and 1%-3% in-network travel times. The relationship between a passion for driving and aggressive driving behavior in three studies was investigated by (62). Study 1 examined the association between passion and aggressive driving behavior in a sample of undergraduate students, study 2 replicated these results with an ecologically valid sample of community-dwelling drivers, and study 3 replicated the results obtained in studies 1 and 2 in a laboratory setting using a driving simulator under controlled frustrating driving situations with judges assessing aggressive driving behavior.

Additionally, Olia et al. conducted microsimulation studies to identify the impacts of CV market penetration on overall network performance. Their results suggested that the market penetration threshold is 50% for CVs. More than 50% of CV market penetration will negatively impact the performance of the network (27, 63).

Some researchers used microsimulation to investigate the relationship between the CV market penetration rate and change in travel time. PARAMICS software was used to identify potential impacts of CVs on mobility by (64). Their results showed that CVs' market penetration of around 50% improved the travel time on the main corridors by 30% to 40% from a baseline condition with no CVs (14, 64). Different route guidance performance was evaluated based on V2V communication in microsimulation models, and the result showed that when CV concentration was 30% and 70%, network-wide travel time was reduced by 29% and 48%, respectively (65). Another study investigated the travel time improvement by 25% when 40% of drivers had access to real-time traffic information through the Advance Traveler Information System (ATIS) (66).

Some researchers used microsimulation to investigate the relationship between LOS and travel time. Studies on performance measure or evaluating LOS with respect to the market penetration of CV features and vehicles include a traffic monitoring application in a microsimulator to measure the impacts of information dissemination from each V2V-equipped vehicle interacting with an RSU (67). The objective function of their research used either delay-only, or a combination of delay, stops, and deceleration. To measure the objective function, the algorithm used a microscopic simulation driven by present vehicle positions, headings, and speeds. Unlike most adaptive control strategies, the algorithm was relatively simple, didn't require point detectors or signal-to-signal communication, and was completely responsive to immediate vehicle demands. Results from simulation showed that the algorithm maintains or improves performance compared to a state-of-practice coordinated-actuated timing plan optimized by Synchro at low- and mid-level volumes, but performance worsens during saturated and oversaturated conditions.

The relationship between market penetration rates of CVs and variable speed limit (VSL) in the microsimulation environment was scrutinized by (28). Their research showed that traffic congestion can be improved by 7%-12% depending on different CV market penetration rates. On the other hand, a microsimulation environment was employed to evaluate the potential benefit of CVs in identifying spillbacks and reducing system-wide cycle time (68). They proposed a model predictive VSL control strategy and evaluated its safety and mobility impacts. The strategy used second-order traffic flow models to predict the traffic state and provide a speed for optimizing corridor operational performance. A sensitivity analysis of the VSL update frequency and the safety constraints for the VSL strategy were utilized to determine the best scenario in terms of safety and mobility. The results indicated that the recommended VSL control strategy can improve safety by approximately 50% and mobility by approximately 30%. A VSL update frequency of 5 min and a maximum speed difference of 10 km/h between successive time steps yielded the best performances.

Researchers, e.g., (69), applied a microsimulation environment to collect signal location and timing information and then, through V2I, communicated to the driver a suggested speed that would result in a green light. Researchers, e.g., (67), tested an algorithm in VISSIM to control the traffic signals depending on the connected vehicle demand and compared the improved performance with actuated signals. Results from simulation showed that the algorithm maintains or improves performance compared to a state-of-practice coordinated-actuated timing plan optimized by Synchro at low- and mid-level volumes, but performance worsens during saturated and oversaturated conditions. Testing also showed improved performance during periods of unexpected high demand and the ability to automatically respond to year-to-year growth without re-timing.

Due to the diversity of specific factors and considerations, it was difficult to generalize the earlier research on mobility (70) and safety (71). (72) concluded that CV technologies can reduce rear-end collisions by 85% with a 100% market penetration rate. The reduced number of rear-end conflicts was approximately 84.3%, with a 100% MPR under Level of Service D traffic conditions. Analysis of the standard deviation of speed showed that a reduction of 39.9% was achieved. The outcomes of this study could be valuable to derive smarter operational strategies for ISWS, the inter-vehicle safety warning information system. ISWS is a technology to enhance driver attentiveness by providing warning messages about upcoming hazards through the use of CV environments.

The study by Mei, Hu, Rouphail, & Lee (2010) aimed to provide an additional tool or code for the existing commercial microsimulation system so that the effective transportation-related information could be disseminated via the wireless communication system within the vehicular ad hoc network (73). The transmitted information elicited timely responses to driver behavior for speed or path changes realistically. A simulation model developed by following the prescribed design was used in a case study application to simulate vehicle dynamic route diversion and variable speed limits following a severe incident in a small network. Simulation results indicated that the model results are sensitive to both different market penetration levels of vehicles equipped with wireless communications capabilities and various control strategies, which therefore gives credibility to the utility of the system design.

AIMSUN recently released a V2X module in version 8.4.0 to better simulate a connected environment for vehicles such as cars and buses. The V2X Software Development Kit (SDK) was designed to allow a modeler to simulate autonomous and connected vehicles. This kit will be capable of creating a special network (called VANET) to simulate different parts of autonomous and connected vehicles in a fairly realistic environment (26). A Vehicle Ad Hoc Network (VANET) is an ephemeral network spontaneously created by a collection of CVs in proximity to each other or to a similarly connected roadside unit (RSU). The communications are generically referred to as V2V for Vehicle to Vehicle communications, V2I for Vehicle to Infrastructure communications, or, when both are operating together, V2X communications. Communication to roadside infrastructure is introduced when a traffic management organization installs RSUs to monitor intra vehicle communications and uses that information to act locally, sending messages to connected vehicles, or managing the road network, aggregating information from multiple RSUs in an urban or regional traffic management center.

Several studies concentrated on V2I and V2V communication using a micro-simulator platform (19, 65, 74, 75) to evaluate services such as route guidance (65). Under these studies, a number of route guidance protocols, strategies, and APIs have been developed such as NS-2 (76) and QUALNET (77) to serve various research purposes (78, 79). The most-used software packages were VISSIM (19), CORSIM (20, 21), and PARAMICS (22, 23), along with significant integrations such as PARAMICS and QUALNET (79) VISSIM and NS-2 (24) and AIMSUN and QUALNET (25). However, Lee, J. and Park, B. (2008a) mentioned that it was difficult to synchronize these last two (AIMSUN and QUALNET) as transportation simulation tools updated the information in a fixed time step, but communication tools are discrete events (65). The paper by Mei, B. et al. (2010) focused on the gaps of previous studies such as the logic or traffic condition behind issuing warning messages, traffic data collection type, time, storing method and processing steps, reliability of information transferred via VANET and the impact on drivers' behavior (73).

2.4. Equity in Transportation

The term "equity" has multidimensional definitions that consider different disciplines. Generally, equity can be defined as the fair and appropriate distribution of impacts such as benefits and costs to access information or services, income distribution, and access to economic activities across the population (80). Similarly, transportation equity refers to the fair distribution of the benefits and burdens of transportation investments across demographic groups and space (81). Many of today's transportation systems were built with an emphasis on a single purpose and a limited range of users. Equity in transportation recognizes the full array of people present in different places – for example, not just those who own or operate a motorized vehicle. Equity enables transportation planners and designers to enhance city accessibility for everyone, including seniors, people with disabilities and low incomes, and individuals living in underserved areas. Increasing accessibility and right-sizing resources have ripple effects throughout a community. It improves dignity in the transit-user experience, reduces pedestrian and bicyclist injuries and fatalities, and encourages healthier lifestyles.

In transportation, equity has two types, namely, horizontal and vertical (82-84). Horizontal equity is defined as the same amount of distribution of any resource within a similar number of populations. In this concept of equity, all members of the population group are considered equal, and the service is distributed among them. In the context of transportation, the definition of vertical equity concentrates on the distribution of any attribute among specific groups (85). To elaborate on the definition, it can be said that the group that pays the most receives the best service. This type of equity divides the transportation users based on different demographic criteria (i.e., income, age, gender, ability, etc.). In sum, horizontal equity concerns distribution among individuals or groups with the same necessities, whereas vertical equity should be considered in situations with different levels of needs. Traditionally, equity has been neglected in transportation planning, in best-case scenarios being an afterthought during service provision. Equity will help meet the needs of communities and foster equitable accessibility.

2.5. Equity Measurement

Several studies have been conducted to specify the definition and measuring process of equity in transportation. However, there has been no universal method and list of factors to quantify equity in transportation. The Federal Transit Administration (FTA) prescribed methods for equity analysis, which focus on the transit sector. The guidelines only address horizontal equity with the demographics of the riders and do not recommend more logical, meaningful, and essential measuring factors of vertical equity such as service quality, travel time, rider comfort, etc. (86).

Several studies have investigated the impression of equity in transportation. The implementation of an innovative, online, inter-professional advisory board in the context of transportation equity research was described by (87). Their case study underscored the importance of 1) ensuring broad, inter-professional membership; 2) utility of online meeting formats for reducing participation barriers and promoting more diverse participation; 3) designing active strategies to promote board members' interaction and networking during meetings, and 4) continually orientating members to the board's contribution to the research. Various theories of justice, either implicitly or explicitly, within the context of transportation financing, investments, and service allocations were presented by (88). Their research used concepts and theories from the fields of social psychology, philosophy, and economics to understand and clarify the concept of equity within the field of transportation. (89) investigated the concept of transportation equity. They explored the multiple channels through which transport and land use policies can create conditions for more inclusive cities and transport systems that allow different people to flourish, satisfy their basic needs and lead a meaningful life. They also found that equity is a crucial part of a broader concern with transport and mobility justice. The call for transport justice goes beyond distributive concerns, and yet justice cannot be achieved without equity.

The result of the horizontal equity evaluation showed that access to all population subgroups is reduced due to the centralized service (90). According to Litman, T. (2002), there are three impacts of transportation equity. These are user costs and benefits (i.e., operation and maintenance, social and environmental, etc.), service quality (mobility, travel time, schedule, route level of service, etc.), and external impacts (i.e., congestion, travel time, etc.). The units used for evaluating transportation equity were congestion impacts (level of service), vehicle miles traveled (VMT), Passenger Miles Traveled (PMT), Passenger Trips, and Affordability (80). A study on transportation equity argued that transportation evaluation remained significant, but the equity measurement was insufficient and required consideration of more factors such as mobility. The major challenge for equity assessment in the transportation domain was to define and operationalize costs and benefits, and the distributive principle (91). Transportation technologies (e.g., electric vehicles) and services (e.g., shared mobility) to provide efficient, sustainable, and cost-effective alternatives to traditional travel modes were studied by (92). They comprehensively reviewed methods from the existing literature for assessing the equity of a few important system outcomes – accessibility, traffic emissions, and safety. The existing methodologies were unified into a three-step framework that includes population measurement, cost/benefit measurement, and equity assessment, and they summarized the applicable measurements for each step, in detail (92).

Meanwhile, a number of equity effects have been identified that relate to using travel time calculation for cost and benefit analysis of transportation projects. The effects may occur due to a new road or rail link, improved level of service of a road or facility, or improved public transit, and save travel time (93). The study by Szeto & Lo (2006) measured the intergenerational user equity in the transportation network design problem, which considered link tolls and discounted origin-destination cost, but overlooked travel time or congestion (94). Another study that measured the efficiency and equity of a fixed time ramp meter considered the speed and travel time of the vehicle. The result showed that ramp equity degraded with the fixed time control strategy in relation to the equity of the mainline and overall corridors (95). Despite the benefits of CVs in transport networks, they have some shortcomings. Transportation equity helps us consider an equilibrium indicator to investigate the effects of CV market penetration rates. Transportation equity is a way to frame distributive justice concerns in relation to how social, economic, and government institutions shape the distribution of transportation benefits and burdens in society. Therefore, the positive impressions of CV gradual deployment can be better distinguished by transportation equity.

2.6. Summary

Earlier studies conducted by several researchers had some limitations. The only factors considered by Liu et al. (2019) were market penetration rate and information update intervals. The study also assumed that drivers' behavior is not affected by CV technology, whereas in the real-world scenario it is. Lastly, the software platform PARAMICs used in the study applied all-or-none and the shortest path based on the distance, which is not considered as an optimal assumption (46).

One of the major limitations of the study on sensitivity analysis was concentrating only on MP without additional focus on other factors such as stochastic assignment (perturbation), level of demand, familiarity rate, and network configuration. Human factors or driver behavior and reaction to CV technology may affect the overall performance, which was not considered in this study. Frequent sharing of information may lead to increased driver's workload and act as a distraction, which was not counted in the sensitivity study (13). Mei et al. focused on the shortcomings of previous studies and addressed those by including more sophistication in the communication network with imposed bandwidth restriction and delayed information updates; deploying V2V in a more realistic environment in which drivers receive more en-route information through sources other than Vehicular ad-hoc Network (VANET); validating the ad hoc message priority and reliability index presently in use to work across the network; and having different market penetration (73).

Aforementioned studies considered evaluating the performance of routing algorithms and/or CV technologies. But they have not directly considered the equity topic associated with CV dynamic route guidance technology. A significant impact of well-performed route guidance is reducing the travel time of CV users. To address the limitations of earlier studies, this study evaluates two types of equity. Considering the horizontal equity concept, this study recognizes the "travel time factor" as an essential parameter to measure transportation equity among all road users. On the other hand, from the vertical equity point of view, the road users in our proposed study are divided into three groups of CV users, non-CV users, and public transit users. The impact on the travel time of all users due to various concentrations of specific types of users helps measure the vertical equity of different users. The proposed study considers four different vehicle types: connected cars, connected buses, conventional cars, and conventional buses. The attributes of connected cars and buses (e.g., reaction time, standard gap, maximum acceleration, maximum deceleration, and sensitivity factor) were determined based on the suggested values by (96). Moreover, percentage changes of "delay time" in different market penetration rates of CVs are investigated. Changing of fuel consumption and pollutants, e.g., $CO_2, PM, NO_x, and\ VOC$ also are investigated in the rest of this study.

3. METHODOLOGY

This study evaluates the potential benefits of using Connected Vehicle systems to improve traffic mobility and safety while saving energy and reducing emissions. In order to quantify the potential benefits of the V2V system, different types of vehicles were considered, including connected and conventional cars and buses. The proposed research developed and calibrated a microscopic traffic simulation model to replicate the fairly realistic behavior of such vehicles in the traffic simulation environment. In order to do this, the aforementioned vehicle types were modeled in AIMSUN traffic microsimulation software. Fifteen scenarios consisting of different market penetration rates of CVs were defined. The percentage of every vehicle type in every scenario was determined, and its demand matrix was assigned in the microsimulation model. The market penetration of V2V enabled vehicles is assumed as a variable ranging from 0% to 100% to study the impact of this variable. To model a V2V system in AIMSUN, two APIs have been developed. The first API is responsible for creating an incident in the middle section of the network. It was assumed the incident would happen from 7:15 AM to 7:30 AM and that all the non-CV cars would be assigned statically in the network during the one-hour simulation period. All the connected vehicle cars can re-route dynamically during the 15-minute incident period. Despite the gradual deployment of CVs and due to the incident happening at 7:15 AM, significant congestion did not happen since the connected vehicles used other links to avoid the incident. The second API simulated CVs' attributes. CVs can reroute dynamically once they are informed of the incident along the route to take the shortest path. All the attributes of CVs (e.g., physical features, reaction time, standard gap, max/min acceleration, normal deceleration, sensitivity factor, and overtaking maneuver time) were determined. Unlike the majority of prior studies that used hypothetical study areas with simple networks, our study developed a real-world urban road network. Different penetration rates of CVs (0%-100%) were developed, and the system-wide effects of CV-equipped vehicles with route guidance features on mobility and equity were analyzed. The developed dynamic assignment model in AIMSUN facilitates V2V communication for connected vehicles, collects vehicle statistics, and implements incidents.

3.1. Travel Time Calculation

As mentioned earlier, the V2V model has two types of vehicles, connected and conventional. Conventional vehicles do not communicate with any other vehicles and always take the shortest known path to the destination, regardless of real travel time. CV cars exchange information with other connected vehicles within range and traverse the shortest route by duration to their destination. The V2V model encompasses tracking all connected vehicles within the network as well as their information dissemination and use of the shared information. In this model, connected vehicles share link travel times. Each V2V-enabled vehicle has an internal link travel timetable encompassing all the links in the network. At the beginning of a trip, all link travel times are null or uninitialized. When a CV enters and exits a link, the respective timestamps are recorded. We assumed the travel time is updated every 30 seconds. When a V2V-enabled vehicle exits a link, the link travel time is computed from the previously recorded times. A timestamp is recorded for the link travel time and can be disseminated to any CVs within the range. When a V2V-enabled vehicle receives information from another CV, the incoming information`s timestamp is compared with the internal link travel timetable timestamps, and the most recent one is used in route calculations. The link travel time's timestamp ensures that vehicles will only use the newest information. When a V2V-enabled vehicle arrives at a node with more than one exit link, the CV consults its internal link travel timetable and decides which link to travel using the shortest path algorithm. If a CV has no link travel time information, a surrogate link travel time is computed using the length of the link and the average vehicle speed of the network. At the beginning of the simulation, no data is known about link travel times in the network. If a V2V-enabled vehicle has to choose between a link that has a V2V-enabled vehicle traveling on it and a link that has no travel time information collected, it chooses the latter to gain a more complete understanding of the network's link travel times.

After running each replication, the travel time between every OD can be determined by the "path assignment" tab. Through this tab, a travel time matrix for all the OD pairs in the network is acquired. The average travel time matrix for each scenario is an average matrix of 10 replications. Based on Figure (4), The middle link of the (1886-1880) OD pair experiences a 15-minute incident from 7:15 AM to 7:30 AM. Therefore, acquiring the average travel time for the (1886-1880) OD pair is one of the main objectives of our research.

3.2. Air Pollution Coefficients

There are three environmental models in AIMSUN with various parameters. The AIMSUN user should define the exact value of every parameter to obtain outputs. The next section explains AIMSUN's three environmental models (26). The second model (Panis et al., 2006) with its proposed attributes was selected for our research.

3.2.1. QUARTET Emission Model

This utility is designed to draw up a balance sheet of the pollution generated during the simulation. When a pollutant is created in a vehicle type, it is automatically created for all other vehicle types. Likewise, when the name of a pollutant is changed, it is deleted from one vehicle type, and that change is applied to all vehicle types. This ensures every vehicle type always has the same list of pollutants. Only the emission rates will differ between types. Speed-emission rates are used for vehicles traveling at a constant speed. If the speed is not constant, then the IER (Idling Emission Rate), AER (Acceleration Emission Rate), and DER (Deceleration Emission Rate) are used. If there is only one speed-emission pair for a pollutant, that emission rate will be used for all vehicles traveling at any constant speed. If there is more than one pair, the emission rates for vehicles traveling at a constant speed will depend on the speed intervals defined by different pairs. The speed intervals are given by their upper limit. For example, if the speeds on the list are 10, 20, 30, 40, 50, 60 and 70 (km/hour), then the emission rate at constant speed has different values for speeds in the intervals 0-10, 10-20, 20-30, 30-40, 40-50, 50-60 and 60-70 km/h. It is worth noting that vehicles traveling at speeds greater than 70 km/h are assumed to have the same emission rate as those traveling at 70 km/h. This is an experimental-design decision. Furthermore, the slope in the sections where the vehicle is traveling also can be considered when gathering emissions. When no slope ranges have been defined, the emission rates will be those defined in the cruising rates table. If slope ranges are defined, the emission rates will be multiplied by the factor defined in the slope ranges. It is normally considered that when the slope is 0%, the emission rates will be the same as the cruising rates; when the slope is ascending, the multiplying factor will be higher than 1 and when the slope is descending the multiplying factor will be between 0 and 1.

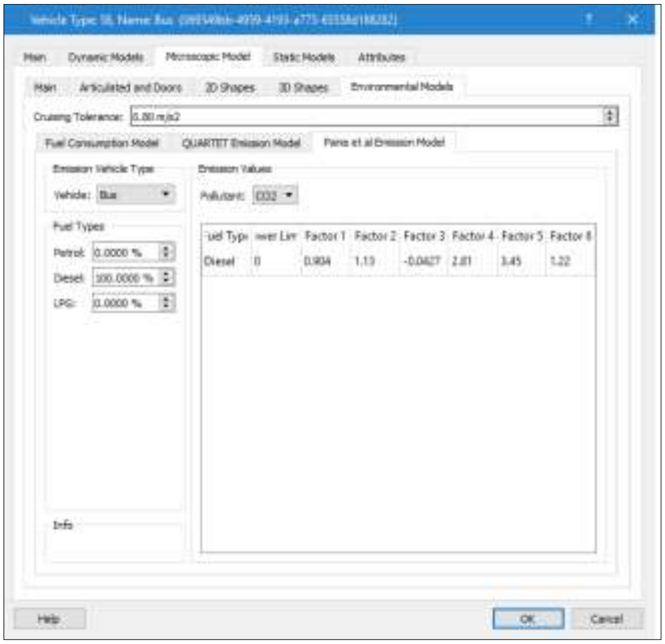
Both the speed intervals and the slope percentages are given by their lower limit. For example, the speeds and slopes on the list define a slope impact of 0.4 when the vehicle's speed is between 0 and 60 and the slope is descending from -4% to 0%; it has no impact when the slope is ascending from 0 to 4%, and it has an impact of 5.16 when the slope is ascending and higher than 4%. For speeds higher than 60 km/h and slopes higher than 4% the slope impact factor is 8.6. The QUARTET Emission Model tab is shown in Figure (1). This model is more accurate than others. Many values should be determined by the user before running the scenario.

Figure 1. QUARTET Emission model in AIMSUN

3.2.2. Panis et al. Model

AIMSUN can model instantaneous pollution emissions caused by acceleration-deceleration and speed for all the vehicles in the simulation. An instantaneous traffic emission model based on the influence of traffic speed limits was proposed by (97). Each simulation step measures the emissions for each pollutant using the same formula but considering different factor values according to the vehicle type, fuel type, and instant acceleration/deceleration measures. In particular, the instantaneous emission model considers Carbon Dioxide (CO2), Nitrogen Oxides

(NOx), Volatile Organic Compounds (VOC), and Particulate Matter (PM). The Panis emission model is based on empirical measurements that relate vehicle emission to the type, instantaneous speed, and vehicle acceleration. The traffic model captures the second-by-second speed and acceleration of individual vehicles traveling in a road network based on their individual driving style, the vehicle mechanics, and their interaction with other traffic and with traffic control in the network. AIMSUN users must define different factors for the model and note that the model assumes that bus and HDV vehicles use diesel. If the user sets a percentage in Petrol or LPG greater than 0, the model will only calculate pollution values for diesel vehicles. Once the simulation has been run, eight-time series will be added to the sections, nodes turns, and the replication, two for each kind of pollutant (CO2, NOx, PM, and VOC), giving the values in g and in g/km (labeled as "interurban"). This project used the Panis et al. model and the emission parameters proposed by (97). The initial coefficients were entered in the software, and it can determine the values of CO2, NOx, PM, and VOC. The Panis et al. model tab in AIMSUN is shown in figure (2).



Vehicle Type: 58, Name: Bus

Cruising Tolerance: 0.80 m/s2

Vehicle: Bus

Petrol: 0.0000 %

Diesel: 100.0000 %

LPG: 0.0000 %

Pollutant: CO2

uel Typ	wer Lim	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Diesel	0	0.904	1.13	-0.0427	2.81	3.45	1.22

Figure 2. Panis et al. emission model in AIMSUN

3.2.3. London Emission Model (LEM)

The London Emission Model (LEM) can estimate the CO2 and the NOx emissions for a vehicle using a calibrated emissions model developed in collaboration with Transport for London. The calibration was carried out in 2017 using measurements taken in London. The LEM was developed in response to observations that average speed models tended to under-predict emissions at low speeds and variability in in-vehicle activity meant that predictions based on average link speeds on short links or for short time periods had significant uncertainty. External emissions models based on individual vehicle traces address these issues but are data-intensive and require microsimulation. The approach taken by the LEM model is to derive the emissions for an individual vehicle using its average speed in a set of micro trips that form its whole journey. A micro trip is defined as a segment of the trip where the speed rises from stationary to > 5 km/h and back to stationary. The LEM then uses one of two polynomial relationships, derived by regression analysis, to fit an emission factor for CO2 and NOx. The regression equations (1) and (2) are:

$$y = ax^z + b \;\;:\;\; x < 10\; km/h \tag{1}$$

$$y = ax^3 + bx^3 + x + c \;\;:\;\; x \geq 10\; km/h \tag{2}$$

In this model, y is the emission (grams/km); a, b, c, and z, are derived constants; and x is the average speed in the micro trip. The emissions per micro trip are provided for micro, meso, and hybrid dynamic simulations.

3.3. Network-Level Equity Calculation

This research considers horizontal and vertical equity concepts simultaneously. In addition, the effect of dynamic re-routing of CVs on different paths is efficiently analyzed. Dynamic re-routing of CVs during the 15-minute incident period may increase the average travel time in some paths. On the other hand, it may decrease the average travel time for some other origin-destination pairs. Therefore, network-level equity was calculated based on the following steps:

1- The average travel time for 15 ODs was determined through AIMSUN. Ten replications for each scenario were run. Then, the average travel time of the network (all ODs) for each replication was analyzed, and the mean travel time was calculated among 10 replications.
2- The trend of Non-CV cars and CV-cars for each OD were drawn in separate charts. The average travel time for Non-CV buses and CV-buses were also drawn for the ODs with bus routes.
3- The average travel time of each vehicle type (i.e., Non-CV cars and CV cars) for 15 ODs were multiplied by the number of that vehicle type in the network under that scenario to calculate a weighted average of travel time in each OD.

A direct comparison of path flows or trajectory patterns is hard to achieve. Previous studies showed that a breakpoint occurs at a particular demand level when, after this level, the pattern of the path flow loading is changed or the set of active alternatives with at least one assigned user is modified. For instance, a breakpoint occurs when the volume assigns to new paths, or when the flow of one path becomes zero. The equilibrium changes qualitatively when the demand is increasing, which results in breakpoints for the demand level at which the equilibrium solution changes significantly by the definition of breakpoints.

3.4. CVs' Re-Routing Algorithm

As explained before, our model in AIMSUN was created based on static behavior of Non-CVs during the one-hour simulation and dynamic re-routing of CVs during a 15-minute incident period. We used user-equilibrium assignment, which is first defined by (98) as follows: no one can decrease his or her travel time by unilaterally changing his or her route choice decisions. One key assumption of Wardrop’s user equilibrium principle is that there is no uncertainty in users’ decision-making in a traffic network. However, uncertainty is inherent in demand (e.g., travel demand fluctuation) and (or) supply (e.g., road capacity degradation). The user equilibrium distributes the volume of demand according to every 30 seconds of updated travel time of network arcs. It means all the paths are updated every 30 seconds and the software automatically assigns the volumes in paths with shorter travel time. We used the “path assignment” tab, whichcan show the average travel time of all the used paths in the simulation period. Ten replications for each scenario were run, then the number of re-routing CVs for the OD pairs travelling through the link where the incident took place were calculated through the path assignment tab. Finally, a simple average was calculated for 10 replications of each scenario to find the exact number of re-routing CVs. The results showed that the more the CV cars in each path were rerouted, the more the average travel time of that path decreased.

4. DATA

A simple real-world urban network was considered in this project. The case study is located to the west of Lake Montebello in the Ednor Gardens-Lakeside area of Baltimore, Maryland. The case study consisted of three north-south links (Loch Raven Blvd., the Alameda, and Tivoly Ave.) and two east-west links (Windemere Ave. and Lakeside Ave.). Figure (3) shows the study area.

Figure 3. Case study of the project

-Loch Raven Blvd. is a secondary north-south road with 35 mile/hour speed and 1400 PCU/h capacity.
-The Alameda is a primary north-south road with 45 mile/hour speed and 1800 PCU/h capacity.
- Tivoly Ave. is a residential north-south road with 25 mile/hour speed and 700 PCU/h capacity.
-Windemere Ave. is a residential east-west road with 25 mile/hour speed and 1000 PCU/h capacity.
- Lakeside Ave. is a residential east-west road with 25 mile/hour speed and 1000 PCU/h capacity.

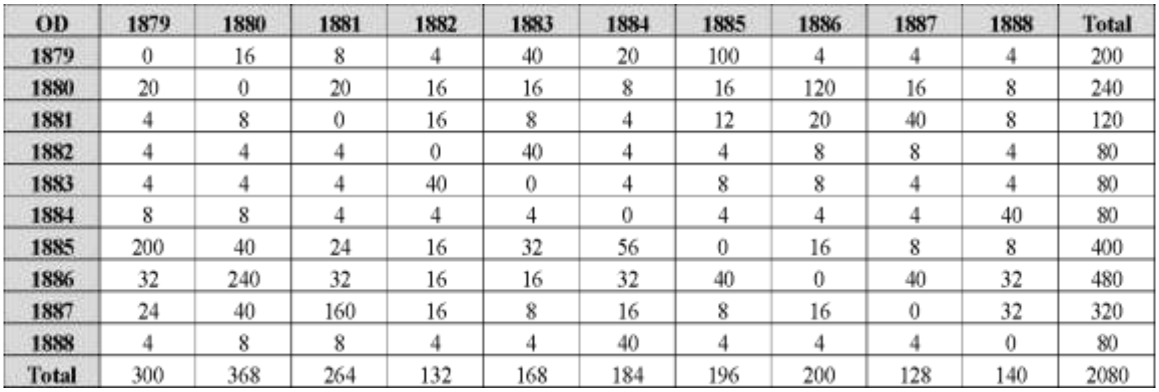
It was hypothesized that the morning peak hour for the case study is 7AM to 8 AM. All the transit lines on the case study were investigated from an MTA portal (99). We considered 7 AM to 8 AM as the peak hour of our case study, based on:

1) Following the bus schedule of line 53 (99)
2) Following another similar bus schedule (99)
3) The AM peak hour in the U.S.: For 2017, INRIX defines congestion as a speed below 65% of the free-flow speed, which is the typical uncongested speed on that road segment, and defines peak hours locally based on the actual driving habits in each city, as opposed to the more typical fixed peak periods of 6 AM to 9 AM and 4 PM to 7 PM. (The INRIX data, which are computed only for selected cities, are extended to all U.S. metropolitan areas and then rolled up by the state.) (99).

Figure (4) shows the simulated network in AIMSUN with 10 end nodes. It was hypothesized that the incident happens between 7:15 AM and 07:30 AM in the southbound (SB) direction of the Alameda (green rectangle in Figure (4)), and blocks both travel lanes.

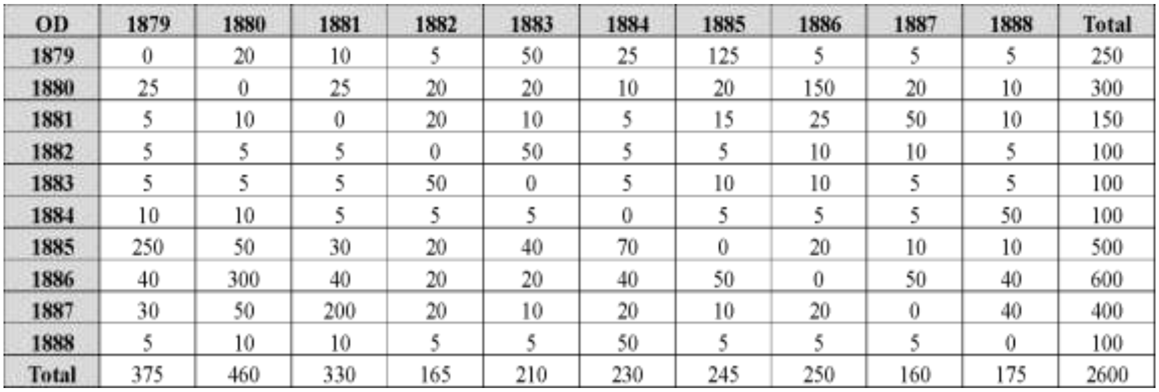
Figure 4. The simulated network (case study) in AIMSUN 8.4.0.

Three traffic volumes regimes were defined for this project to evaluate the impact of traffic volume on travel time under various CV penetration rates. The corresponding OD demand matrices are shown in Figures (5) to (7) that represent low, moderate, and high traffic volume scenarios.



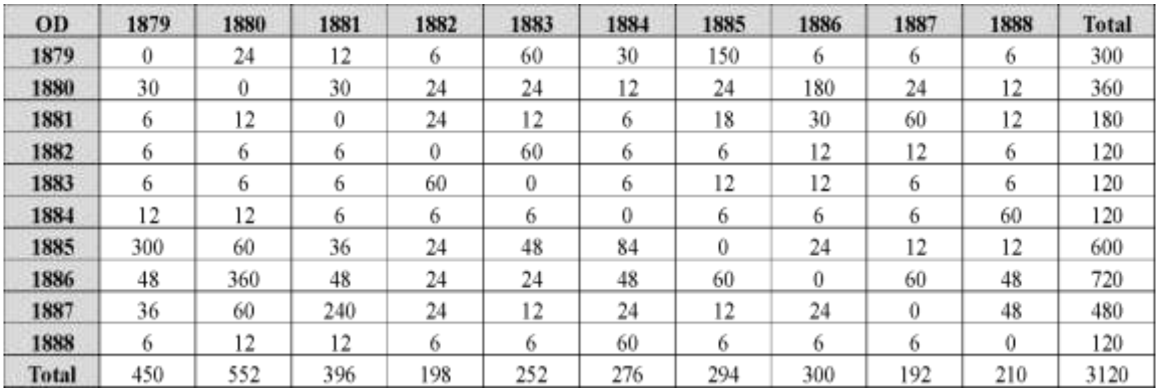
OD	1879	1880	1881	1882	1883	1884	1885	1886	1887	1888	Total
1879	0	16	8	4	40	20	100	4	4	4	200
1880	20	0	20	16	16	8	16	120	16	8	240
1881	4	8	0	16	8	4	12	20	40	8	120
1882	4	4	4	0	40	4	4	8	8	4	80
1883	4	4	4	40	0	4	8	8	4	4	80
1884	8	8	4	4	4	0	4	4	4	40	80
1885	200	40	24	16	32	56	0	16	8	8	400
1886	32	240	32	16	16	32	40	0	40	32	480
1887	24	40	160	16	8	16	8	16	0	32	320
1888	4	8	8	4	4	40	4	4	4	0	80
Total	300	368	264	132	168	184	196	200	128	140	2080

Figure 5. OD demand matrix for "Low" traffic volume condition



OD	1879	1880	1881	1882	1883	1884	1885	1886	1887	1888	Total
1879	0	20	10	5	50	25	125	5	5	5	250
1880	25	0	25	20	20	10	20	150	20	10	300
1881	5	10	0	20	10	5	15	25	50	10	150
1882	5	5	5	0	50	5	5	10	10	5	100
1883	5	5	5	50	0	5	10	10	5	5	100
1884	10	10	5	5	5	0	5	5	5	50	100
1885	250	50	30	20	40	70	0	20	10	10	500
1886	40	300	40	20	20	40	50	0	50	40	600
1887	30	50	200	20	10	20	10	20	0	40	400
1888	5	10	10	5	5	50	5	5	5	0	100
Total	375	460	330	165	210	230	245	250	160	175	2600

Figure 6. OD demand matrix for "Moderate" traffic volume condition



OD	1879	1880	1881	1882	1883	1884	1885	1886	1887	1888	Total
1879	0	24	12	6	60	30	150	6	6	6	300
1880	30	0	30	24	24	12	24	180	24	12	360
1881	6	12	0	24	12	6	18	30	60	12	180
1882	6	6	6	0	60	6	6	12	12	6	120
1883	6	6	6	60	0	6	12	12	6	6	120
1884	12	12	6	6	6	0	6	6	6	60	120
1885	300	60	36	24	48	84	0	24	12	12	600
1886	48	360	48	24	24	48	60	0	60	48	720
1887	36	60	240	24	12	24	12	24	0	48	480
1888	6	12	12	6	6	60	6	6	6	0	120
Total	450	552	396	198	252	276	294	300	192	210	3120

Figure 7. OD demand matrix for "High" traffic volume condition

We hypothesized that all six intersections are controlled by stop signs and none of them have traffic lights. Three transit lines pass on the Alameda link, and the timetable of these three lines was based on the Maryland Transit Administration website (99). The characteristics of the three transit lines are shown in Table (1). Two bus stops were located along the northbound and southbound lanes of the Alameda link, and both were north of the incident area (120 m, 0.0745 miles).

Table 1. Characteristics of transit lines in the case study

Number of bus line	Headway (min)	Route
CityLink Green **MDOT MTA**	10	NB & SB the Alameda
CityLink Silver **- CURTIS BAY - HOPKINS/MORGAN**	24	NB & SB the Alameda
Route #53 **- STATE CENTER - TOWSON**	30	NB & SB the Alameda

4.1 SCENARIOS

To more effectively investigate dynamic route guidance during an incident, three groups of traffic conditions have been defined in this research. One of the applications of the CV is route guidance based on vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-smart terminal (V2T) technologies. This project studied the impression of the CV guidance system. The moderate traffic condition was considered as the basic traffic condition. The low and high traffic conditions were built by adding and reducing the base volumes by 20%, respectively. Fifteen similar scenarios were provided for each traffic condition. The details of the scenarios are shown in Table (2). As shown, traffic demand is similar in scenarios 1, 2, and 3. The only difference between scenarios 1 & 2 is the incident, and the only difference between scenarios 2 & 3 is the number of connected buses (CV buses). Traffic demand of scenarios 8 & 9 is similar. Traffic demand of scenarios 14 & 15 is also the same. The percentage of connected cars increases from scenario 1 to 15, whereas the percentage of non-connected (conventional) cars decreases simultaneously, and the majority of substituted vehicles can reroute dynamically. It is worth noting that the role of connected buses will be evaluated in scenarios 3, 9, & 15. Scenario 3 was designed to examine the impact of connected buses compared to Scenario 2. This issue is similar for scenario 9 compared to scenario 8, and scenario 15 compared to scenario 14. We hypothesized two types of buses. Conventional buses, also called Non-CV buses, and connected buses, termed CV buses, both travel on the network based on a fixed headway. The details of each scenario are shown in Table (2).

Table 2. Detail of the scenarios

Scenario	Incident	Total connected vehicles		Total Non-connected vehicles	
		CV Car (%)	**CV Bus (%)**	**Non-CV Car (%)**	**Non-CV Bus (%)**
1	No	0	0	100	100
2	Yes	0	0	100	100
3		0	100	100	0
4		10	0	90	100
5		20	0	80	100
6		30	0	70	100
7		40	0	60	100
8		50	0	50	100
9		50	100	50	0
10		60	0	40	10
11		70	0	30	100
12		80	0	20	100
13		90	0	10	100
14		100	0	0	100
15		100	100	0	0

4.2. VEHICLE TYPE ATTRIBUTES

Four vehicle types have been defined in our research: Conventional car (Non-CV Car), Conventional bus (Non-CV Bus), Connected Car (CV-Car), and Connected bus (CV-Bus). The physical and behavioral features of each vehicle type were determined, and these attributes were assigned in AIMSUN. Physical and behavioral attributes of each vehicle type consist of Length (m), Width (m), Maximum desired speed (km/h), Maximum acceleration ($\frac{m}{s^2}$), Normal deceleration ($\frac{m}{s^2}$), Max deceleration ($\frac{m}{s^2}$), Normal gap (sec), Overtaking maneuver time (sec), Average reaction time (sec), Reaction time at stop (sec), and Reaction time for the front vehicle at traffic (sec).

The default values of conventional cars and conventional buses were considered for Non-CV Cars and Non-CV Buses. The length of all Non-CV and CV cars is 5 m (16.4 ft). Their width is 2.5 m (8.2 ft). The length of Non-CV buses is 12 m (39.4 ft) and their width is 2.6 m (8.53 ft). The length of CV buses is 14 m (45.9 ft) and their width is 2.6 m (8.53 ft).

Suggested numerical values for connected cars in (100) were used. Two models are able to simulate connected vehicles (CVs) in AIMSUN. Adaptive Cruise Control (ACC) is an advanced version of cruise control that is able to automatically maintain a certain set speed and also detect the speed of the vehicle in front and adapt to maintain a set distance. The second model is Cooperative Adaptive Cruise Control (CACC) that is a further development of ACC, which adds communications with multiple vehicles. Hence, CACC vehicles are able to send and receive speed information, enabling smoother and faster responses than ACC. These systems take over a part of the driving task, influencing the driving behavior of drivers and vehicles on the road. The ACC model was used to simulate connected cars (CV-Car) and connected buses (CV-Bus). Moreover, suggested numerical values (physical attributes) for connected buses by (101) were used to model CV-buses.

4.3. OTHER ATTRIBUTES FOR EACH SCENARIO

After defining 15 scenarios with varying traffic conditions, the number of replications for each scenario was determined. We ran each scenario for one hour of simulated time (7:00 AM to 8 AM), conducted 10 replications with different random speeds, and averaged the results. Ten replications were defined for each scenario to ensure that the results are reliable. The number of replications was determined through delay or density as a measure of effectiveness (MOE). A confidence interval of 95% and a tolerance error of 10% were considered to determine the minimum number of replications. The microscopic simulation was selected to simulate the scenarios. In microscopic traffic simulations, vehicles are represented as separate agents, whose motion is governed by specific rules. Those agents may interact, which also impacts their behavior. Inside the microscopic simulation, the static assignment was defined for Non-CV cars because we hypothesized all Non-CV cars can move statically on the network during a one-hour simulation. Non-CV Cars cannot reroute during the incident period, and they continued their usual path. We also hypothesized all CV cars can dynamically reroute during a 15-minute incident period (7:15 AM to 7:30 AM). When the incident happens in the southbound lanes of the Alameda, all connected cars (CV-Cars) can reroute on the network, and they use substitute routes. It is worth mentioning that, connected buses (CV-Bus) and Non-CV buses move on their predefined paths (NB and SB the Alameda), and they cannot reroute during the incident period. A dynamic assignment model updates the network every 30 seconds. In addition, a 10-minute warm-up period was used for all the scenarios. The simulation is initiated from 6:50 AM to 7 AM as the warm-up period, and after that, the one-hour simulation is started.

Finally, the incident was defined as a strategy (policy) in AIMSUN. A traffic management strategy consists of a number of policies that are applied to a traffic network to solve a problem or achieve a goal, i.e., to reduce congestion at a peak hour or manage traffic around roadworks. Each policy has an action or may have a number of complementary actions, i.e., a lane closure may be matched with corresponding permission for vehicles to use a center turn lane or shoulder, or an incident resulting in a lane closure, modeled on one side of a divided highway, may be matched with reduced speed on the other side to simulate "rubber necking." Therefore, strategies are intended to solve difficulties where these difficulties are owned by one or more transport authorities. In AIMSUN, a strategy may contain multiple policies where each policy may be owned by a different authority; the simulation is therefore providing tools to include the administration of traffic management strategies in the model as well as the implementation of these strategies (102).

5. DATA ANALYSIS

The collected data for 15 scenarios (Table 2) of CV- and RSU-equipped roads was analyzed, and the impact of different traffic mixes and traffic conditions on mobility and equity was investigated. The optimum traffic mix of CVs, as well as the optimum market penetration rate of CVs (MPR), was determined. Additionally, the average travel time for CV-equipped and non-CV in each scenario was calculated to find the benefits (if any) of CVs on non-connected vehicles in the traffic stream.

As mentioned earlier, three groups of traffic conditions were considered. The moderate traffic was considered as the basic traffic volume. Twenty percent of the moderate OD demand matrix was reduced to generate "low-volume traffic group (-20%)." In addition, 20% of the moderate OD demand matrix was increased, and "high-volume traffic group (+20%)" was created. The simulation outputs for the moderate traffic group (0%) are presented in Figure (8).

5.1. Moderate Traffic Group (0%) Output

A moderate OD demand matrix was considered as the basic matrix. Total delay times (sec/km) acquired from the software are shown in Figure (8). The average percentage of total delay time that was improved when there are connected vehicles in the road network compared to when there are no connected vehicles is 20.6%.

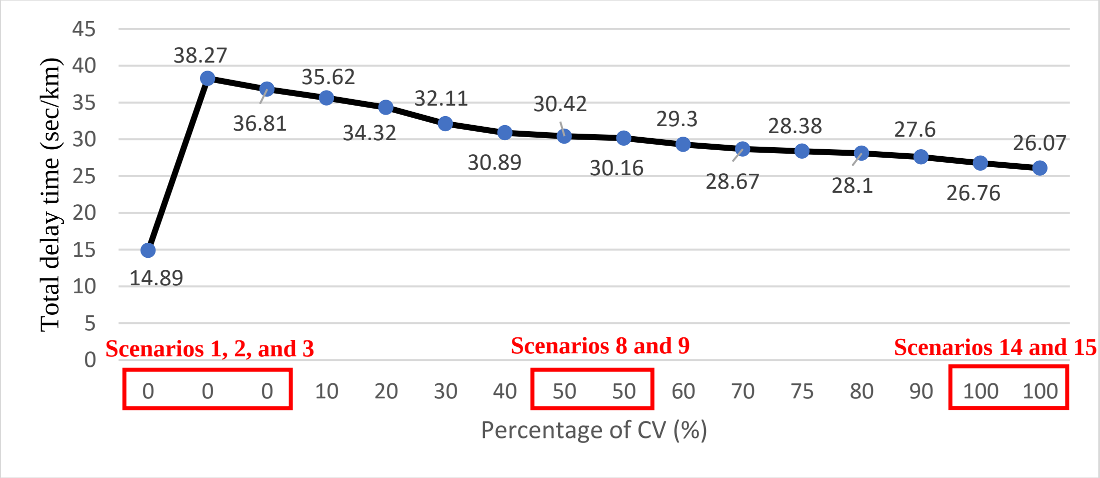


Figure 8. Total delay time changes for moderate traffic group (0%)

Three Non-CV car and CV car charts are aggregated in one figure to compare the effect of traffic volume in travel time under various CV penetration scenarios. Figures (9) and (10) show relative changes in travel time for CV-Cars and Non-CV cars, respectively, when the CV penetration rate grows.

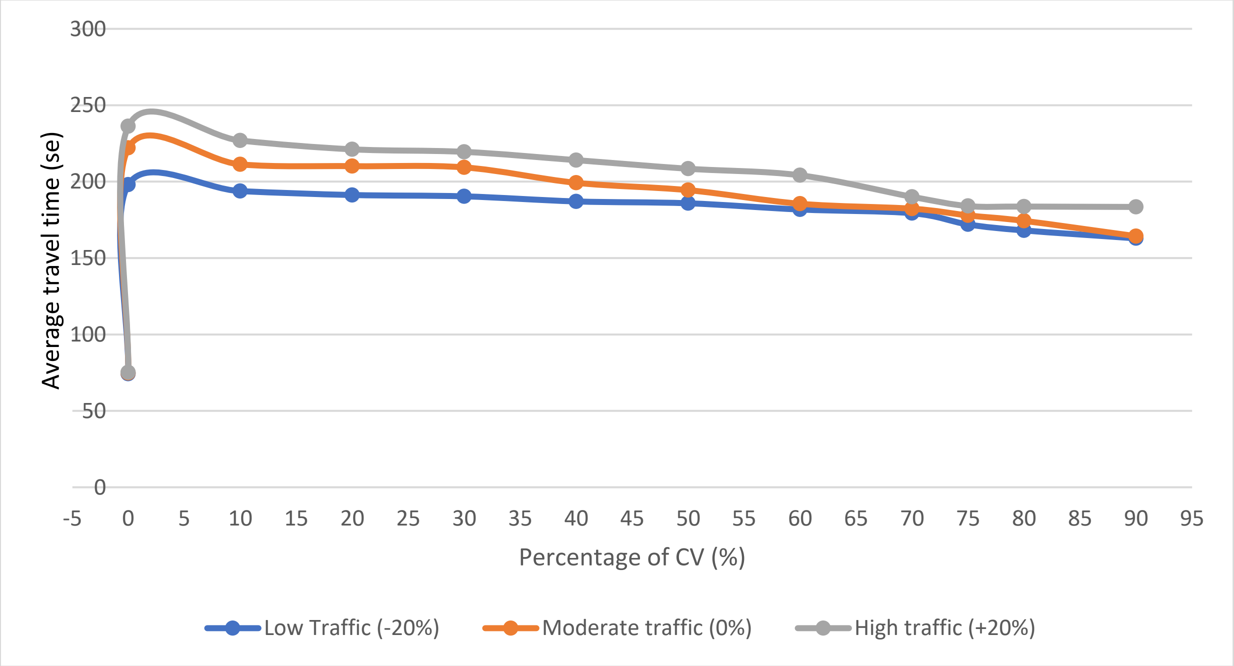


Figure 9. Non-CV cars average travel time changes in three traffic groups

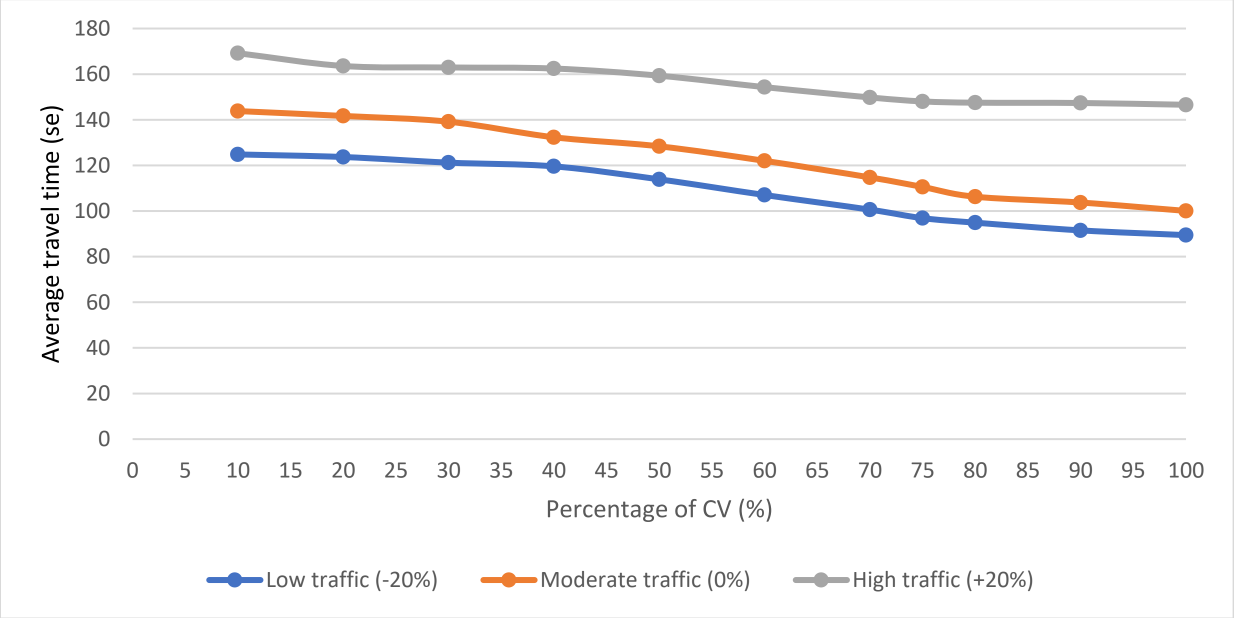


Figure 10. CV cars average travel time changes in three traffic groups

As shown in Figure (10), there are considerable drops in CV car travel time when MPR jumps from 50% to 70%, which led us to examine further that area by adding more scenarios of MPR; which will be discussed further in the report.

5.2. Emission Pollutants Outputs

Section (3.2) explains the methodology of emission pollutants. There are three emission models in AIMSUN, QUARTET, Panis et al., and the London model. We used the "Panis et al." emission model to determine CO2, NOx, PM, and VOC pollutants. The unit of all pollutants is (gr). The Panis et al. model can simulate instantaneous pollution emissions caused by acceleration-deceleration and speed for all the vehicles in the simulation. It is an instantaneous traffic emission model based on the influence of traffic speed limits. Each simulation step measures the emissions for each pollutant using the same equation but considering different factor values according to the vehicle type, the fuel type, and instant acceleration/deceleration measures. Initial input coefficients for each pollutant were determined by (97). The input coefficients were assigned to our model and then each scenario was run. The results were divided into:

-Total emissions (CO2, NOx, PM, VOC)
- "Non-CV car" air pollution emissions (CO2, NOx, PM, VOC)
- "CV car" air pollution emissions (CO2, NOx, PM, VOC)
- "Non-CV bus" air pollution emissions (CO2, NOx, PM, VOC)
- "CV bus" air pollution emissions (CO2, NOx, PM, VOC)

Figure (11) shows the trend of total CO2, Figure (12) shows the trend of total NOx, Figure (13) shows the trend of total PM, and Figure (14) shows the trend of total VOC in three traffic groups.

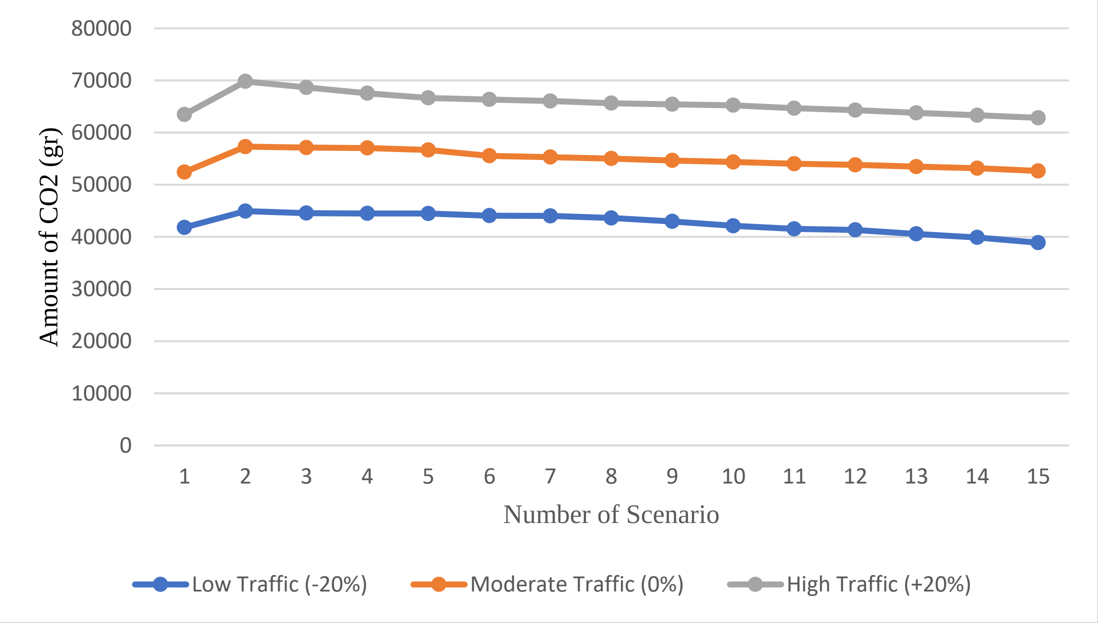


Figure 11. Total CO2 emission in three traffic groups

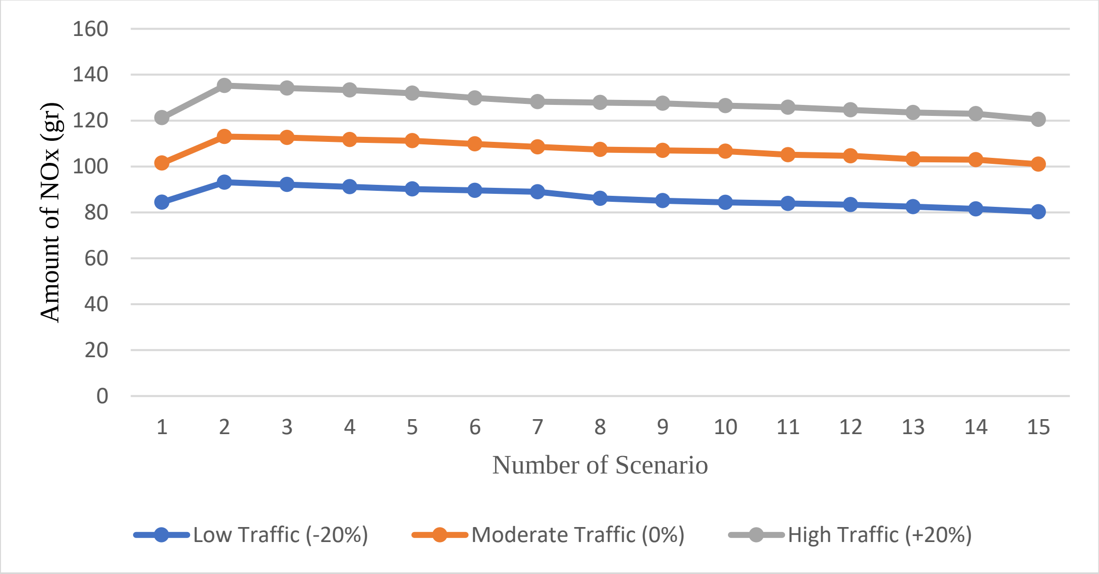


Figure 12. Total NOx emission in three traffic groups

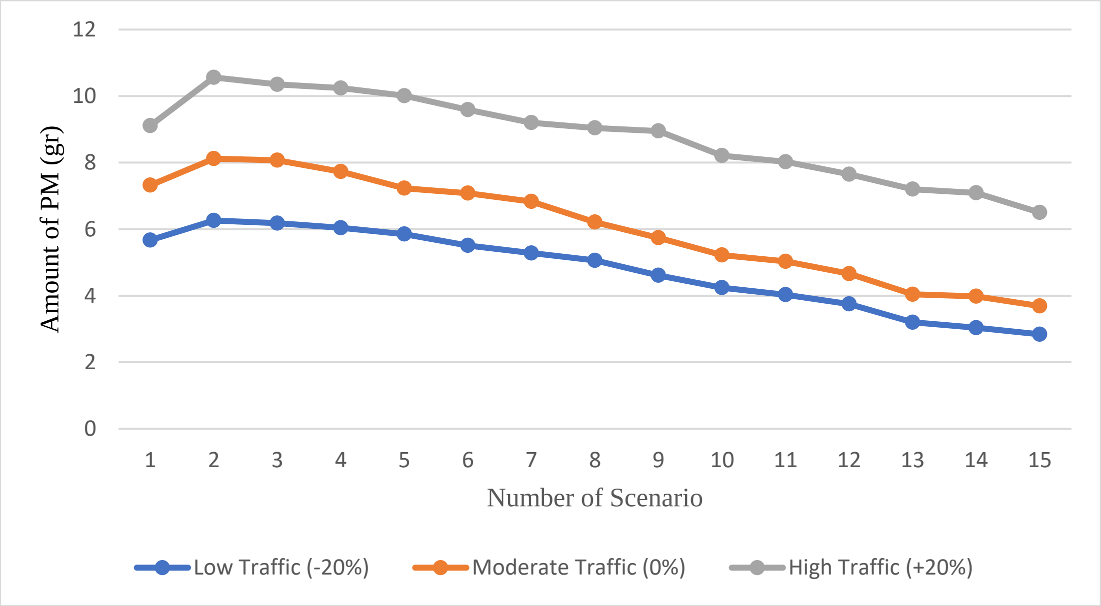


Figure 13. Total PM emission in three traffic groups

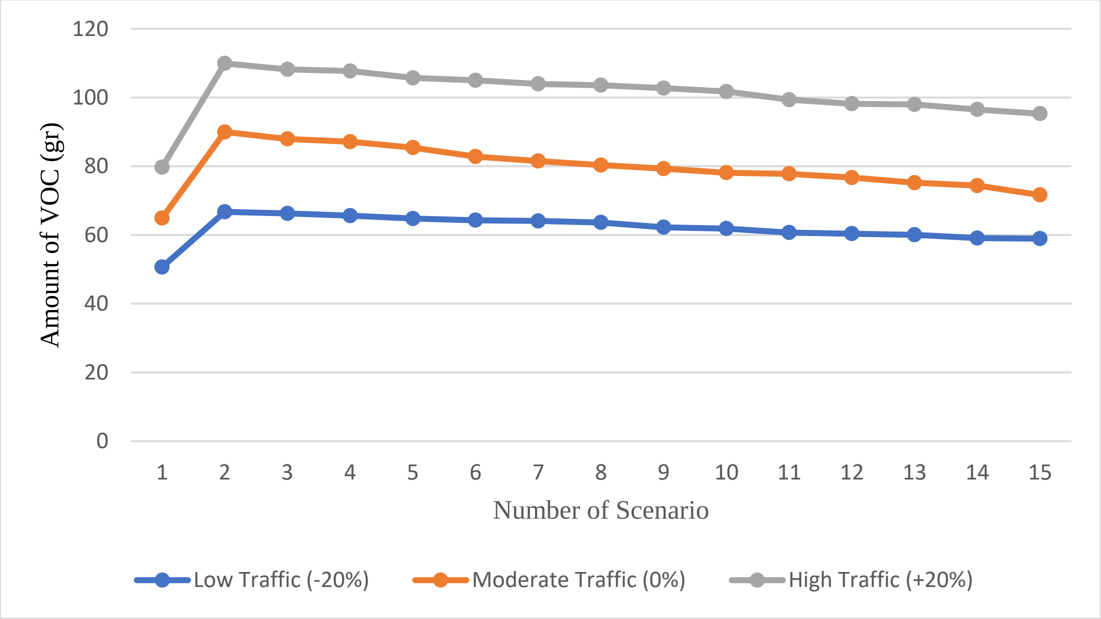


Figure 14. Total VOC emission in three traffic groups

As shown in figures (11) to (14), four pollutants are increased from scenario 1 to scenario 2. CV buses broadcast on the network in scenario 3. Due to their special attributes, CV buses can mitigate the trend of air pollutions from scenarios 2 to 3. CV cars are assigned to the network in scenario 4. Therefore, a significant percentage of CV cars divert to other paths, and accordingly, as the number of CV cars increases, the total pollutants are diminished. Therefore, a descending trend continues from scenario 4 to 15.

Figure (15) shows the trend of Non-CV cars' CO2, Figure (16) shows the trend of Non-CV cars' NOx, Figure (17) shows the trend of Non-CV cars' PM, and Figure (18) shows the trend of Non-CV cars' VOC in three traffic groups.

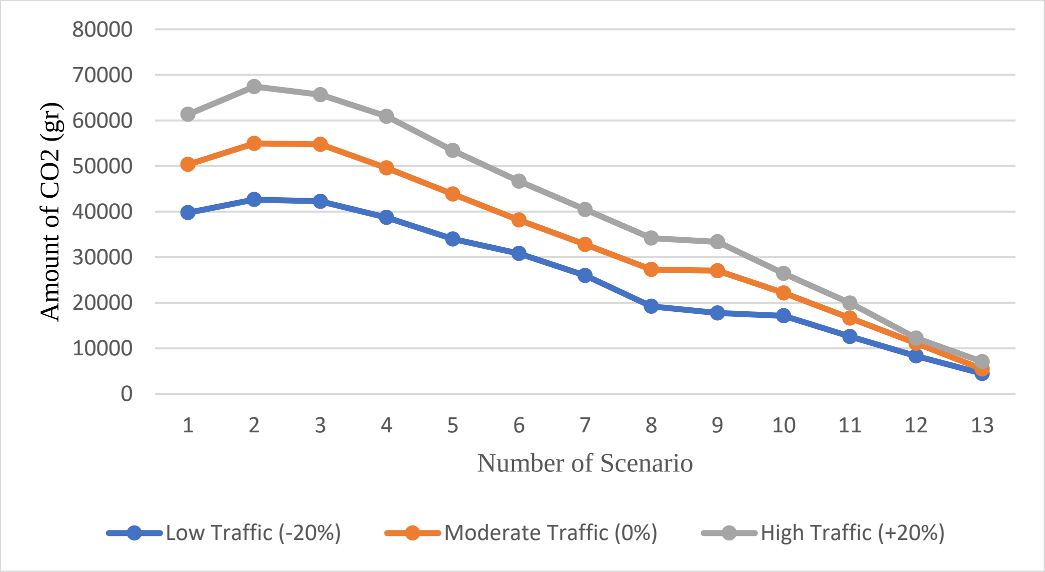


Figure 15. Non-CV cars CO2 emission in three traffic groups

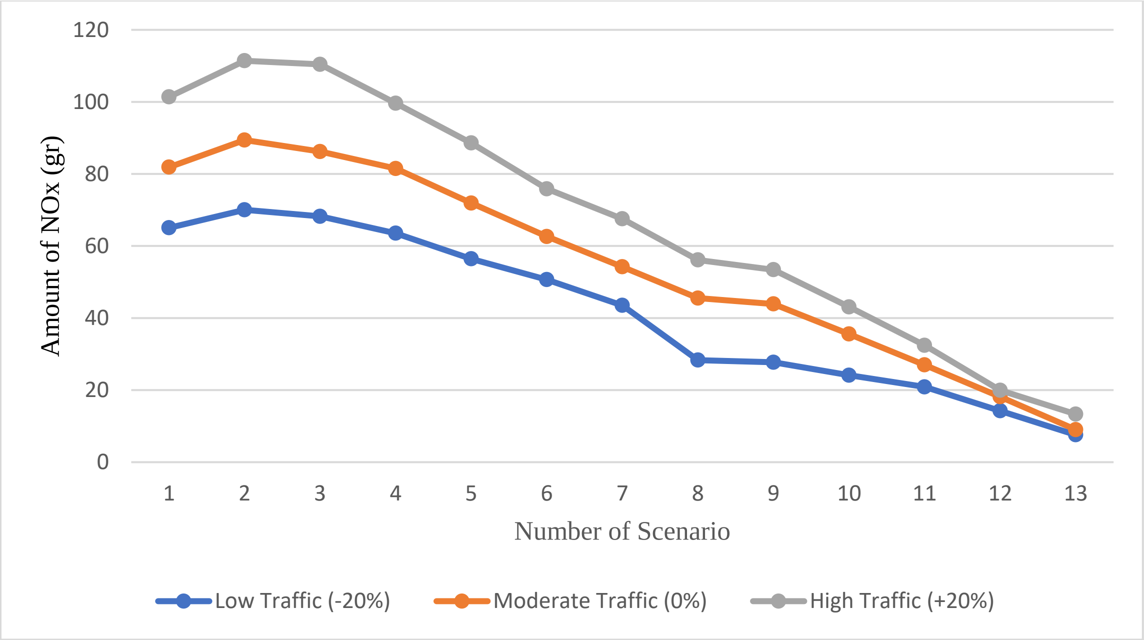


Figure 16. Non-CV cars NOx emission in three traffic groups

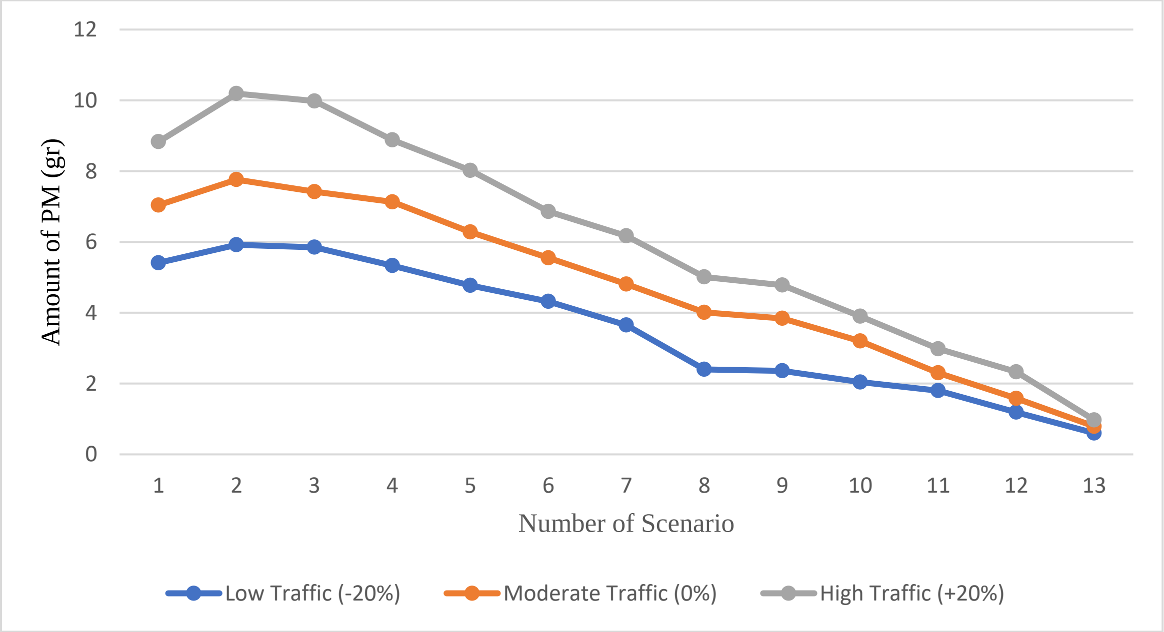


Figure 17. Non-CV cars PM emission in three traffic groups

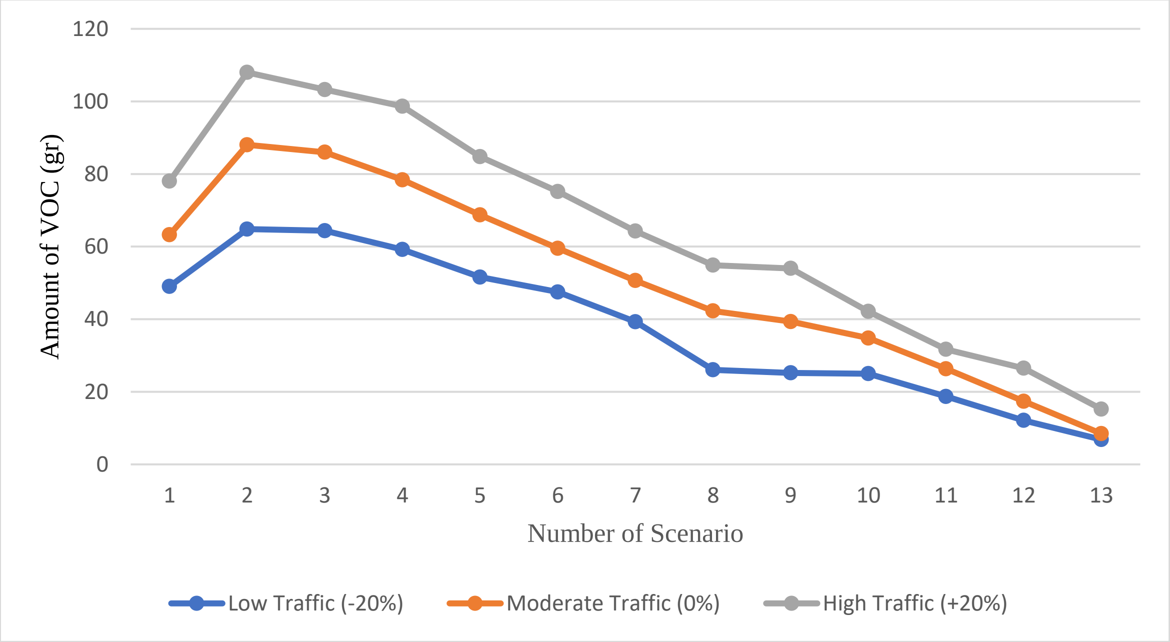


Figure 18. Non-CV cars VOC emission in three traffic groups

As shown in figures (15) to (18), four pollutants experience a descending trend from scenario 2 to scenario 13. The percentage of Non-CV cars decreases from scenario 1 to scenario 13. Therefore, a descending trend for all four pollutants was achieved.

Figure (19) shows the trend of CV cars' CO2, Figure (20) shows the trend of CV cars' NOx, Figure (21) shows the trend of CV cars' PM, and Figure (22) shows the trend of CV cars' VOC in three traffic groups.

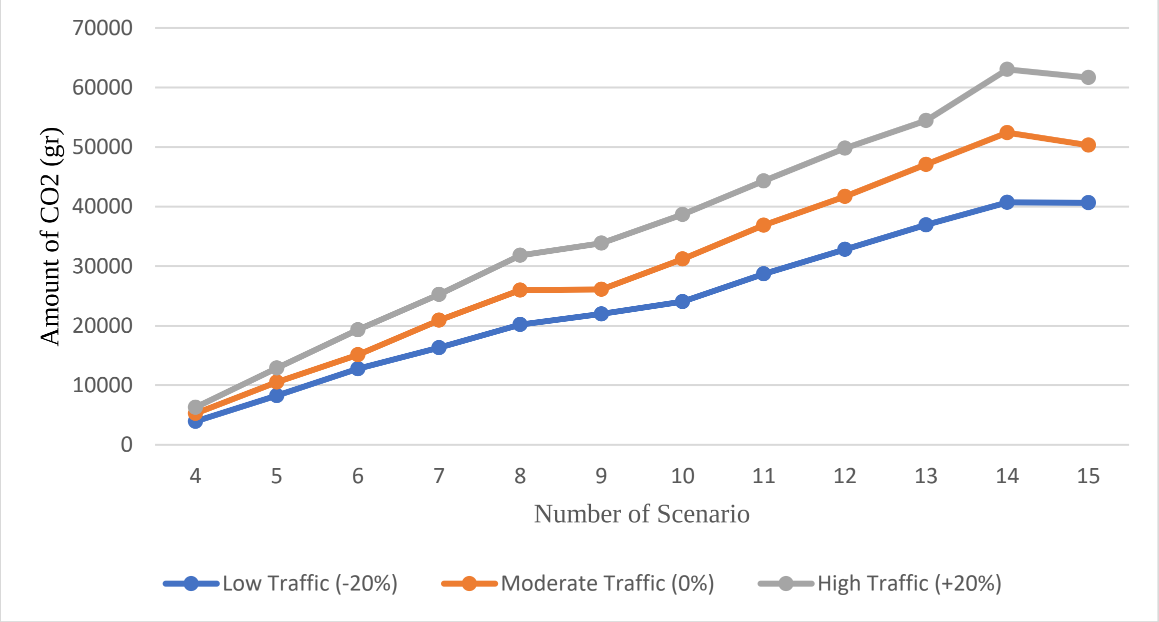


Figure 19. CV cars CO2 emission in three traffic groups

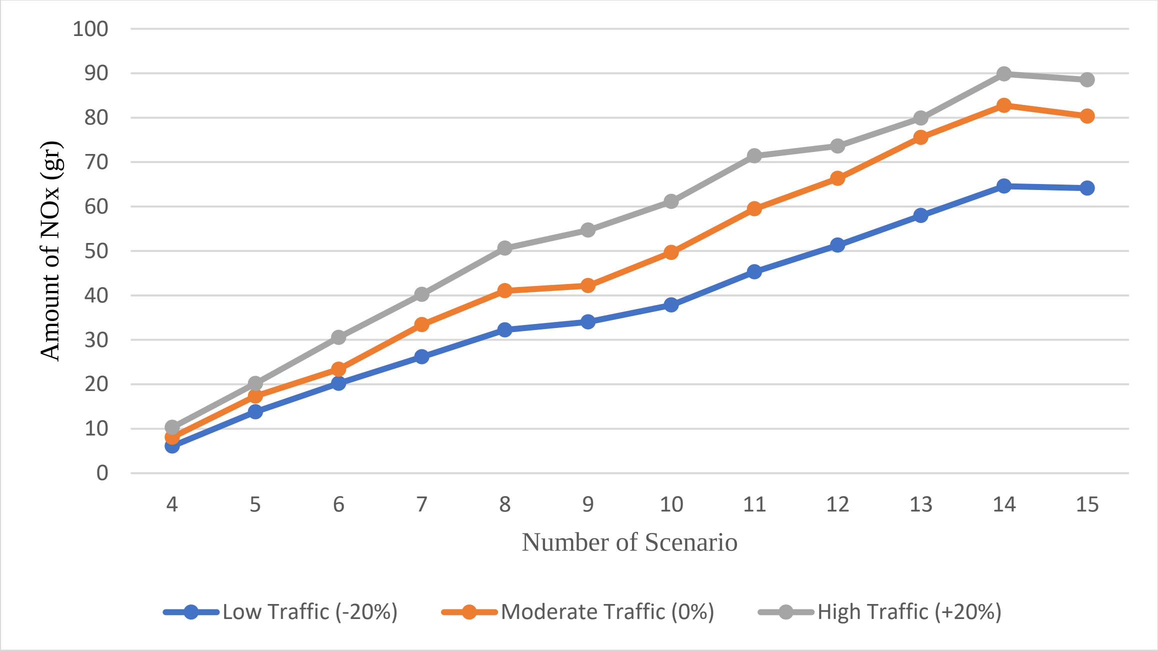


Figure 20. CV cars NOx emission in three traffic groups

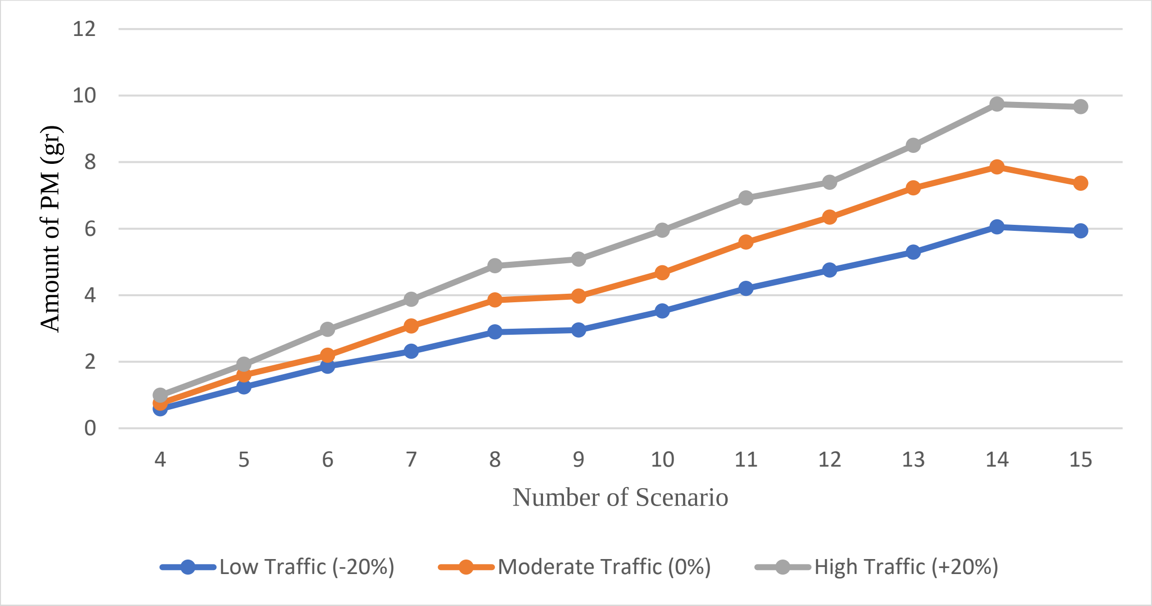


Figure 21. CV cars PM emission in three traffic groups

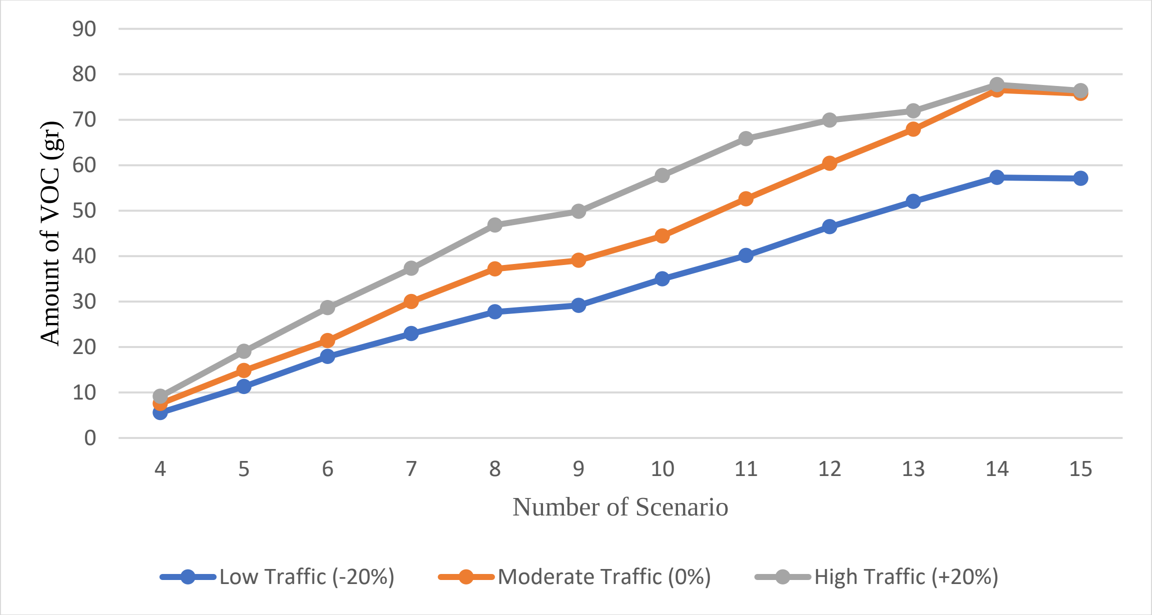


Figure 22. CV cars VOC emission in three traffic groups

As shown in figures (19) to (22), four pollutants experience an ascending trend from scenario 4 to scenario 14. The percentage of CV cars increases from scenario 4 to 15. Therefore, an ascending trend is acquired for all pollutants. CV buses are assigned to the simulation in scenario 15. Accordingly, CV buses can diminish pollutants from scenario 14 to scenario 15. Figure (23) shows the trend of Non-CV buses' CO2, Figure (24) shows the trend of Non-CV buses' NOx, Figure (25) shows the trend of Non-CV buses' PM, and Figure (26) shows the trend of Non-CV buses' VOC in three traffic groups.

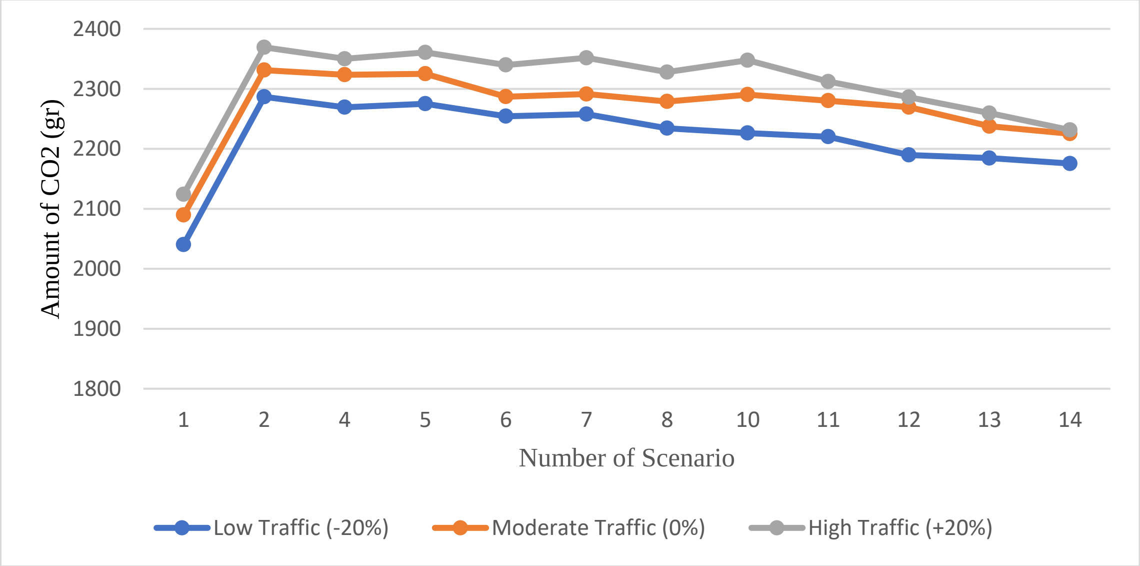


Figure 23. Non-CV buses CO2 emission in three traffic groups

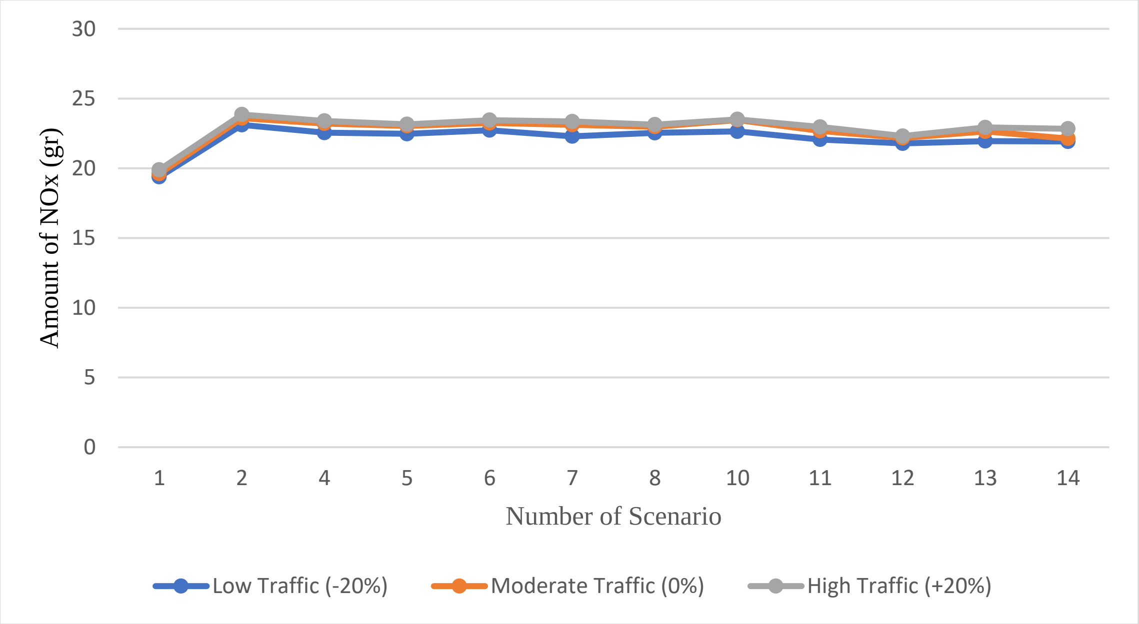


Figure 24. Non-CV buses NOx emission in three traffic groups

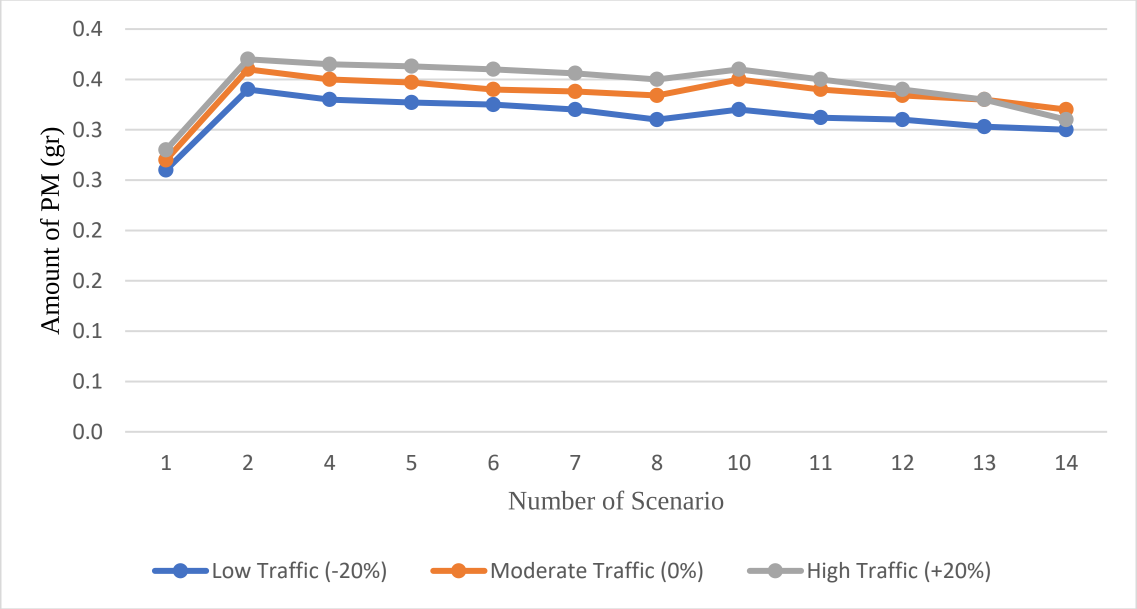


Figure 25. Non-CV buses PM emission in three traffic groups

Figure 26. Non-CV buses VOC emission in three traffic groups

Figure (27) shows the trend of CV buses' CO2, Figure (28) shows the trend of CV buses' NOx, Figure (29) shows the trend of CV buses' PM, and Figure (30) shows the trend of CV buses' VOC. As shown in Table (2), CV buses have been assigned in scenarios 3, 9, and 15. Hereupon, CV bus emission charts consist of two line segments.

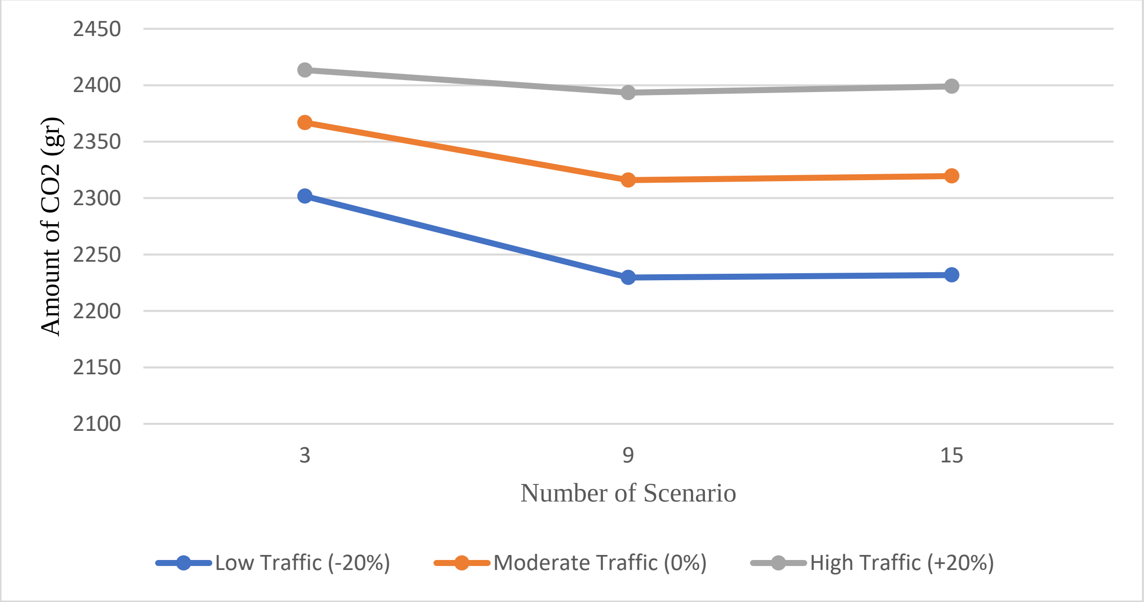


Figure 27. CV buses CO2 emission in three traffic groups

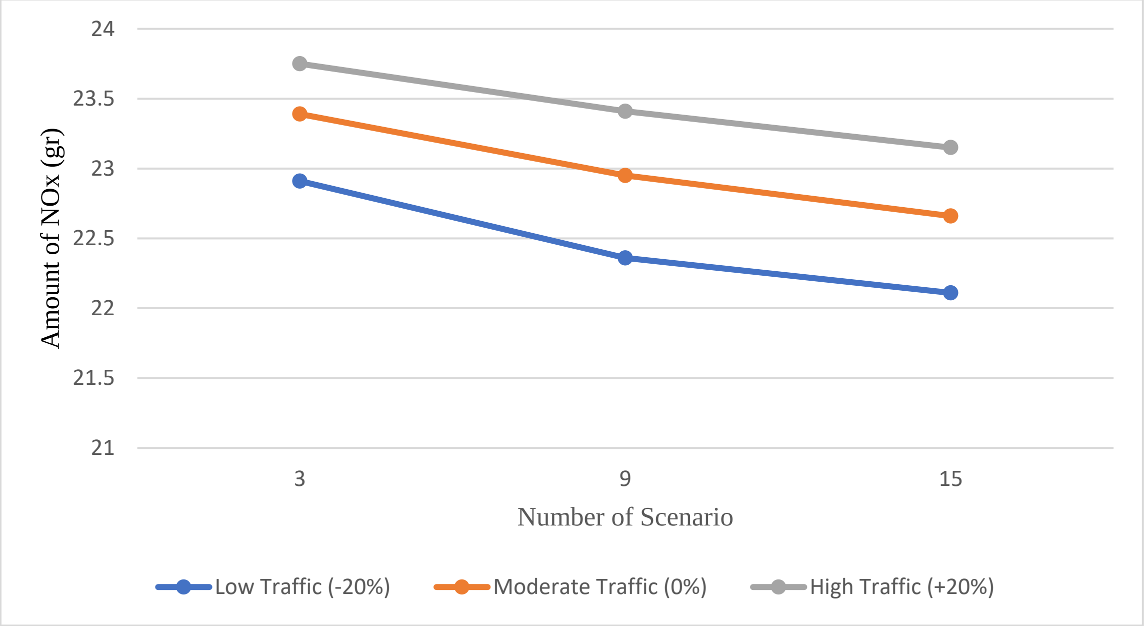


Figure 28. CV buses NOx emission in three traffic groups

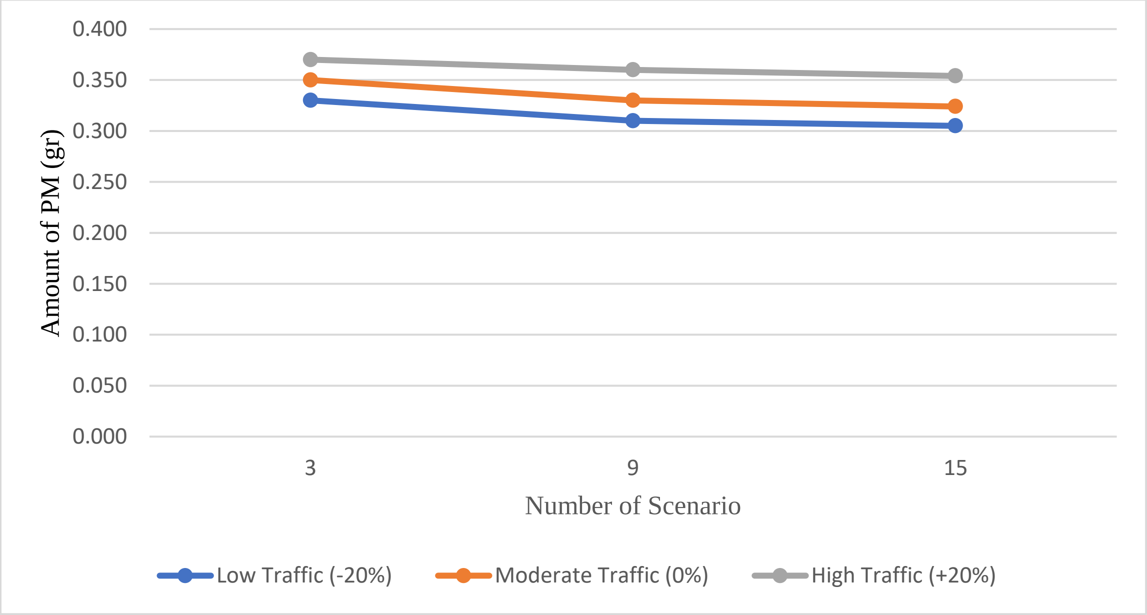


Figure 29 CV buses PM emission in three traffic groups

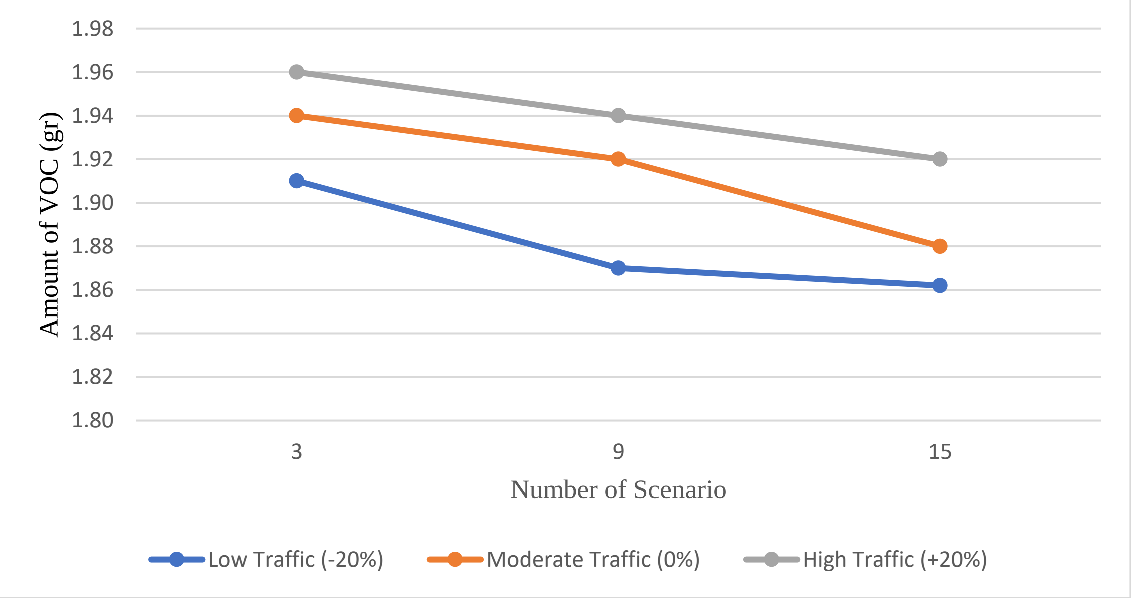


Figure 30 CV buses VOC emission in three traffic groups

As shown in figures (27) to (30), four pollutants experienced a descending trend from scenario 3 to scenario 9, and from scenario 9 to scenario 15. Due to increasing the percentage of CV cars from scenario 4 to 15, and special attributes of CV buses, four pollutants diminished from scenario 3 to 15.

Figures (11) to (14) showed that the total amount of pollutants diminish with the gradual deployment of CVs market penetration rates. It means as the market penetration rate of CVs increases, the amount of pollutants decreases. Recent studies have shown that connected vehicles (CVs) can save energy and reduce emissions. Previous studies regarding the effects of CVs gradual deployment on pollutant changes were mentioned in the literature review section. The results of our research regarding the effects of CVs MPR are on the same page as the results of previous studies.

5.3. Incident Route Travel Time Analysis

SB the Alameda corridor (OD: 1886-1880) is the most important origin-destination pair of our case study. A 15-minute incident period was hypothesized for SB the Alameda to investigate the effects of CVs re-routing. The aggregated charts for 100% Non-CV bus scenarios (scenarios with a 10% increment in MPR from 0 to 100% CV Cars) were drawn for low, moderate, and high traffic groups. In each chart, the trend of Non-CV cars, Non-CV buses, and CV-car are shown. Figures (31), (32), and (33) show that Non-CV bus travel time is always between Non-CV cars and CV cars’ travel time charts. The difference between Non-CV cars’ and Non-CV buses’ travel time diminishes as the total volume of the network increases.

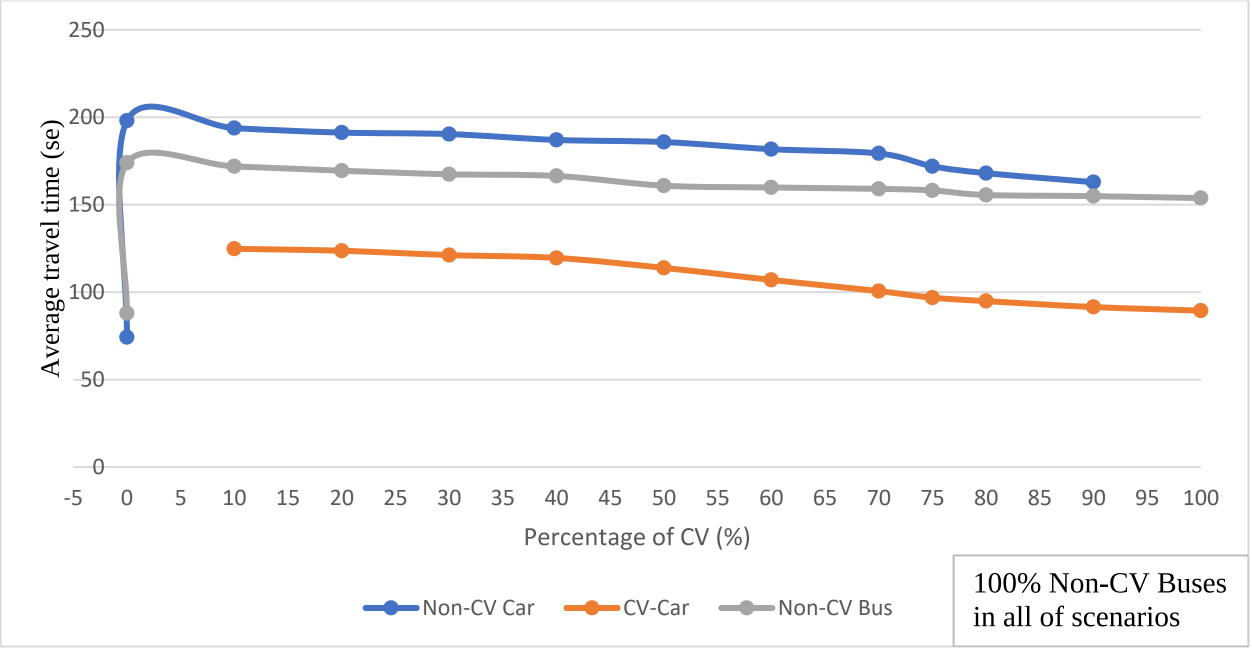


Figure 31. Aggregated average travel time chart for 100% Non-CV bus scenarios in low traffic group (-20%)

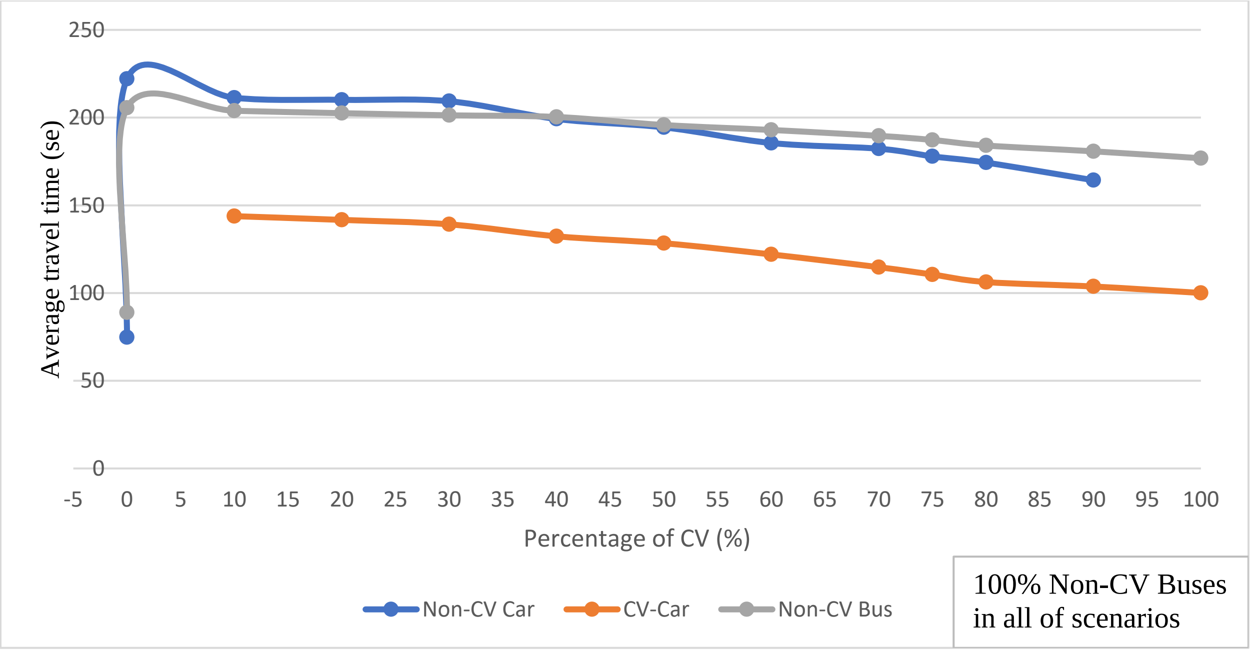


Figure 32. Aggregated average travel time chart for 100% Non-CV bus scenarios in moderate traffic group (0%)

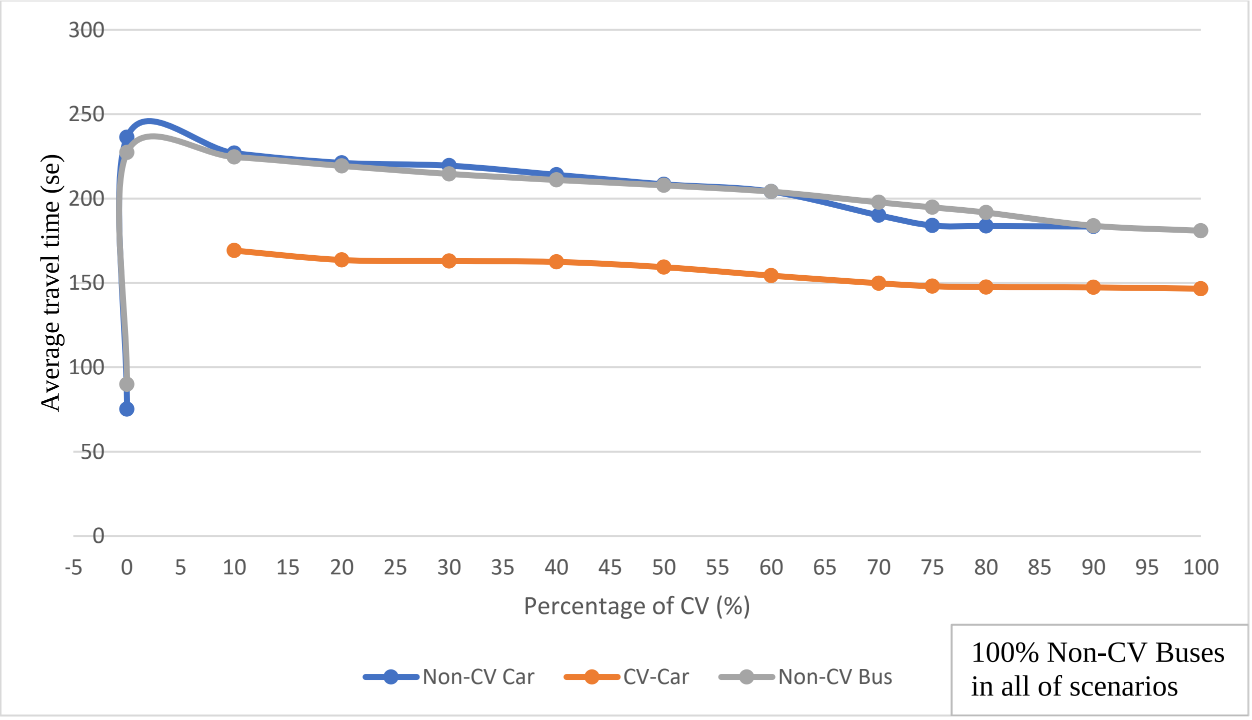


Figure 33. Aggregated average travel time chart for 100% Non-CV bus scenarios in high traffic group (+20%)

As shown in Figures (34), (35), and (36), a descending trend was observed for CV-bus average travel time changes in low, moderate, and high traffic groups. Hereupon, as the MPR of CVs increases, the average travel time of CV buses decreases. These changes are due to the gradual deployment of CV cars and supplementary assistant of CV buses. Figure (34) charts CV bus average travel time in scenarios (3), (9), and (15) in the Low traffic group. Figures (35) and 36) show similar issues in moderate and high traffic groups.

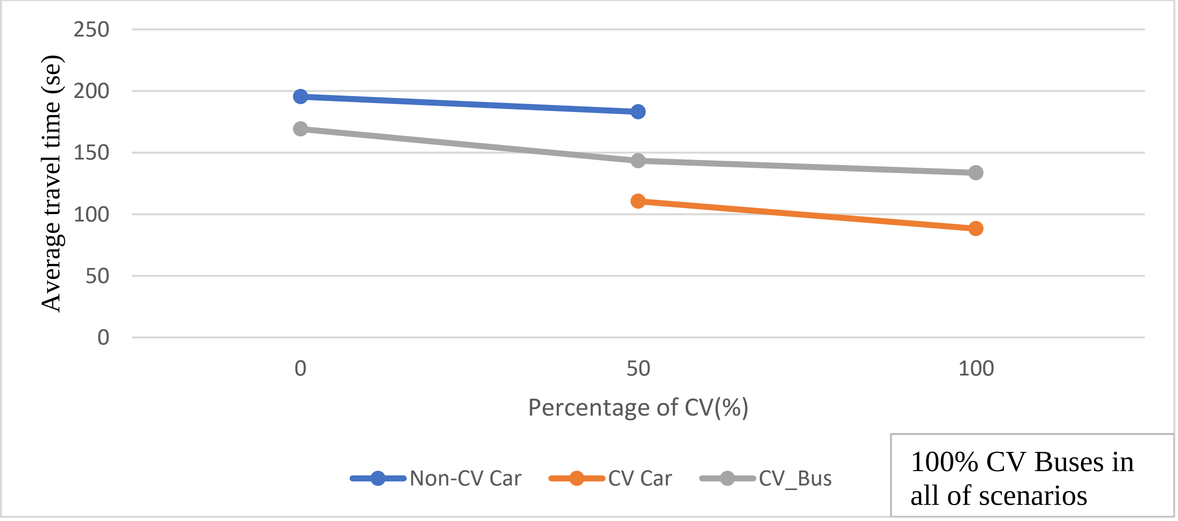


Figure 34. Aggregated average travel time chart for 100% CV bus scenarios in low traffic group

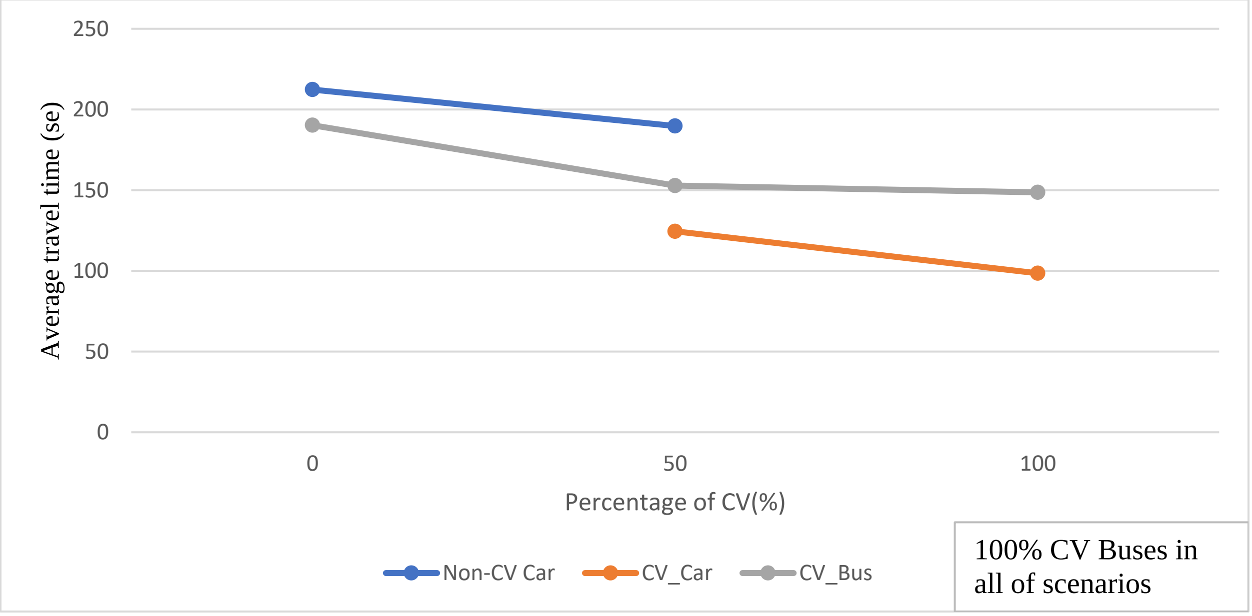


Figure 35. Aggregated average travel time chart for 100% CV bus scenarios in moderate traffic group (0%)

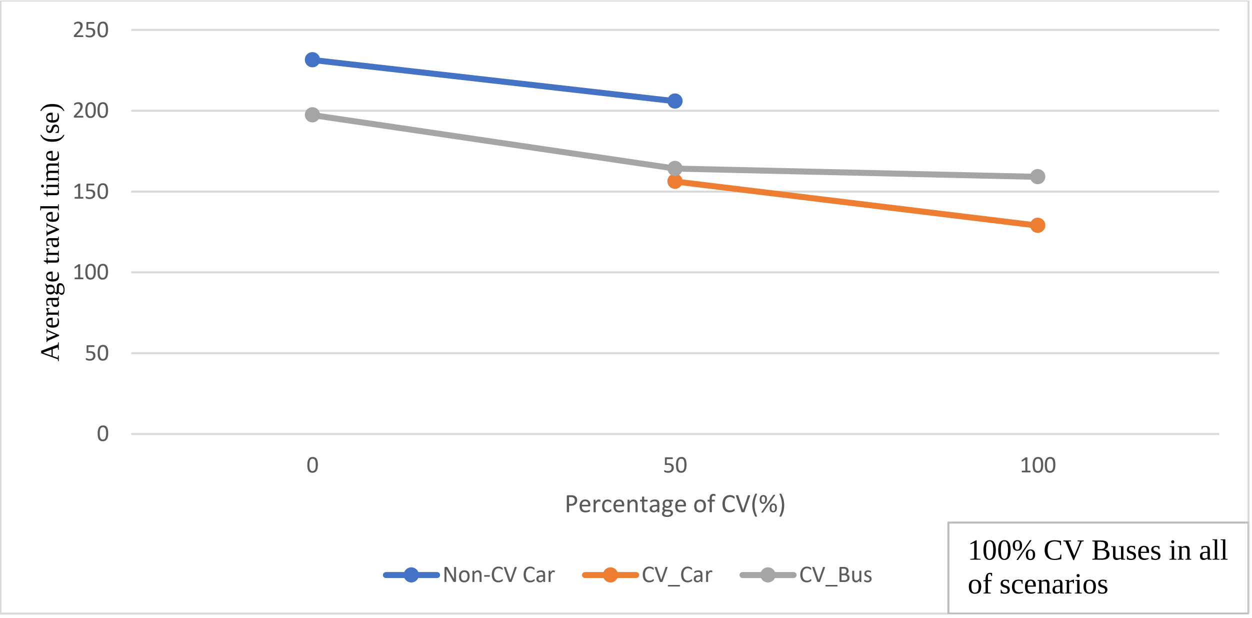


Figure 36. Aggregated average travel time chart for 100% CV bus scenarios in high traffic group (+20%)

Improving average travel time through the gradual deployment of CV buses was drawn in low, moderate, and high traffic groups. These charts are shown in Figures (37), (38), and (39) for low, moderate, and high traffic groups, respectively.

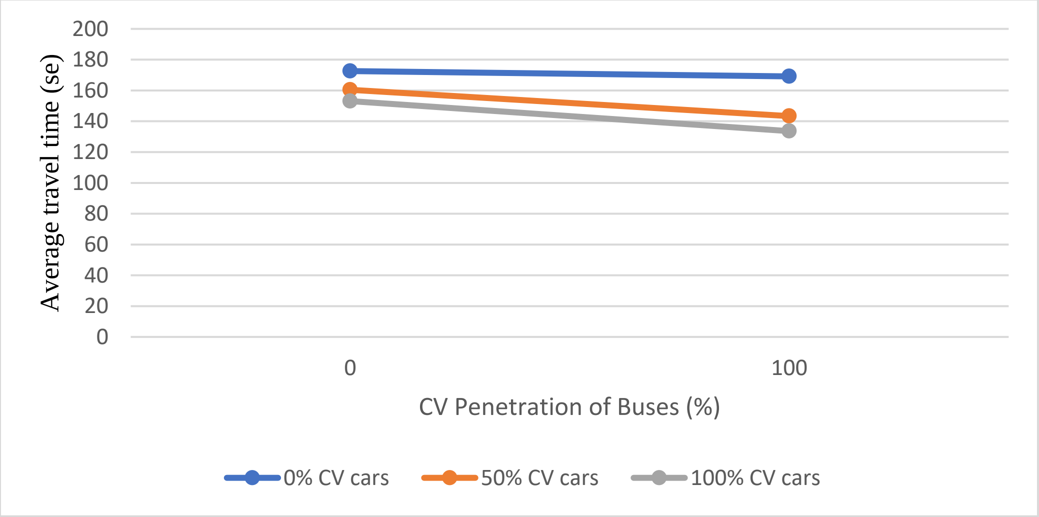


Figure 37. Average travel time improvement through gradual deployment of CV buses in low traffic group (-20%)

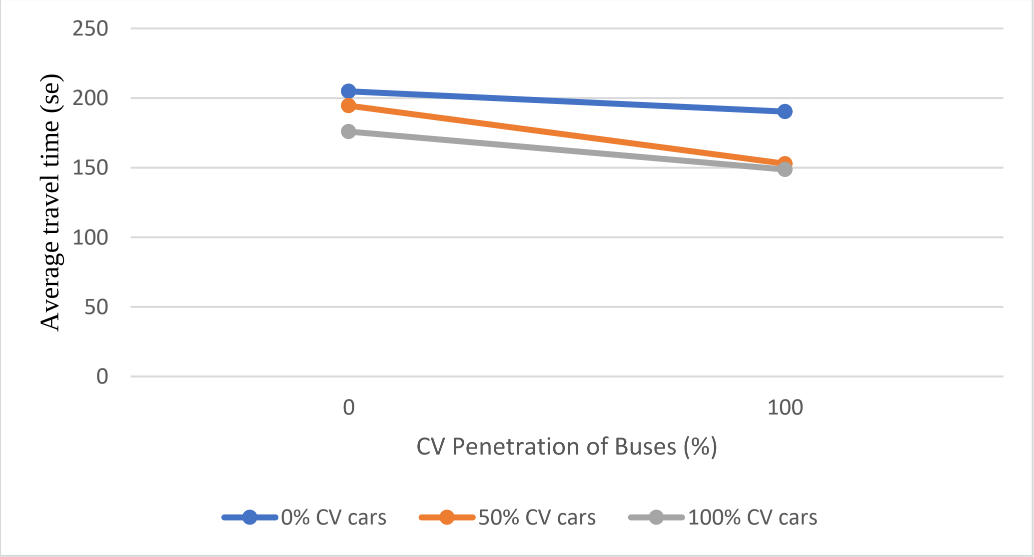


Figure 38. Average travel time improvement through gradual deployment of CV buses in moderate traffic group (0%)

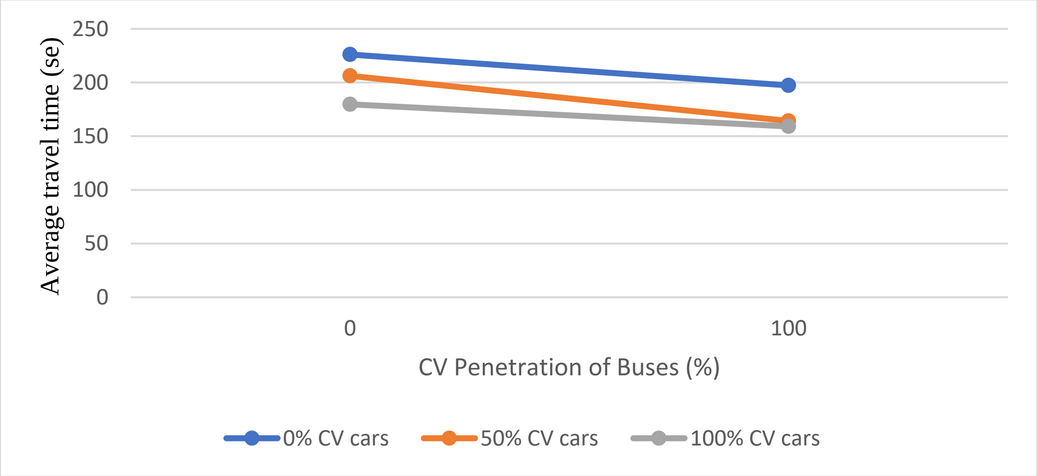


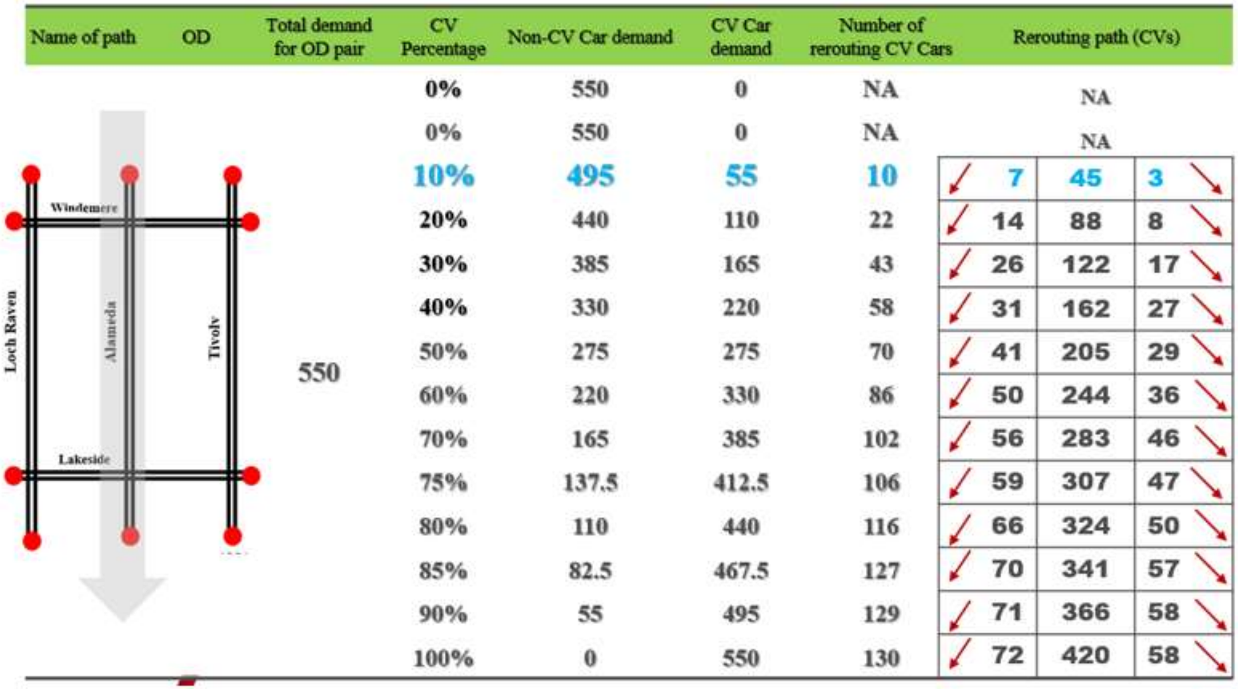
Figure 39. Average travel time improvement through gradual deployment of CV buses in high traffic group (+20%)

As shown in Figures (37), (38), and (39), gradual deployment of CV buses improves average travel time. Special features of CV buses efficiently mitigate the average travel time.

5.4. Analyzing dynamic re-routing of CV cars for the Incident Route

The proposed algorithm in AIMSUN is able to assign Non-CV cars statically and assign CV cars dynamically when an incident happens in the network. The proposed algorithm uses user-equilibrium, it updates the network every 30 seconds, and then it assigns CV cars in such a way that the average travel time of the network is reduced by re-routing of the CV cars. The number of re-routing CVs and their average travel times were acquired from the "path assignment" tab in AIMSUN. The average travel time for each scenario is an average of 10 replications. The results highlighted that, as the number of re-routing CVs increases, the average travel time decreases. We investigated the re-routing pattern of CVs for SB the Alameda. Other ODs may experience re-routing, but the changes of (1886-1880) origin-destination were reported. The high traffic group (+20%) was analyzed as the most critical condition of the network. It is worth mentioning that the initial matrix of this section differs from the presented matrix in Figure (7). The former total volume (3120 PCUs/hour) was changed to 2400 (PCUs/hour) due to the unstable condition of the network. We reduced the total volume to 2400 (PCUs/hour) to ensure that the re-routing of CVs resembles real-world conditions. Furthermore, the volume of (1886-1880) OD pair was grown to 550 (PCU/hour). In order to perform a more detailed analysis, a new scenario (85% CV cars) was added to the simulation process. Finally, the results were reported for 100% Non-CV bus scenarios (the scenarios 0% base, 0% with incident, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 75%, 80%, 85%, 90%, and 100% MPR). The results are shown in Tables (3) and (4).

Table 3. Re-routing behavior of CV cars in the incident route under various MPR scenarios



Name of path	OD	Total demand for OD pair	CV Percentage	Non-CV Car demand	CV Car demand	Number of rerouting CV Cars	Rerouting path (CVs)		
		550	0%	550	0	NA	NA		
			0%	550	0	NA	NA		
			10%	495	55	10	↙ 7	45	3 ↘
			20%	440	110	22	↙ 14	88	8 ↘
			30%	385	165	43	↙ 26	122	17 ↘
			40%	330	220	58	↙ 31	162	27 ↘
			50%	275	275	70	↙ 41	205	29 ↘
			60%	220	330	86	↙ 50	244	36 ↘
			70%	165	385	102	↙ 56	283	46 ↘
			75%	137.5	412.5	106	↙ 59	307	47 ↘
			80%	110	440	116	↙ 66	324	50 ↘
			85%	82.5	467.5	127	↙ 70	341	57 ↘
			90%	55	495	129	↙ 71	366	58 ↘
			100%	0	550	130	↙ 72	420	58 ↘

L.R. = Loch Raven Blvd.   T.I. =Tivoly Ave.   A.L. =The Alameda

As shown in Table (3), as the total volume increases, the number of re-routing CVs increases. Based on the user equilibrium condition on the network, less commonly used routes are utilized by other CVs. It is worth mentioning that the average travel time in each scenario for the incident path (SB the Alameda) were computed and shown in Table (4).

Table 4. Average travel times for all re-routing paths in (1886-1880- SB the Alameda) OD pair

Percentage of CV (%)	Scenario	Number of re-routing CV cars in path Loch Raven Blvd.	Re-routing travel time in path Loch Raven Blvd.	Number of re-routing CV cars in path Tivoly Ave.	Re-routing travel time in path Tivoly Ave.	Number of CV cars in SB the Alameda	Re-routing travel time in SB the Alameda
10	4	7	179.5	3	180.1	45	179.1
20	5	14	169.8	8	169.9	88	169.6
30	6	26	163.8	17	163.9	122	163.6
40	7	31	155.8	27	156.1	162	155.6
50	8	41	152.6	29	152.8	205	152.1
60	10	50	150.7	36	150.9	244	150.4
70	11	56	145.9	46	146.1	283	145.8
75	75%	59	145.8	47	145.9	307	145.7
80	12	66	144.9	50	145.3	324	144.7
85	85%	70	140.6	57	140.9	341	140.3
90	13	71	140.3	58	140.8	366	140.2
100	14	72	140.2	58	140.5	420	140.1

The number of re-routing CVs and the average travel time in each path are shown in Figures (40-45). It is worth mentioning that all the following results were acquired from the "path assignment" tab, and the 10-minute warm-up has not been considered in the result. The average (arithmetic mean) of 10 replications was reported as "average travel time" of each path.

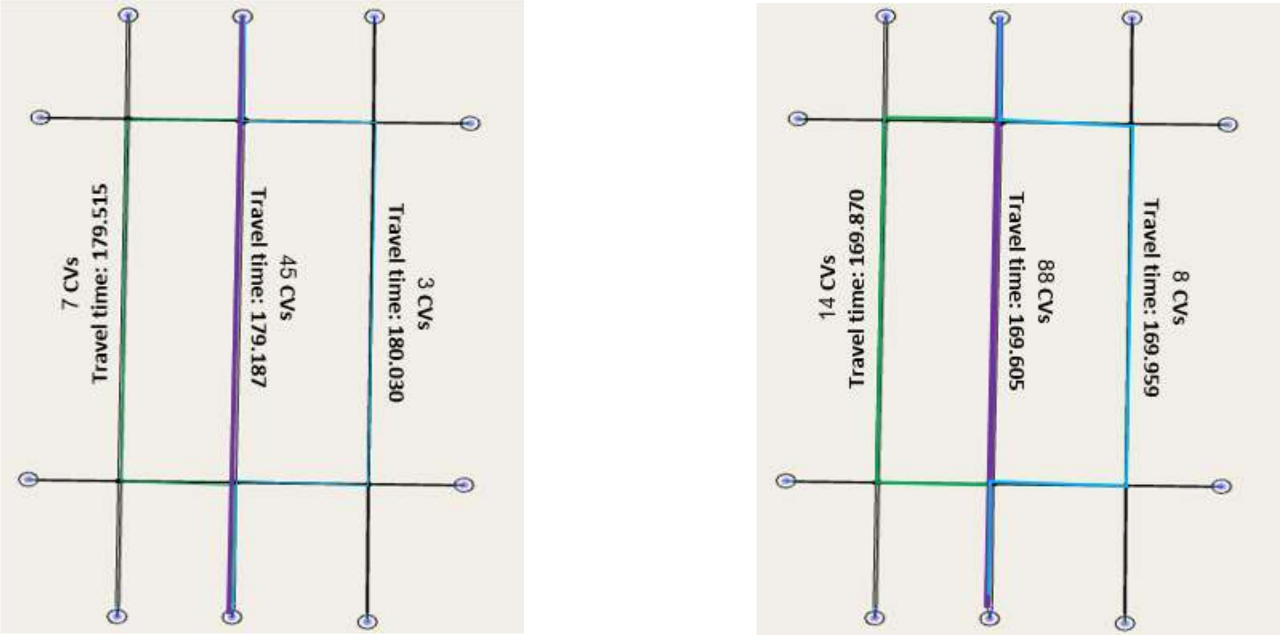


Figure 40. Re-routing paths in scenario 4 (left figure) / Re-routing paths in scenario 5 (right figure)

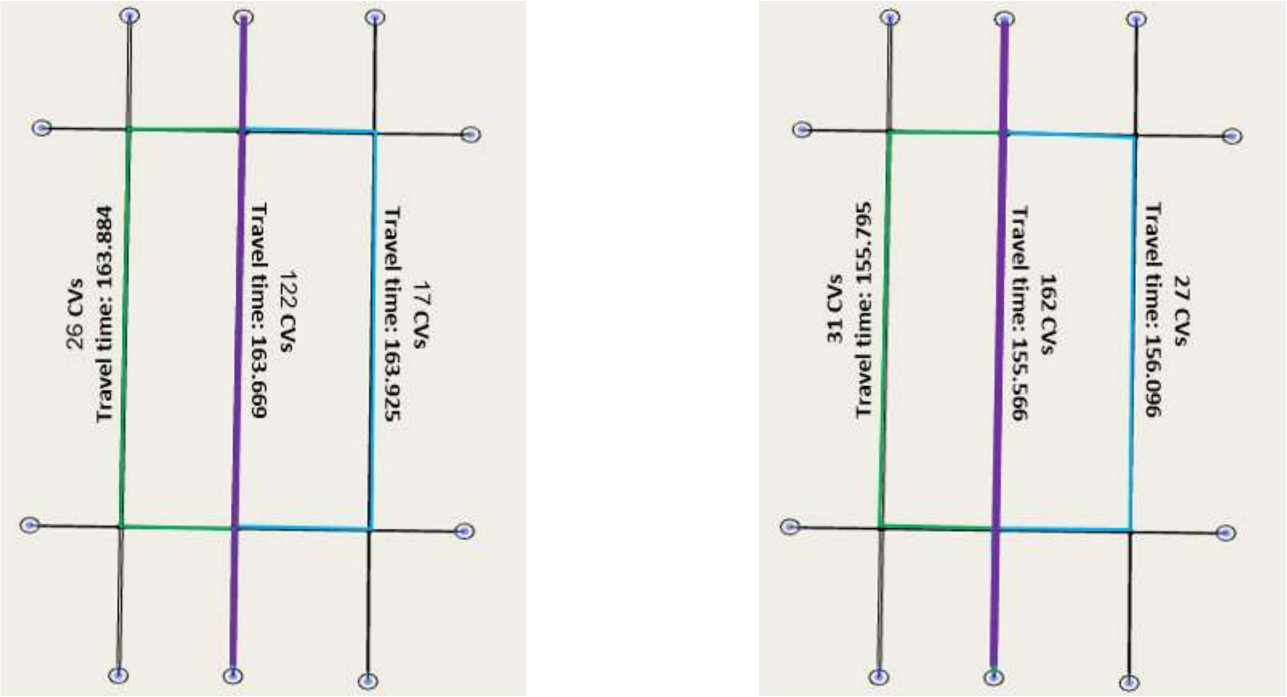


Figure 41. Re-routing paths in scenario 6 (left figure) / Re-routing paths in scenario 7 (right figure)

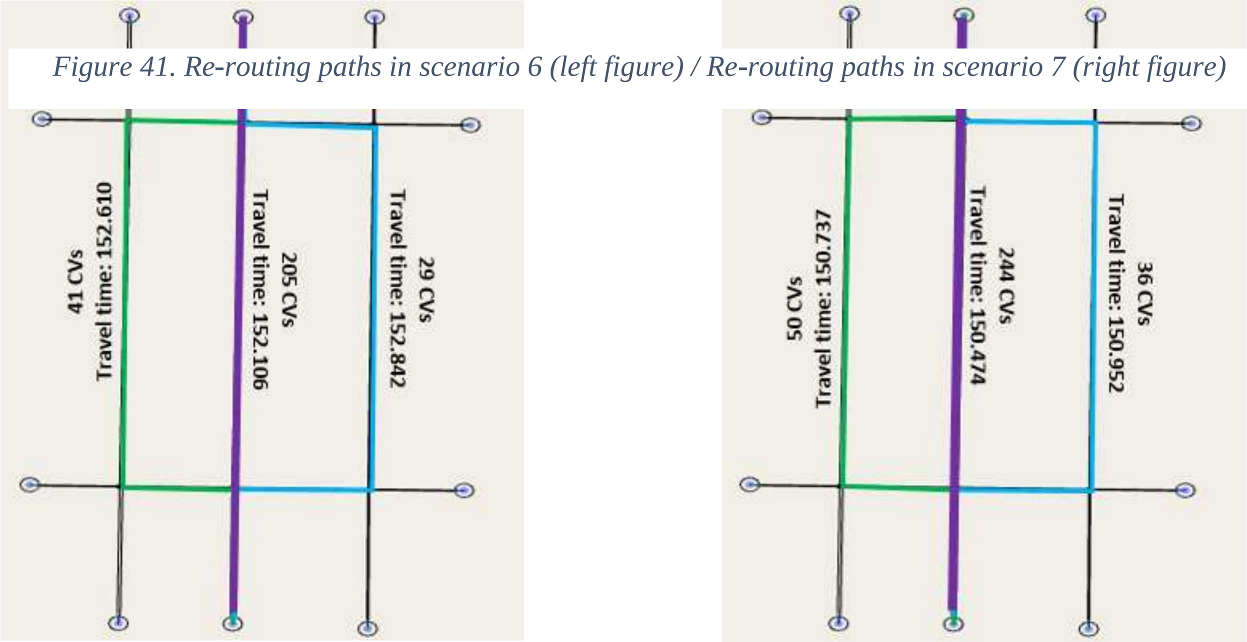


Figure 42. Re-routing paths in scenario 8 (left figure) / Re-routing paths in scenario 10 (right figure)

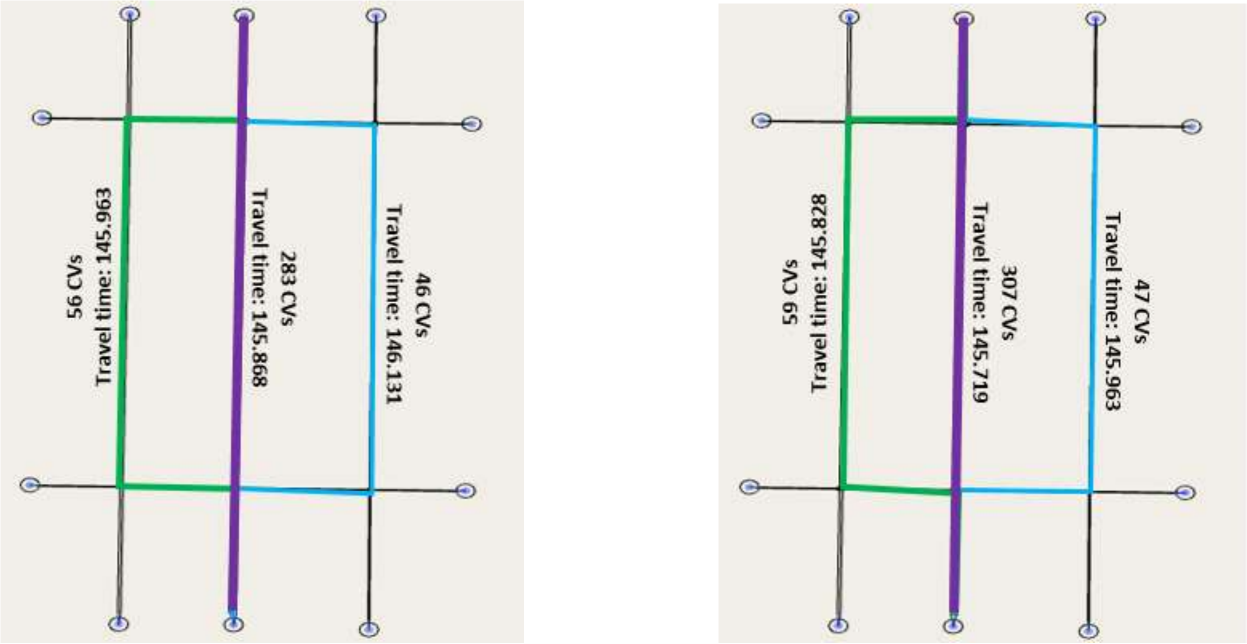


Figure 43. Re-routing paths in scenario 11 (left figure) / Re-routing paths in scenario 75% (right figure)

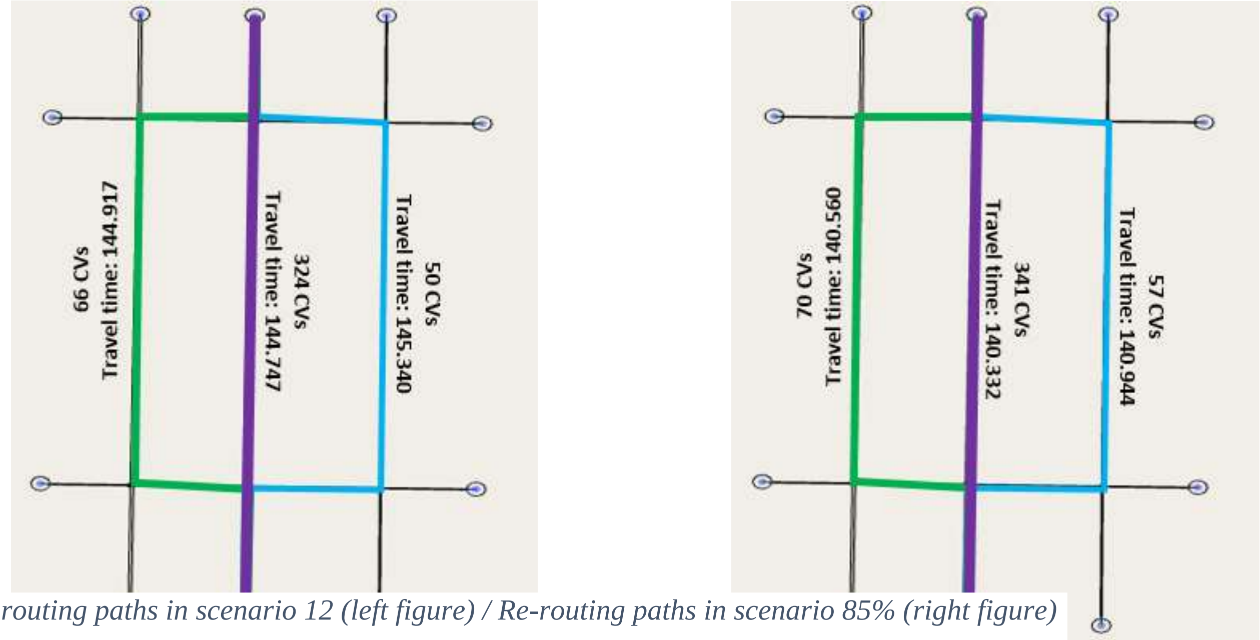


Figure 44. Re-routing paths in scenario 12 (left figure) / Re-routing paths in scenario 85% (right figure)

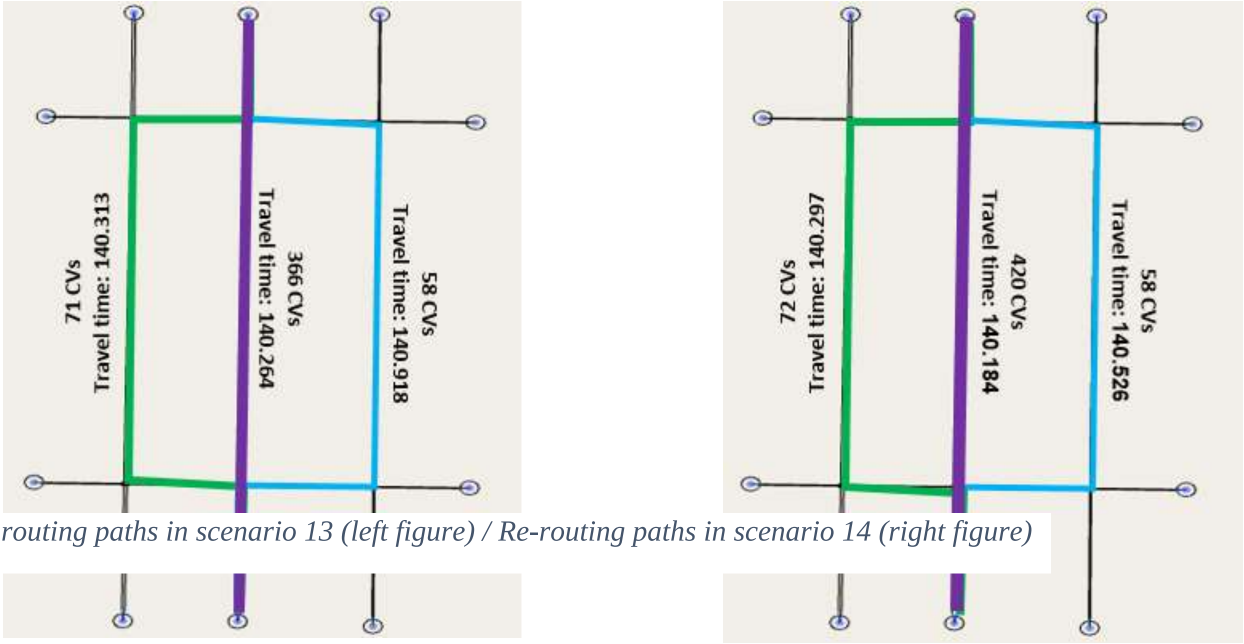


Figure 45. Re-routing paths in scenario 13 (left figure) / Re-routing paths in scenario 14 (right figure)

5.5. Dynamic CV Bus Lane

The attractiveness of public transport is significantly impacted by urban traffic congestion. To improve the efficiency of buses, many transit agencies and/or cities have developed and implemented several solutions for allowing buses to avoid traffic queues. Dynamic bus lanes (or dedicated bus lane: DBLs) have become widely accepted and spread all over the world (103). In order to improve the performance of buses, prioritize the movement of mass public transportation systems in urban areas, and reduce travel time and delay time of these systems in heavy traffic, a separate lane is designed. A dynamic bus lane temporarily allocates a general traffic lane to the buses to facilitate their movement at congestion times. In examples implemented in some metropolitan areas of the world, dynamic bus lanes are characterized by the lighting of LEDs on the ground and lighting panels of drawdown, indicating to the users they must wait when a bus is approaching. Thus, as soon as the lane is dedicated to buses, the corridor is "reserved," and the cars are directed not to cross it.

We designed a dynamic bus lane for the proposed case study. The first southbound lane of The Alameda was reserved for CV buses. Two scenario groups were analyzed to investigate the efficiency of the proposed dynamic CV bus lane when the road is congested. When an incident happens on the network (7:15 AM ~ 7:30 AM), the first SB lane of The Alameda is reserved once for a 15 minutes, and in the second scenario for 30 minutes. After the restriction is lifted, other vehicle types (e.g., Non-CV cars and CV cars) can drive in the reserved lane. Figure (46) shows the average travel time of CV buses without a CV bus lane, with a 15-minute CV bus lane, and a 30-minute CV bus lane.

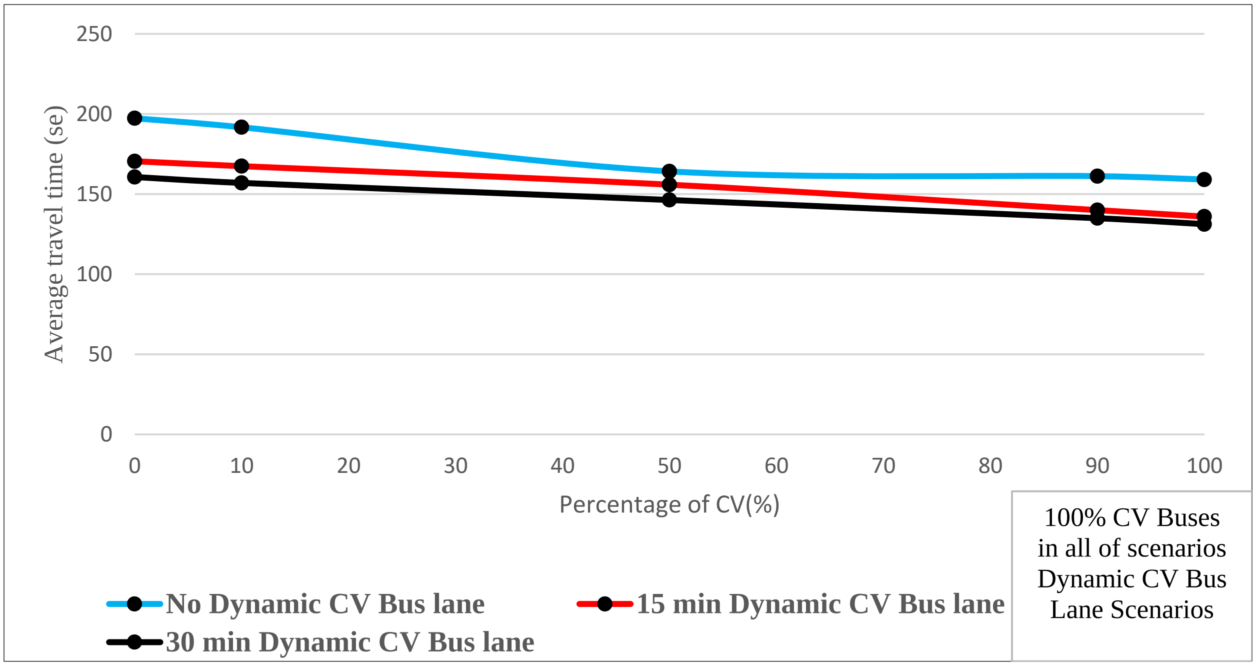


Figure 46. Average travel time changes of CV buses through dynamic CV bus lane

Figures (47) and (48) show the average travel time of Non-CV cars and CV Cars, respectively, without a CV bus lane, with a 15-minute CV bus lane, and a 30-minute CV bus lane.

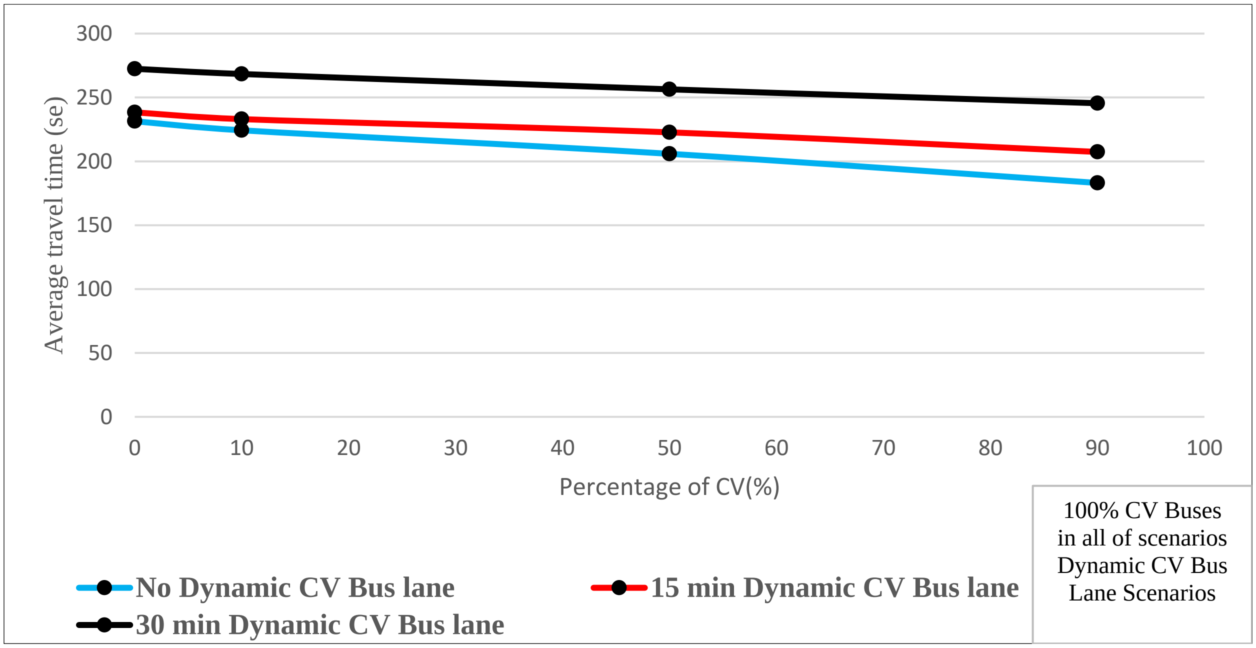


Figure 47. Average travel time changes of Non-CV cars through dynamic CV bus lane

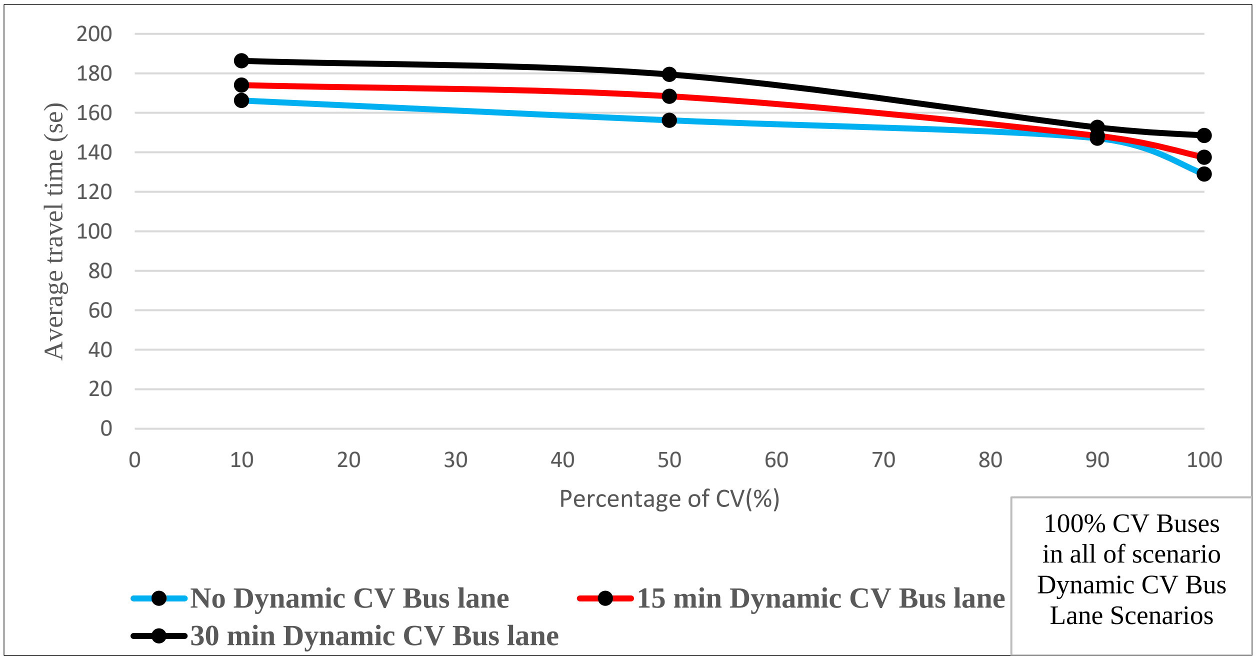


Figure 48. Average travel time changes of CV cars through dynamic CV bus lane

As shown in Figures (46), reserving one lane as a dynamic CV bus lane significantly improves the average travel times for CV buses. The results of a 30-minute dynamic CV bus lane highlighted that the average travel time for buses in that scenario is reduced by 5% compared to the scenario with a 15-minute dynamic CV bus lane. Additionally, as shown in Figure (47), for Non-CV cars, a 30-minute dynamic CV bus lane increased their average travel time by 15% compared to a 15-minute dynamic CV bus lane. Finally, as shown in Figure (48), for CV cars, a 30-minute dynamic CV bus lane increased their average travel time by 6% compared to a 15-minute dynamic CV bus lane.

Figures (49) and (50) show the average travel time changes of Non-CV cars, CV cars, and CV buses in 15-minute and 30-minute dynamic CV bus lane scenarios.

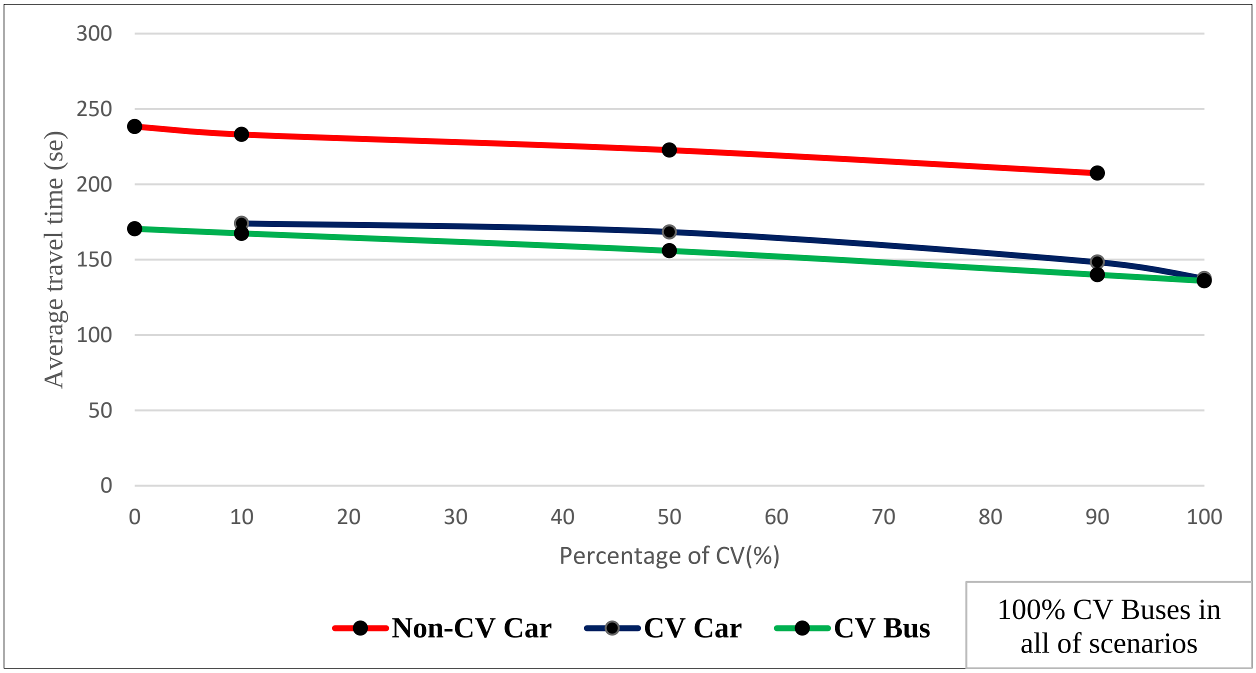


Figure 49. Average travel time changes of Non-CV cars, CV cars, and CV buses in a "15-minute" dynamic CV bus lane scenario

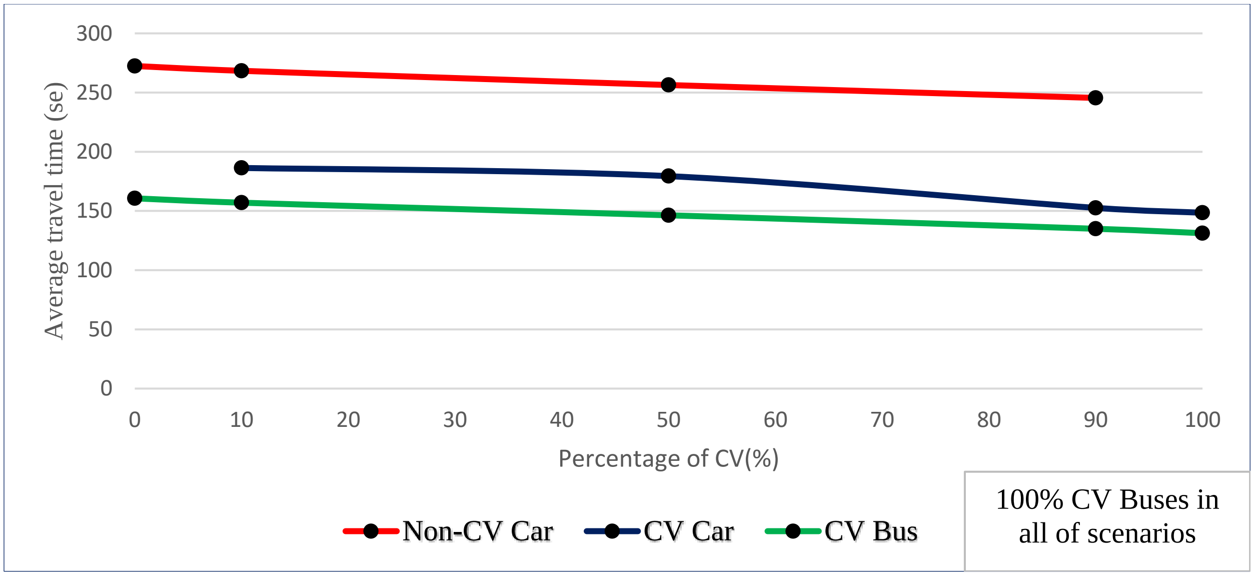


Figure 50. Average travel time changes of Non-CV cars, CV cars, and CV buses in a "30-minute" dynamic CV bus lane scenario

Consequently, the aforementioned results specified that a dynamic CV bus lane improves the performance of CV buses during congestion, significantly improves CV buses' mobility, and mitigates their delay time. Other solutions such as Transit Signal Priority (TSP) can be used with dynamic CV bus lanes simultaneously. Unfortunately, two major drawbacks can still be found during heavy traffic conditions: (i) effectiveness of TSP is reduced since green phases of the traffic signal have to arrange for both buses and remaining traffic; (ii) dynamic CV bus lanes are not necessarily appropriate because the lane reduction limits the available capacity for traffic. However, the advantages of dynamic CV bus lanes should not be ignored, especially in congested transport networks. Dynamic bus lanes can significantly improve the efficiency of mass transit systems in cities, and their implementation can considerably improve passengers' satisfaction with these systems.

5.6. Network-wide equity analysis

Transportation equity is a critical thread that should be investigated before implementing any transportation policy for network users. A variety of demographic, social, and economic factors result in people having different experiences while using the same mode of transportation or mobility service. As a result, equity is not an afterthought or standalone task, but a key consideration at each stage of a project. Transportation equity was scrutinized in our research by analyzing travel times of various travel modes when CVs emerge. CV vehicles can connect to each other, roadside units (RSU), and traffic management centers (TMCs). Due to the connection between CVs, and broadcasting traffic messages from TMCs to RSUs, and then from RSUs to CVs, CVs can reroute dynamically to find less congested paths. Consequently, the delay time and travel time of other users who are moving on other paths of the network may be dramatically changed.

Equity in our case study was evaluated through "Average travel time" as a measure of effectiveness (MOE). Fifteen OD pairs consisting of the following ODs were considered to scrutinize the effects of CV cars' re-routing on the other users.

1) South-bound (SB) of Loch Raven Blvd. (1885-1879),
2) North-bound (NB) of Loch Raven Blvd. (1879-1885),
3) South-bound (SB) of the Alameda (1886-1880),
4) North-bound (NB) of the Alameda (1880-1886),
5) South-bound (SB) of Tivoly Ave (1887-1881),
6) North-bound (NB) of Tivoly Ave (1881-1887),
7) East-bound of Windemere Ave (1884-1888),
8) West-bound of Windemere Ave (1888-1884),
9) East-bound of Lakeside Ave (1883-1882),
10) West-bound of Lakeside Ave (1882-1883),
11) OD pair (1885-1880),
12) OD pair (1885-1881),
13) OD pair (1886-1879),
14) OD pair (1886-1881),
15) OD pair (1887-1879).

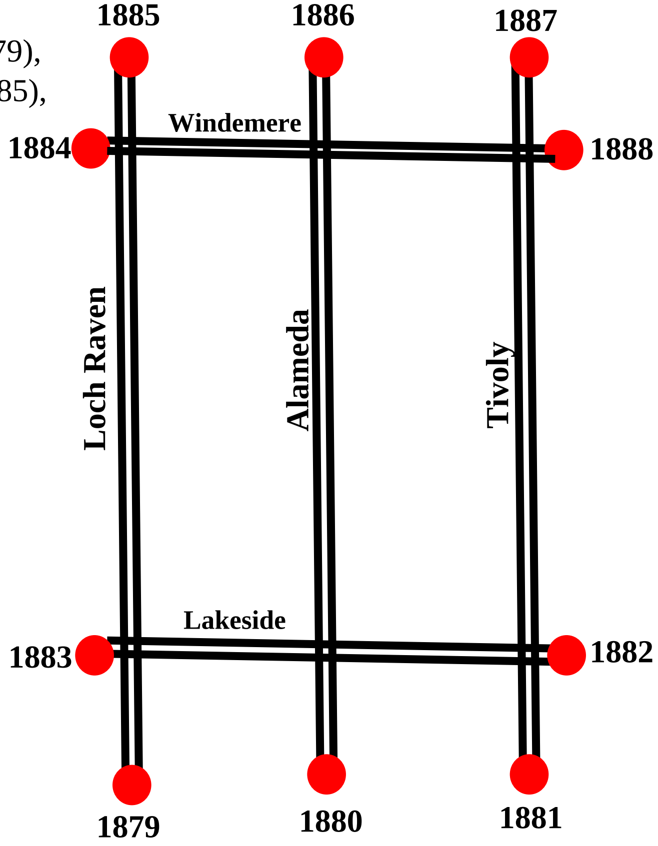


Figure 51. Considered network in our research

It is worth mentioning that, the average travel time changes were drawn for the scenarios with a 100% Non-CV bus. It means the average travel time of scenarios 3, 9, and 15 were not drawn in the following charts. The average travel time changes of Non-CV buses in SB and NB lanes of the Alameda are shown in Figures (54) and (55). Section 3.3 explains our methodology for finding the average travel times, and weighted average of network-level.

5.6.1. Average travel time changes in SB Loch Raven Blvd. (1885-1879)

In times of congestion, a considerable percentage of CV cars (especially in 1886-1880 OD pair) were diverted to SB Loch Raven. SB Loch Raven has two lanes, 35 miles/hour (56 km/hour) speed limit, and 1400 (PCU/hour) total capacity. Ten replications were run for each scenario and a simple average (arithmetic mean) among all 10 replications was performed. A chart details the average travel time changes for SB Loch Raven (1885-1879) in Figure (52). As shown in Figure (52), the changes of Non-CV cars and CV cars are almost identical.

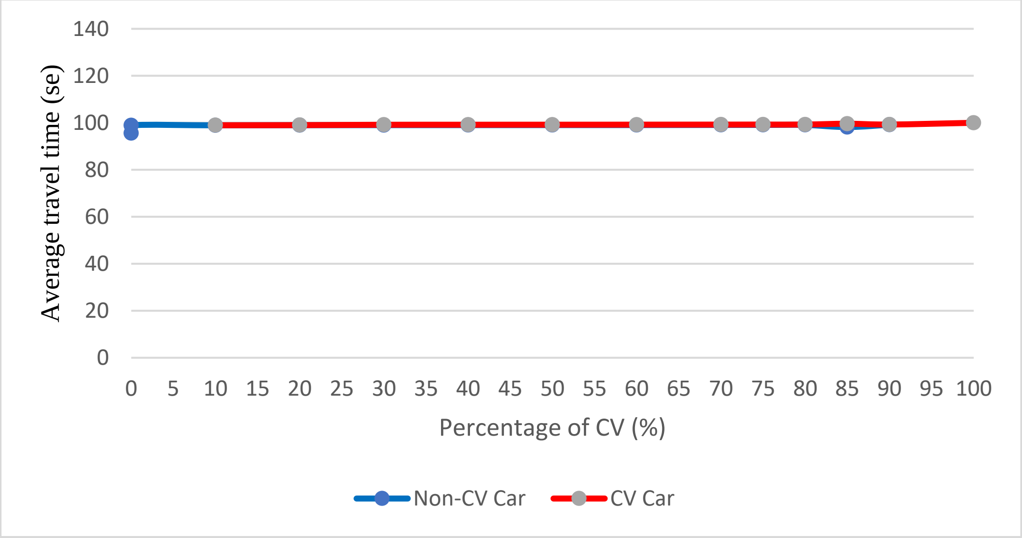


Figure 52. Average travel time changes for SB Loch Raven (1885-1879)

5.6.2. Average travel time changes in NB Loch Raven Blvd. (1879-1885)

The northbound (NB) lanes of Loch Raven are frequently used to transfer the traffic volume of the southwestern part of the network. NB Loch Raven has two lanes, 35 miles/hour (56 km/hour) speed limit, and 1400 (PCU/hour) total capacity. Figure 53 charts the average travel time changes chart for NB Loch Raven (1879-1885). Figure (53) is almost the same as the previous chart, and in both of them Non-CV cars and CV cars change similarly.

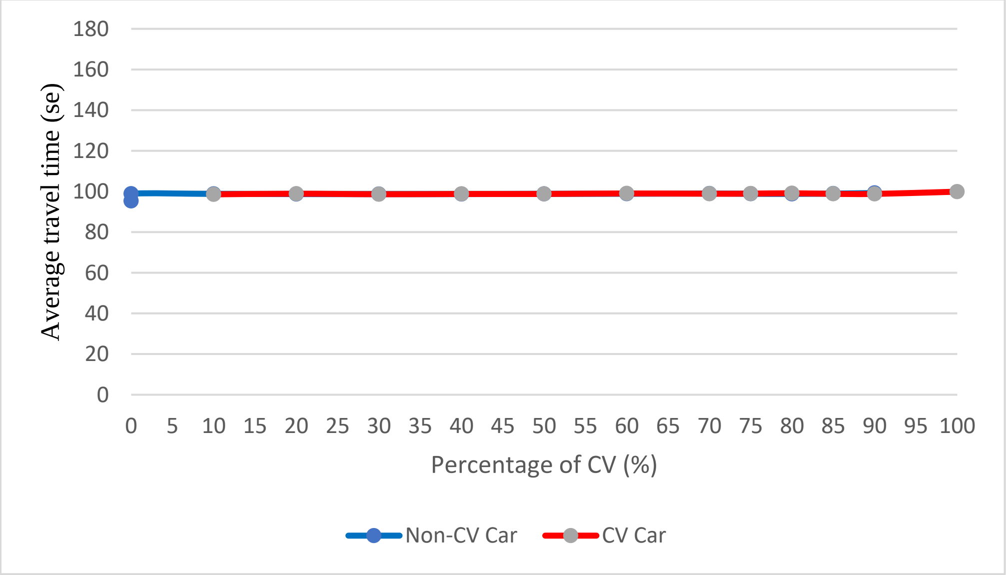


Figure 53. Average travel time changes for NB Loch Raven (1879-1885)

5.6.3. Average travel time changes in SB the Alameda. (1886-1880)

It is obvious that The Alameda southbound is the most important origin-destination of our case study. These are two separate lanes with a 45 miles/hour (72 km/hour) speed limit, and 1400 (PCU/hour) total capacity. The congestion happens on this path in the second quarter of the simulation. When an incident happens, almost all the assigned CV cars for (1886-1880) OD pair were diverted to SB Loch Raven and SB Tivoly Ave. Furthermore, a considerable percentage of re-routing CVs of the (1886-1880) OD pair tend to use SB Loch Raven. Nevertheless, the average travel time SB on The Alameda was decreased and Non-CV cars and Non-CV bus average travel times of (1886-1880) pair experienced a descending trend.

As shown in Figure (54), a remarkable break was acquired from 70% to 85% MPR of CVs. It is worth mentioning that The Alameda SB is used by all five northern centroids of the network to transmit their traffic volumes to southern centroids.

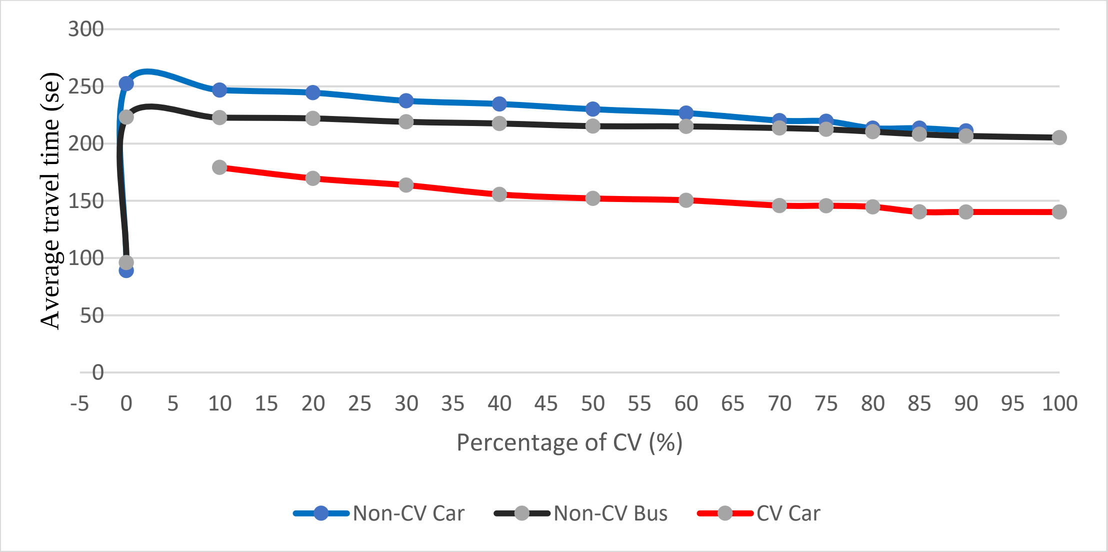


Figure 54. Average travel time changes for SB the Alameda (1886-1880)

5.6.4. Average travel time changes in NB the Alameda. (1880-1886)

The Alameda northbound has two separate lanes, a 45 miles/hour (72 km/hour) speed limit, and an 1800 (PCU/hour) total capacity. The average travel time of Non-CV buses in NB the Alameda was acquired in Figure (55). As shown in Figure (55), Non-CV cars and CV cars have similar changes, and Non-CV buses experienced a descending trend.

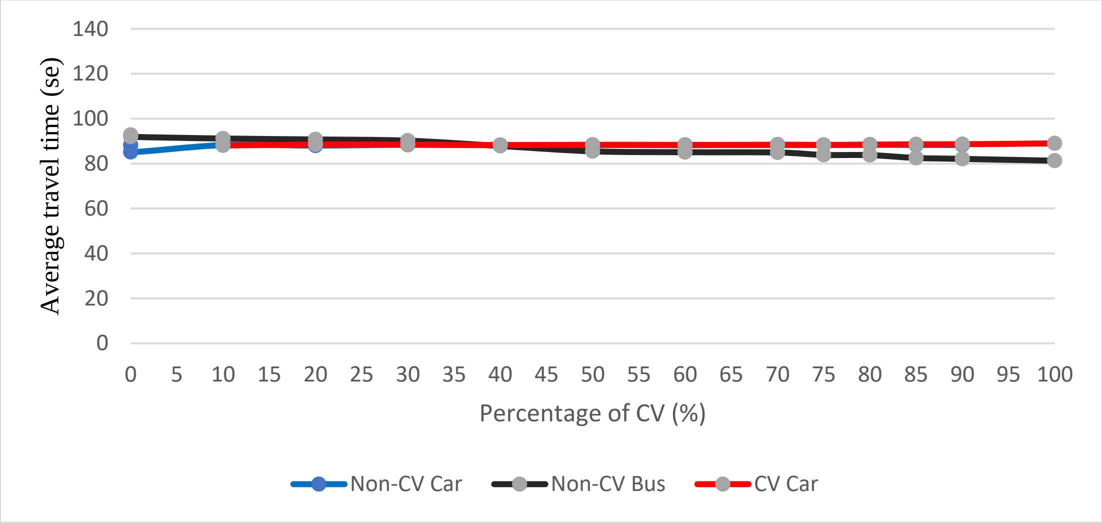


Figure 55. Average travel time changes for NB the Alameda (1880-1886)

5.6.5. Average travel time changes in SB Tivoly Ave. (1887-1881)

One lane, 25 miles/hour (40 km/hour) speed limit, and a 700 (PCU/hour) total capacity were considered for southbound (SB) Tivoly Ave. As shown in Figure (56), when congestion happens on SB the Alameda, a part of the (1886-1880) OD pair total volume is attracted to SB Tivoly Ave. Based on the number of lanes, speed limit, and limited capacity of SB Tivoly Ave, the average travel time of Non-CV cars and CV cars increases dramatically.

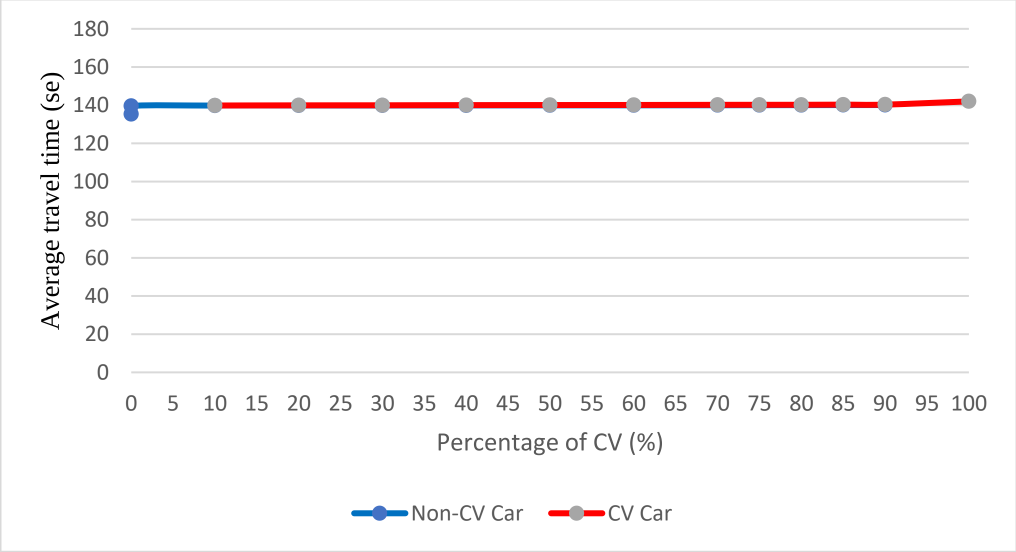


Figure 56. Average travel time changes for SB Tivoly Ave (1887-1881)

5.6.6. Average travel time changes in NB Tivoly Ave. (1881-1887)

One lane, a 25 miles/hour (40 km/hour) speed limit, and a 700 (PCU/hour) total capacity were considered for northbound (NB) Tivoly Ave. As shown in Figure (57), both Non-CV cars and CV cars change similarly.

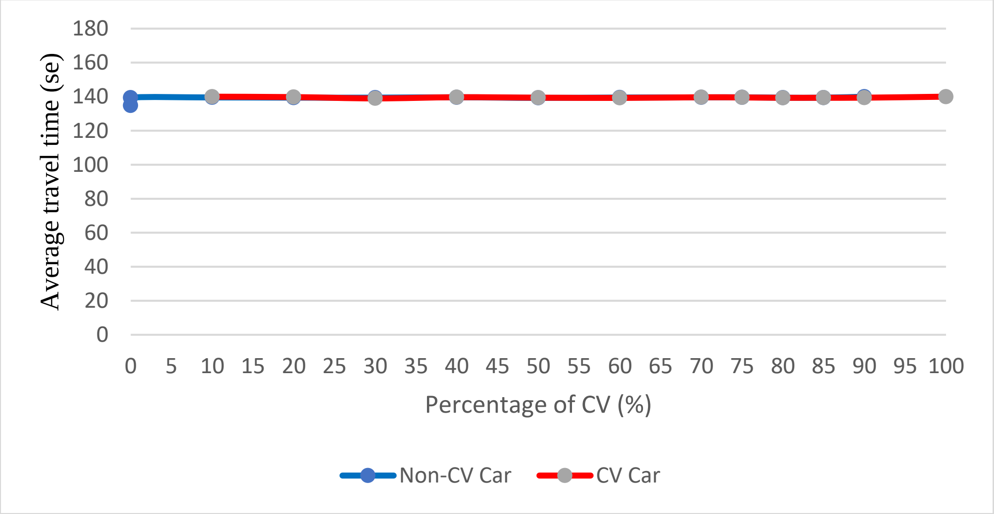


Figure 57. Average travel time changes for NB Tivoly Ave (1881-1887)

5.6.7. Average travel time changes in Eastbound (EB) Windemere Ave. (1884-1888)

Windemere Ave. is a residential road with one lane in each direction (EB and WB), a 25 miles/hour (40 km/hour) speed limit, and a 700 (PCU/hour) total capacity. The same speed limit and total capacity were considered for EB and WB Windemere Ave. Additionally, EB Windemere Ave is used for transmitting the traffic volume of (1883-1888), (1883-1887), (1879-1888), (1879-1887), (1880-1887), and (1880-1888) OD pairs. When the congestion happens, a considerable percentage of the aforementioned ODs were attracted to the EB Windemere Ave. Consequently, an ascending trend of average travel time occurred as shown in Figure (58). The average travel time experienced a considerable jump after 85% CV MPR.

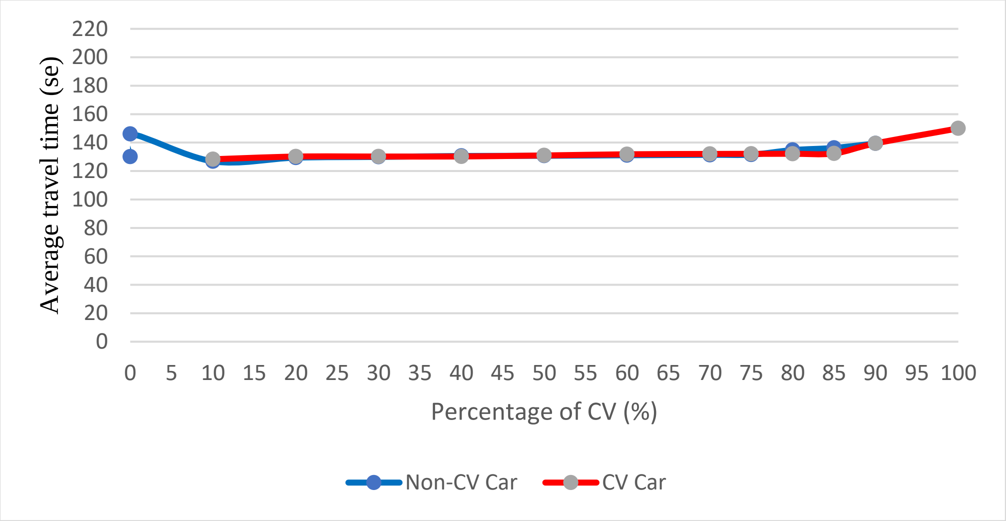


Figure 58. Average travel time changes for EB Windemere Ave (1884-1888)

5.6.8. Average travel time changes in Westbound (WB) Windemere Ave. (1888-1884)

WB Windemere Ave frequently is used by Non-CV cars and CV cars of (1887-1884), (1886-1884), (1882-1884), and (1880-1884) OD pairs. A significant percentage of these OD's volumes were attracted to WB Windemere Ave during 15 minutes of congestion. Accordingly, the average travel time on WB Windemere Ave has a similar ascending trend like EB Windemere Ave. The average travel time changes in WB Windemere Ave are shown in Figure (59). As shown in Figure (59), CV cars' average travel times saliently increase after 50% MPR. Such a significant ascending trend happened because of six stop signs that were located in three northern intersections. The aforementioned stop signs imposed impressive delays on Non-CV cars.

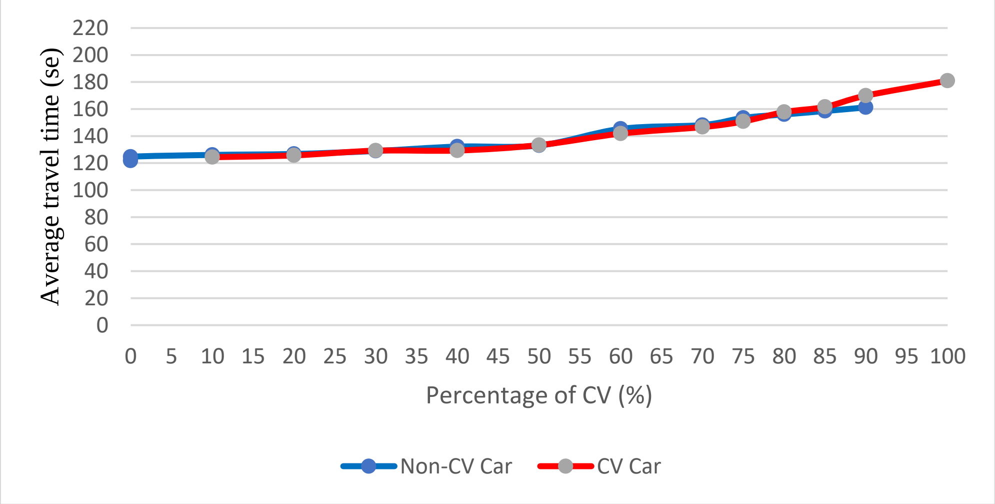


Figure 59. Average travel time changes for WB Windemere Ave (1888-1884)

5.6.9. Average travel time changes in Eastbound (EB) Lakeside Ave. (1883-1882)

Lakeside Ave. is a residential road with one lane in each direction (EB and WB), a 25 miles/hour (40 km/hour) speed limit, and a 700 (PCU/hour) total capacity. The same speed limit and total capacity were considered for EB and WB Lakeside Ave. EB Lakeside is frequently used by Non-CV and CV cars of (1879-1882), and (1880-1882) OD pairs. Six stop signs were considered for three southern intersections. This means all the vehicles on EB and WB Lakeside must completely stop in three southern intersections, and the priority of traffic flow was determined for NB and SB Loch Raven, the Alameda, and Tivoly Ave. Figure (60) shows the average travel time changes for EB Lakeside Ave. As shown in Figure (60), a significant increase was achieved for MPR greater than 85%, and Non-CV cars and CV cars' average travel time changes are similar from 10% to 80% MPR.

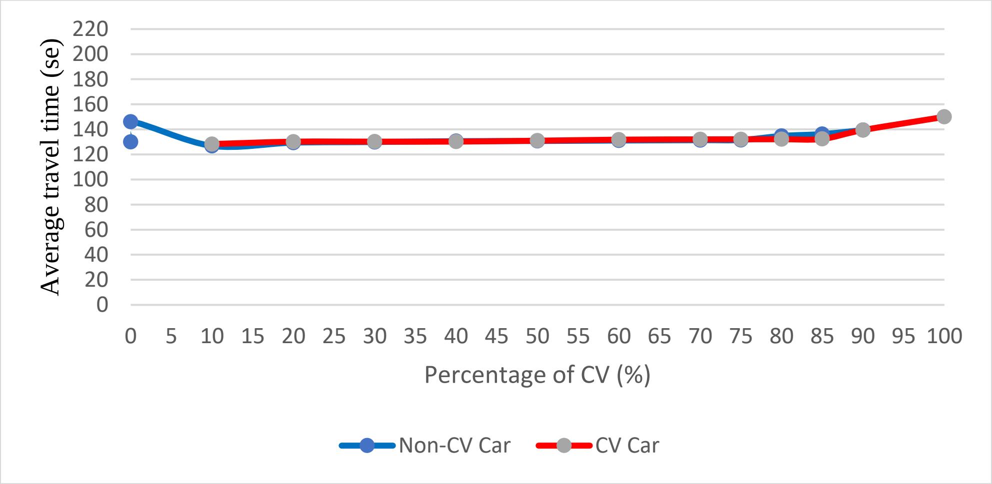


Figure 60. Average travel time changes for EB Lakeside Ave (1883-1882)

5.6.10. Average travel time changes in Westbound (WB) Lakeside Ave. (1882-1883)

The westbound (WB) lanes of Lakeside Ave. frequently are used by Non-CV and CV cars of (1881-1883), (1880-1883), (1888-1883), (1887-1883), and (1886-1883) OD pairs. As shown in Figure (61), a remarkable ascending trend occurred for 90% and 100% MPRs. The principal reason for such an ascending trend could be the saturation of this path in equal and more than 85% of MPR.

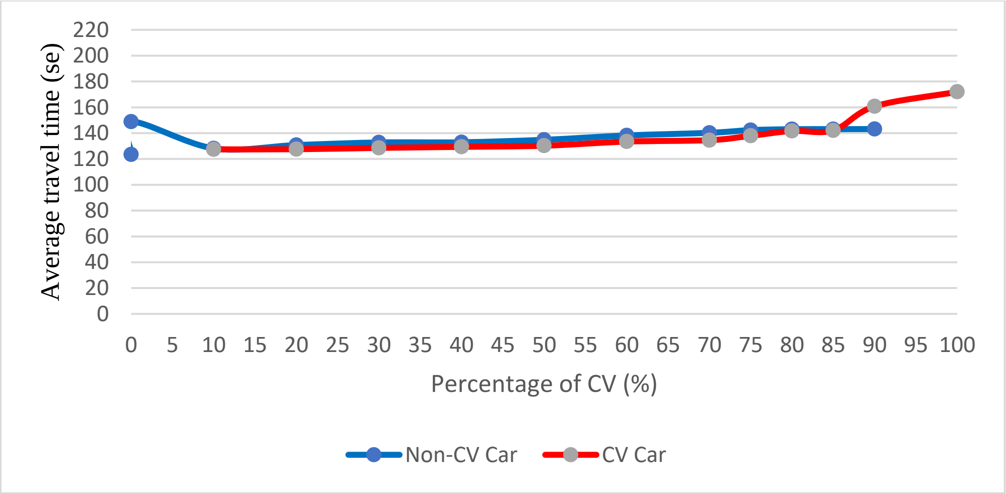


Figure 61. Average travel time changes for WB Lakeside Ave (1882-1883)

5.6.11. Average travel time changes in (1885-1880) OD pair

In order to investigating the network-level equity accurately, the average travel times of five cross-sectional OD pairs were considered and analyzed. Figure (62) shows the average travel time changes in (1885-1880) OD pair. As shown in Figure (62), both charts experienced a descending trend in MPR greater than 40%. The average travel time of CV cars is less than Non-CV cars' average travel time. It means the number of re-routing CV cars in (1885-1880) OD pair increases with the gradual deployment of CVs MPR.

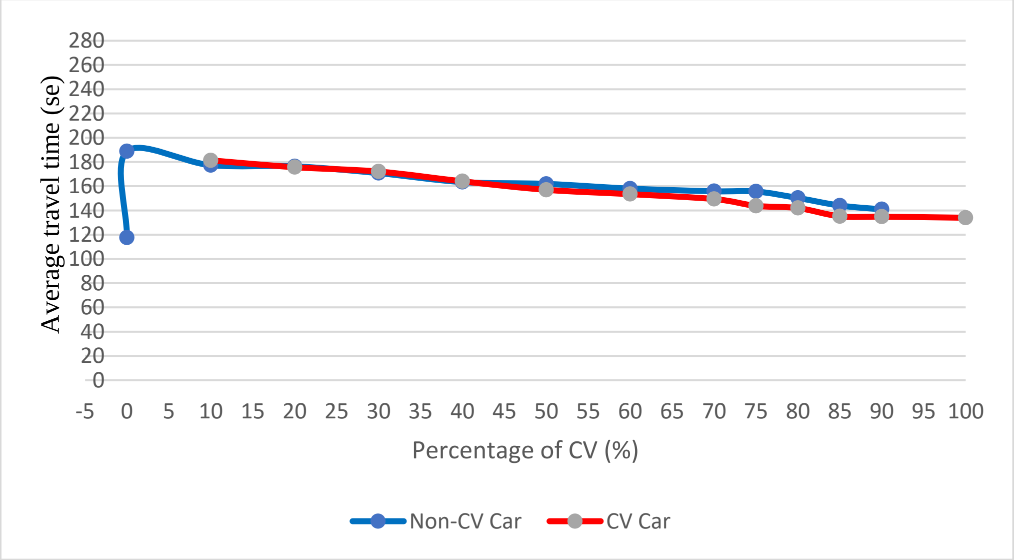


Figure 62. Average travel time changes for (1885-1880) OD pair

5.6.12. Average travel time changes in (1885-1881) OD pair

Figure (63) shows the average travel time changes in (1885-1881) OD pair. As shown in Figure (63), the Non-CV car has three considerable drops from (20%-30%), (60%-70%), and (80%-85%) MPR. Additionally, this chart shows the descending trend of CV cars, especially from 30%-70% MPR. The average travel time changes of CV cars are less than Non-CV cars and both charts almost coincide after 85% MPR.

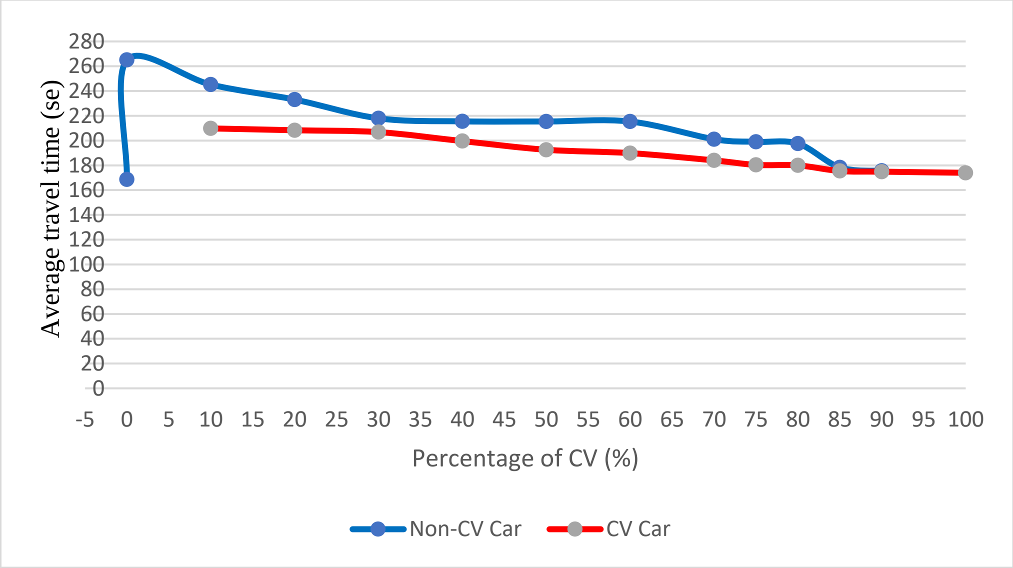


Figure 63. Average travel time changes for (1885-1881) OD pair

5.6.13. Average travel time changes in (1886-1879) OD pair

Figure (64) shows the average travel time changes in (1886-1879) OD pair. As shown in Figure (64), 50% MPR is the critical point for both Non-CV car and CV car charts. Furthermore, the CV car chart has a noticeable drop from (75%-85%) MPR, and both charts have a similar trend, from 20% to 75% MPR. There is no noticeable change in the average travel time of CV cars for MPR greater than 90%.

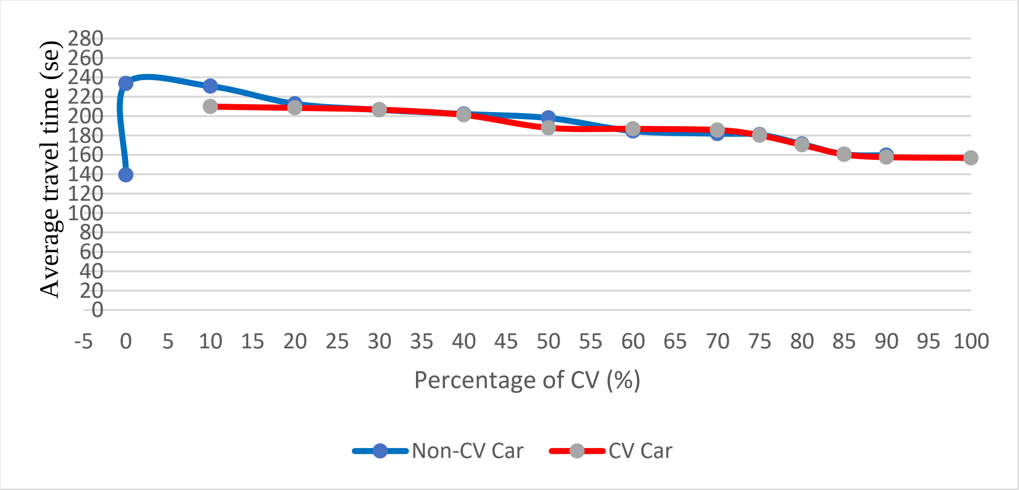


Figure 64. Average travel time changes for (1886-1879) OD pair

5.6.14. Average travel time changes in (1886-1881) OD pair

Figure (65) shows the average travel time changes in (1886-1881) OD pair. As shown in Figure (65), the average travel time of CV cars is always less than Non-CV cars. Additionally, both charts experienced a descending trend, especially in 30%-75%, and 80%-90% MPR.

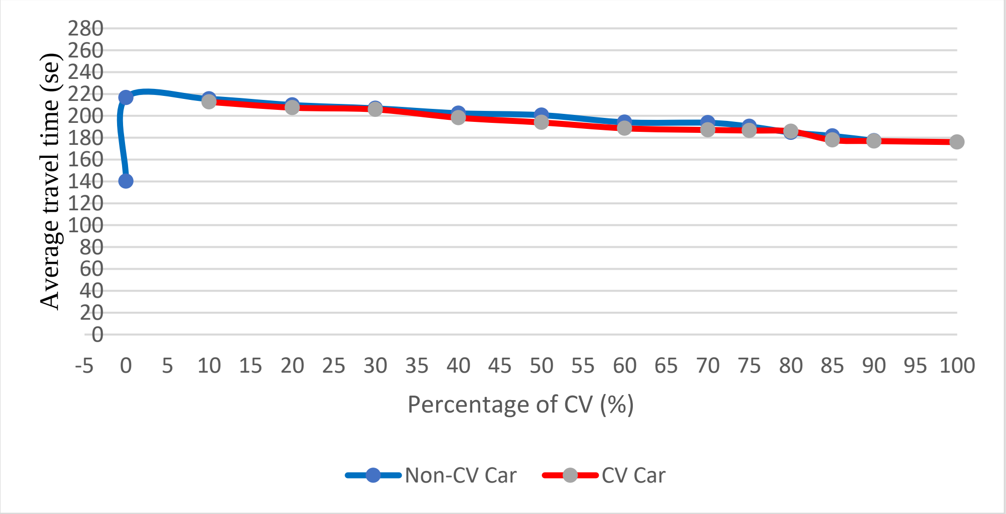


Figure 65. Average travel time changes for (1886-1881) OD pair

5.6.15. Average travel time changes in (1887-1879) OD pair

Figure (66) shows the average travel time changes of (1887-1879) OD pair. As shown in Figure (66), 60% MPR is a critical point for the Non-CV car chart. Furthermore, the CV car chart experienced two considerable drops from 40%-50%, and from 70%-85% MPR. The average travel time of the CV car, as shown in the chart, is always less than the Non-CV car.

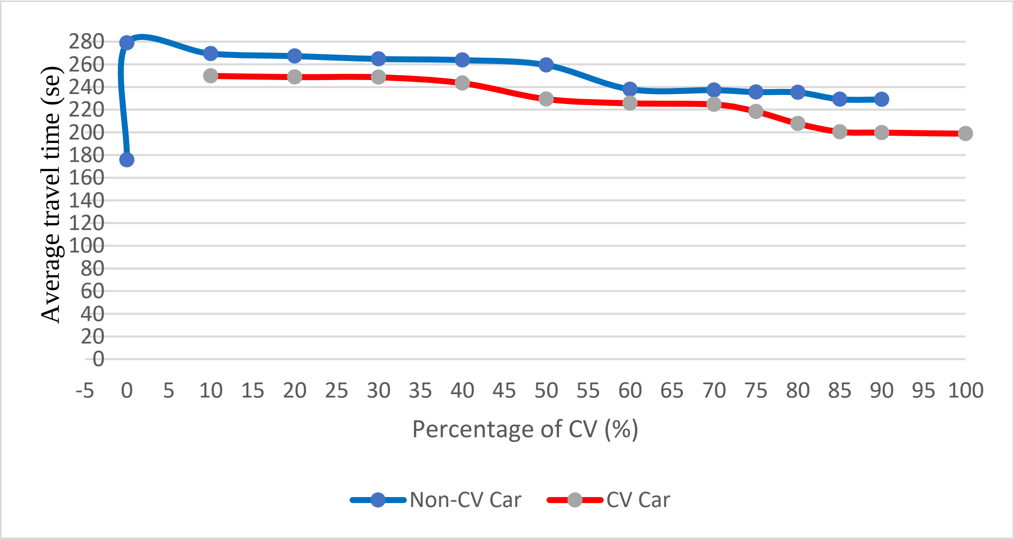


Figure 66. Average travel time changes for (1887-1879) OD pair

5.6.16. Network-wide weighted average travel time, and network-wide equity chart

Consequently, according to the explained methodology in section 3.3, a weighted average network-wide travel time was acquired for each scenario. Figure (67) shows the weighted average network-wide travel time chart for each vehicle type. As shown in Figure (67), 85% MPR is the critical breakpoint. After MPR 85%, the CV chart reveals an ascending trend and the total average travel time of CV cars increases gradually. Finally, a weighted average based on the total volume demand (2400 PCUs/hour) for both Non-CV and CV cars was calculated. It means the average travel time of Non-CV and CV cars for supplementary scenarios, (10%-90%), (20%-80%), (30%-70%), etc., were summed and then divided by 2400 (PCUs/hour). Figure (68) shows the network-wide equity chart for all cars.

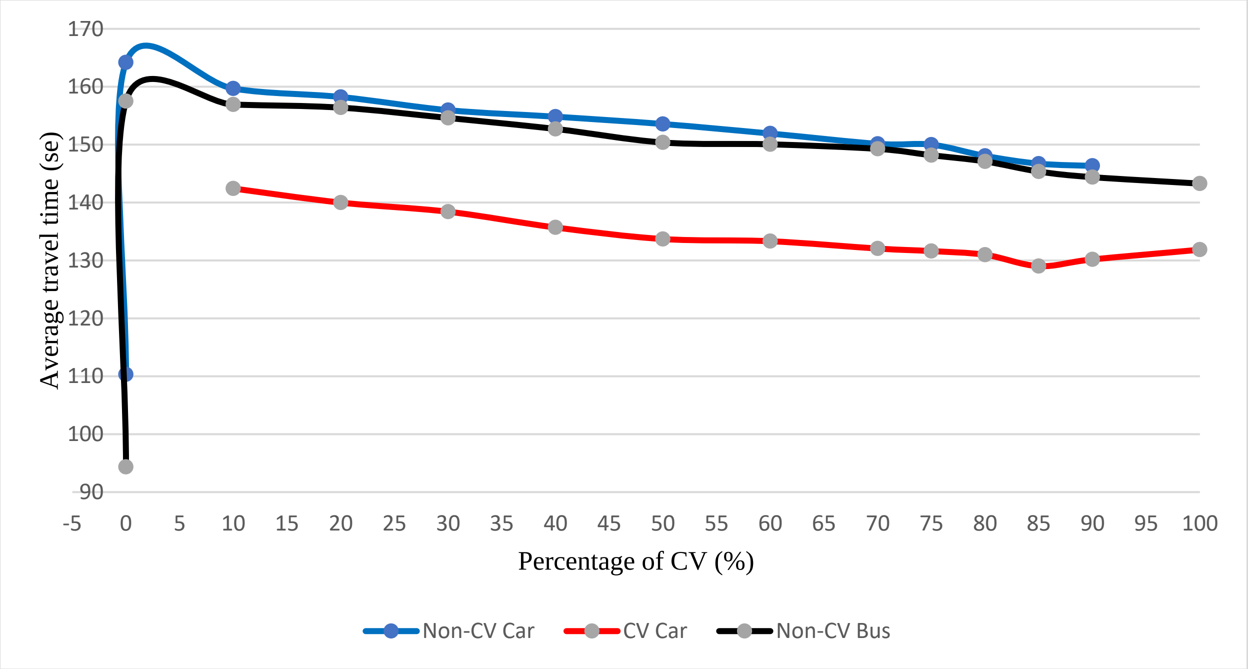


Figure 67. Weighted average network-wide travel time

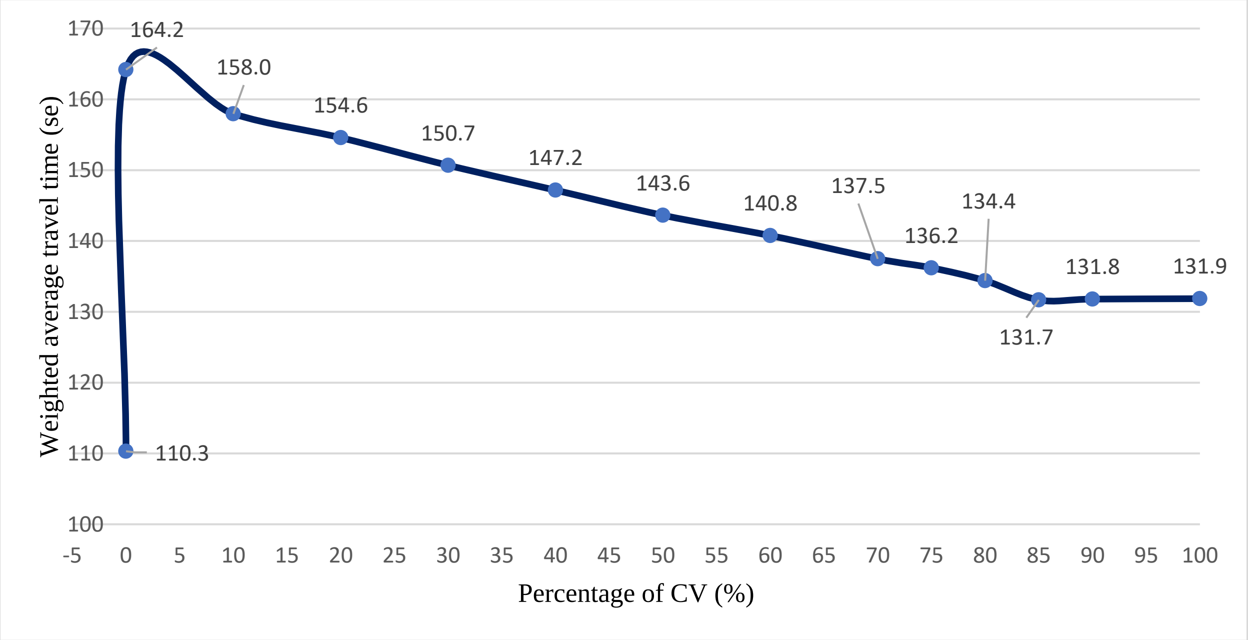


Figure 68. Network-wide equity chart

As shown in Figure (68), the critical breakpoint remains at 85% MPR level. The network-wide average travel time chart shows the descending trend from 0% to 85% MPR and then the travel time stabilizes in the MPRs more than 85%. After MPR 85%, the network-wide equity, as shown in the chart, slightly increases until the 100% MPR level.

We tested various ridership scenarios, but they were all in line and the change was linear. We merged the weighted average travel time charts for Non-CV cars and CV cars as an integrated chart. The network-wide multimodal average travel time is shown in Figure (69).

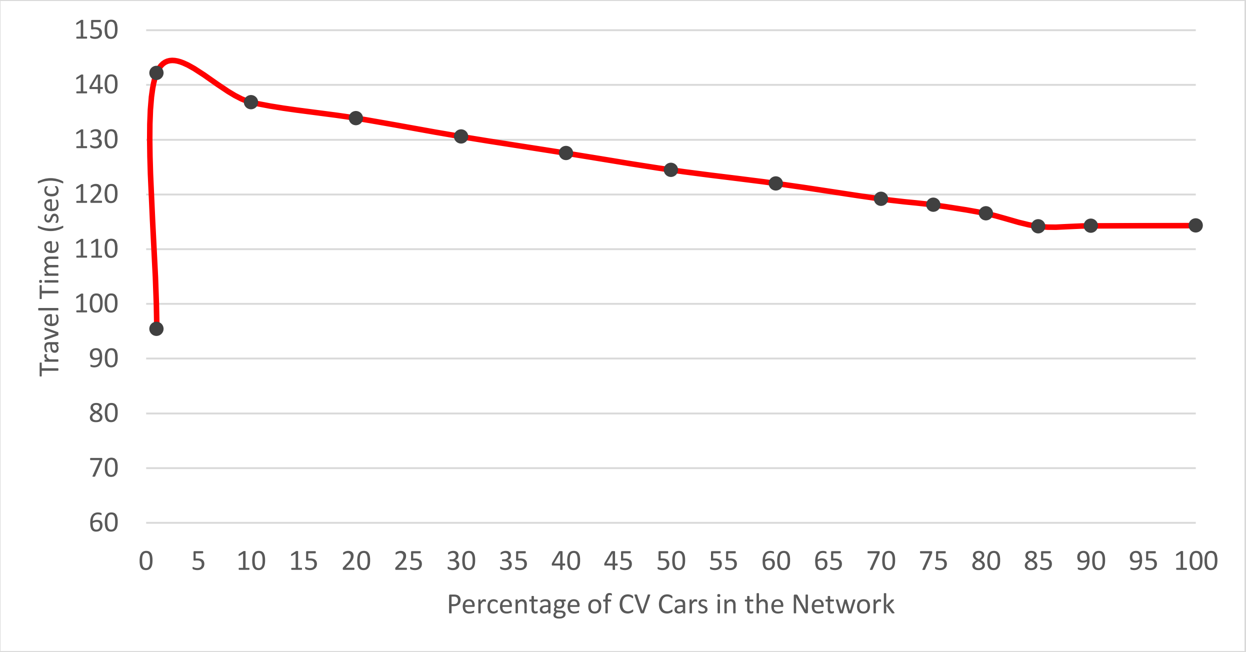


Figure 69. Network-wide multimodal average travel time

The explained methodology was performed for different total volume demands. Different total volume demands were considered (e.g., 2400, 2500, 3000, and 3500 PCUs), and the results highlighted that as the total volume demand increases in the network, i.e., toward saturated conditions, the critical breakpoint tends to shift left in the chart. Figure (70) shows the sensitivity analysis of critical breakpoint by different total volume demands in the network. As shown in Figure (70), enhancement of total volume demand will shift the critical breakpoint of the chart to the left, and the critical breakpoint is acquired in middle MPRs (50~70%) for total volumes higher than 3000 PCUs.

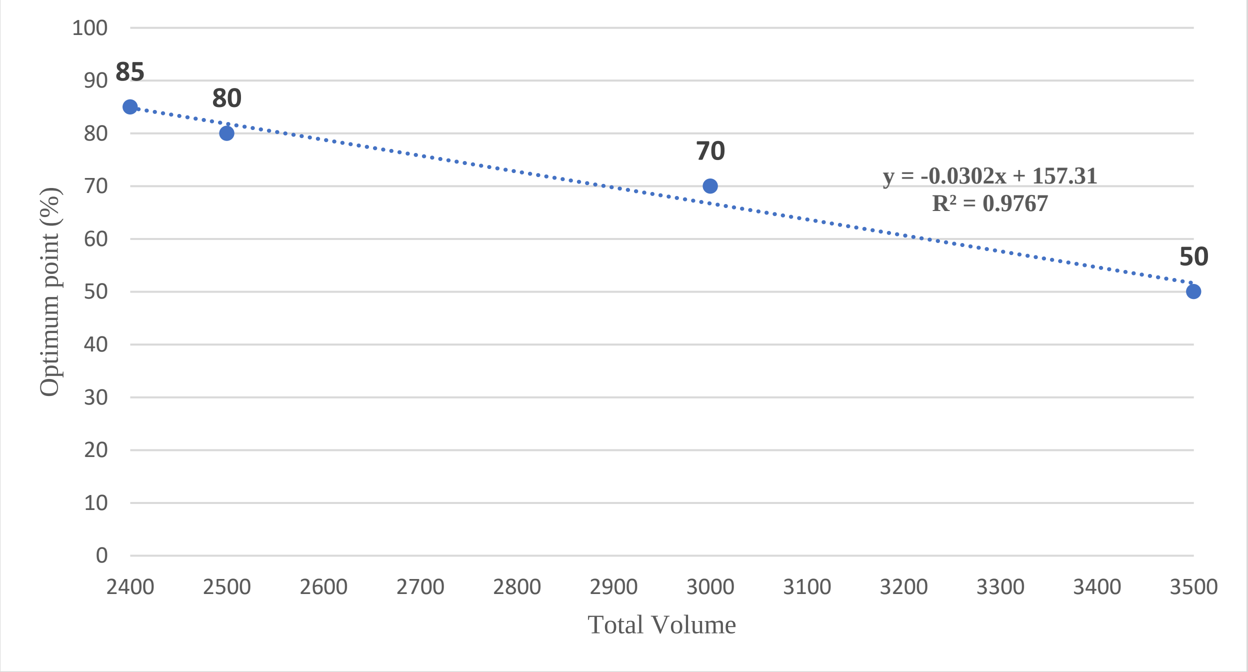


Figure 70. Sensitivity analysis of critical breakpoint

6. SUMMARY AND CONCLUSION

The emergence of Intelligent Transportation Systems (ITS) has paved the way to new innovative prospects for improving the safety, operational, and environmental impacts of transportation networks. Connected vehicles (CVs) are a ground-breaking initiative of "intelligent vehicles," emerging as the next wave of technology to further empower drivers. A Connected Car may therefore be defined as "the presence of devices in an automobile that connect devices within the vehicles together or with devices, networks and services outside the car including other cars, or infrastructure." This research simulated a small urban network in Baltimore City. The public transport lines (bus lines) of the network were simulated based on real-world timetables. Four vehicle types consisting of Non-CV Cars, CV cars, Non-CV buses, and CV buses were defined and then a hybrid model that is able to statically distribute Non-CV cars and dynamically distribute CV cars was developed. Additionally, different penetration rates of CVs (0% - 100%) in the form of 16 scenarios were built and tested. Finally, the system-wide effects of CV-equipped vehicles with route guidance features on mobility and equity were analyzed. The main achievements of our research are divided by:

1) The effects of the gradual deployment of CVs on total delay time

As shown in Figures (8), (9), and (10), gradual deployment of CV cars significantly decreased the total delay time. The total delay time of each link depends on the amount of the vehicle's throughput. The results showed that the percentage of the total delay time that can be improved when there are connected vehicles on the network, compared to when there are no connected vehicles, improved 21.2%, 20.6%, and 14.9% in low (-20%), moderate (0%), and high (+20%) traffic groups, respectively.

2) The effects of the gradual deployment of CVs on emissions

As shown in Figures (11-14), the gradual deployment of CVs improves the amount of CO2, NOx, PM, and VOC. The Panis et al. model was used as an instantaneous accurate emission model to calculate the emission factors. The input coefficients for the emission model were determined and appropriate parameters were defined in AIMSUN. The results highlighted that, as the MPR of CVs increases, the amount of pollutants significantly decreases. Additionally, four emissions were calculated for Non-CV cars, CV cars, Non-CV buses, and CV buses. The results of total emissions showed that:

1) In the low traffic group (-20%): gradual deployment of CVs can improve CO2 by 5.4%, NOx by 7.6%, PM by 26.7%, and VOC by 6.4%.
2) In the moderate traffic group (0%): gradual deployment of CVs can improve CO2 by 4.3%, NOx by 5.3%, PM by 28.5%, and VOC by 11.2%.
3) In the high traffic group (+20%): gradual deployment of CVs can improve CO2 by 6.3%, NOx by 5.8%, PM by 18.4%, and VOC by 7.2%.

3) The effects of dynamic re-routing of CVs in SB the Alameda (1886-1880) OD pair

The developed hybrid model in AIMSUN is able to distribute CV cars dynamically. When the congestion happens (e.g., an incident lasting 15 minutes), our model utilizes the user-equilibrium condition, and it updates the whole network every 30 seconds. As shown in section 5.4, as the number of re-routing CV cars increases, the average travel time in re-routing paths decreases. On average, 25% of connected cars (CVs) rerouted from scenario 4 to scenario 14. The acquired average travel time for 100% MPR (scenario 14) compared to 10% MPR (scenario 4) specified that:

1) Path Loch Raven: The average travel time improved by 21.8%.
2) Path Tivoly: The average travel time improved by 21.9%.
3) Path The Alameda: The average travel time improved by 21.7%.

4) Dynamic CV bus lane

As shown in section 5.5, a 15-minute and a 30-minute exclusive bus lane scenario were simulated to evaluate the effect of CV technology on transit users in the case of non-recurrent congestion. We hypothesized that the first lane of SB Alameda is reserved for CV buses in a 15-minute and a 30-minute scenario, respectively. The dynamic CV bus lane facilitates the movement of CV buses during congestion times. These two scenarios were presented with the aim of improving mobility and reducing travel time and delay time of connected buses. The results showed that a 15-minute dynamic CV bus lane decreases the average travel time by 11.9% for CV buses. Additionally, a 30-minute dynamic CV bus lane can decrease the average travel time by 16.4% for CV buses.

5) The network-wide travel time analysis

The most important contribution of our research concentrated on the effects of the gradual deployment of CVs on network-wide travel time as a measure of equity. As shown in section 5.6, 15 origin-destination pairs with 2400 (PCUs/hour) total volume demand were considered. The average travel time for 10 replications of each scenario was calculated. A weighted average network-wide travel time for Non-CV and CV cars was calculated. The results highlighted that the weighted network-wide average travel time displays a descending trend from 0% MPR to 85% MPR. Consequently, 85% MPR was found as the optimum breakpoint for CV cars and, overall, for all cars (combined CV and Non-CV cars). For MPR greater than 85%, the weighted network-wide average travel time stabilized, and it slightly increased. Our methodology for finding the weighted network-wide average travel time was performed for different total volume demands. As figure (70) showed, as total volume demand increases, the percentage of critical breakpoint decreases and the critical breakpoint shifts to the left in the chart, suggesting that high CV MPR helps non-peak periods more than peak period traffic.

Regarding the system-wide effects of CV-equipped vehicles on transport networks, we found that the gradual deployment of CVs can significantly improve mobility and equity while saving energy and reducing emissions. The results of our research are in line with the previous studies and the research is the first microscopic traffic simulation model to simulate the driving behavior of CV guidance with various penetration rates of CVs, and various traffic conditions. The findings from this research provide insight into the impacts of the gradual deployment of CVs on mobility and equity, which helps planners and transportation agencies to take advantage of their capabilities in incident detection and congestion relief.

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