DEVELOPMENT AND EVALUATION OF C-ITS TRAFFIC INCIDENT MANAGEMENT IMPLEMENTATIONS USING CONNECTED AUTONOMOUS VEHICLES

by

Sarp Semih Özkan

B.S., Civil Engineering, Boğaziçi University, 2020

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Civil Engineering

Boğaziçi University

2024

ACKNOWLEDGEMENTS

First and foremost, I would like to express my special thanks, deepest gratitude, and respect to my advisor Assoc. Prof. Ilgın Yaşar for her unwavering support and guidance, along with invaluable contributions throughout my time as her student. Thanks to her in-depth knowledge, comprehensive insights, and constant encouragement, I have been able to complete this study in a way that I get gratified and honored. Her vision, sincerity, and enthusiasm have made this an inspiring experience for me. It was a great privilege to work and study under her guidance.

This study is supported by the Scientific and Technological Research Council of Turkey (TUBITAK 1001) under grant number 120M574 and by the Boğaziçi University Research Fund under the project, with project number 15387 and project code 19A04R2. I'd like to express my sincere gratitude for their support.

Finally, I would like to express my sincere thanks to Alperen Timurogullari and Rahmi Sahin for their invaluable contributions and sincere support all through my thesis.

ABSTRACT

DEVELOPMENT AND EVALUATION OF C-ITS TRAFFIC INCIDENT MANAGEMENT IMPLEMENTATIONS USING CONNECTED AUTONOMOUS VEHICLES

Traffic incidents are unavoidable and impede traffic flow, reducing safety and efficiency. Different approaches can reduce these incidents' impact. Recently introduced methods include Cooperative Intelligent Transportation System scenarios and connected autonomous vehicle deployment in real-time traffic. This thesis integrates an incident management system with the Cooperative Intelligent Transportation System scenario "Slow or Stationary Vehicle Warning" using connected autonomous vehicles. The method reduces connected autonomous vehicle speeds during incidents to improve traffic safety and efficiency. 6 different connected autonomous vehicle ratios, 3 different incident durations, and 2 traffic demand levels are used in different simulation scenarios to evaluate the C-ITS incident management system using SUMO simulation software. The scenarios are evaluated on two networks. Network #1 is a three-lane, 10-kilometer continuous network without intersections or bottlenecks. A ramp and bottleneck exist at 20-kilometer Network #2. During the simulations of these scenarios, average speed, flow, and density data are collected through sensors. The collected data is visualized, and the implemented method is analyzed. It is observed that, in both networks, the C-ITS incident management method decreased average densities and increased average speeds, considering the whole network. However, analyzing the local incident regions, average densities, and speeds are both decreased in Network #1, whereas in Network #2, average densities are decreased, and average speeds are increased. At both networks, the C-ITS incident management method provided the best performance at a 60% connected autonomous vehicle ratio.

ÖZET

BAĞLANTILI OTONOM ARAÇLARIN KULLANILDIĞI K-AUS TRAFİK KAZA-OLAY YÖNETİMİ UYGULAMALARININ GELİŞTİRİLMESİ VE DEĞERLENDİRİLMESİ

Trafik kaza-olayları, trafiğin normal akışını bozan, trafik güvenliği ve verimliliğinin azalmasına neden olan kaçınılmaz olaylardır. Farklı yöntemler bu olayların etkilerini hafifletebilmektedir. Bu alandaki en yeni yöntemlerden ikisi, Kooperatif Akıllı Ulaşım Sistemlerinin ve bağlantılı otonom araçların trafiğe entegre edilmesidir. Bu tezde, bağlantılı otonom araçların kullanıldığı "Yavaş veya Durağan Araç Uyarısı" adlı Kooperatif Akıllı Ulaşım Sistemleri senaryosuna yeni bir kaza-olay yönetimi yöntemi entegre edilmiştir. Bu yöntem, trafik güvenliğini ve verimliliğini artırmak için bir kaza-olay tespit edildiğinde bağlantılı otonom araçların hızlarını kontrol etmektedir. Bu kaza-olay yönetim sistemini değerlendirmek için 6 farklı bağlantılı otonom araç oranı, 3 farklı kaza-olay süresi ve 2 trafik talebi kullanılarak oluşturulan senaryolar SUMO simülasyon yazılımı kullanılarak simüle edilmiştir. Oluşturulan senaryolar iki farklı ağ üzerinde test edilmiştir. Ağ #1, herhangi bir katılım veya darboğaz içermeyen, 3 şeritli ve 10 kilometre uzunluğunda bir ağdır. Ağ #2 ise katılım ve darboğazın mevcut olduğu 20 kilometrelik bir ağdır. Bu senaryoların simülasyonları sırasında sensörler aracılığıyla ortalama hız, akış ve yoğunluk verileri toplanmıştır. Toplanan veriler görselleştirilmiş ve uygulanan yöntem analiz edilmiştir. Bu bağlamda, kaza-olay yönetim yönteminin her iki ağda da tüm ağın ortalama verisi dikkate alındığında ortalama yoğunlukları azalttığı ve ortalama hızları artırdığı gözlemlenmiştir. Sadece kaza-olay bölgeleri analiz edildiğinde, Ağ #1'de ortalama yoğunluklar ve hızlar azalırken, Ağ #2'de ortalama yoğunluklar azalmış ve ortalama hızlar artmıştır. Uygulanan kaza-olay yönetim yöntemi, %60 bağlantılı otonom araç oranında en iyi performansı göstermiştir.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS . . . iii
ABSTRACT . . . iv
ÖZET . . . v
LIST OF FIGURES . . . viii
LIST OF TABLES . . . xi
LIST OF SYMBOLS . . . xiii
LIST OF ACRONYMS/ABBREVIATIONS . . . xiv
1. INTRODUCTION . . . 1
1.1. Goals and Objectives . . . 2
1.2. Contributions of the Thesis . . . 2
1.3. Outline of the Thesis . . . 3
2. LITERATURE REVIEW . . . 4
2.1. Cooperative Intelligent Transportation Systems . . . 4
2.2. Incident Management Systems . . . 8
2.3. Integration of CAVs into C-ITS Traffic Incident Management Systems . 10
3. THEORY . . . 13
3.1. Standard Normal Deviation (SND) Incident Detection Method . . . 14
3.2. Cooperative Intelligent Transportation Systems . . . 16
3.3. SWSCAV (Shockwave Speed Connected Autonomous Vehicles) Incident Management Method . . . 21
4. METHODOLOGY . . . 25
4.1. Simulation of Urban Mobility (SUMO) Traffic Simulation Software . . 25
4.2. Simulation Modelling . . . 28
4.2.1. Simulation Network Modelling . . . 28
4.2.2. Simulation Infrastructure Modelling . . . 31
4.2.3. Vehicle Modelling . . . 34
4.3. Scenarios . . . 36
4.4. Simulation Results . . . 41
4.4.1. Simulation Results of the Network #1 . . . 41

4.4.2. Simulation Results of the Network #2 47
5. CONCLUSION 53
REFERENCES 56

LIST OF FIGURES

Figure 3.1. C-ITS incident management method. 13

Figure 3.2. SND value frequency distribution of Network #1 base run. 15

Figure 3.3. SND value frequency distribution of Network #2 base run. 15

Figure 3.4. The diagram of a shockwave [58]. 21

Figure 3.5. The sketch of a SWSCAV control boundary. 23

Figure 3.6. The working mechanism flow chart of the SWSCAV incident management method [59]. 24

Figure 4.1. Flow chart followed when creating simulation networks and traffic demands. 27

Figure 4.2. Illustration of the Network #1. 29

Figure 4.3. Illustration of the Network #2. 30

Figure 4.4. Illustration of the sensors on the road network. 31

Figure 4.5. Output format of the induction loop sensors. 31

Figure 4.6. Sensor used to detect the capacity of Network #1. 38

Figure 4.7. Flow vs. density diagram of the Network #1 base run simulated with a traffic demand of 2200 vehicle/hour/lane. 38

Figure 4.8. Sensors used to detect the capacity of Network #2. 39

Figure 4.9. (a) The 10th sensor, (b) the 11th sensor, (c) the 33rd sensor, (d) the 34th sensor flow vs. density diagrams of Network #2 base runs simulated with a traffic demand of 1250 vehicle/hour/lane. 40

Figure 4.10. (a) Unmanaged, (b) managed case density heatmaps of the scenario simulated on the Network #1 and created with a traffic demand of 2400 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 20%. 44

Figure 4.11. (a) Density vs. time, (b) average speed vs. time plots comparing managed and unmanaged cases of the scenario simulated on the Network #1 and created with a traffic demand of 2400 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 20%. 45

Figure 4.12. (a) 0%, (b) 60%, (c) 100% CAV penetration rate density heatmaps of the managed scenario simulated on the Network #1 and created with a traffic demand of 2400 vehicle/hour/lane and an incident duration of 900 seconds. 46

Figure 4.13. (a) Unmanaged, (b) managed case density vs. time plots comparing different CAV penetration rates of the scenario simulated on the Network #1 and created with a traffic demand of 2400 vehicle/hour/lane and an incident duration of 900 seconds. 47

Figure 4.14. (a) Unmanaged, (b) managed case density heatmaps of the scenario simulated on the Network #2 and created with a traffic demand of 1250 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 40%. 50

Figure 4.15. (a) Density vs. time, (b) average speed vs. time plots comparing managed and unmanaged cases of the scenario simulated on the Network #2 and created with a traffic demand of 1250 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 80%. 51

Figure 4.16. (a) 0%, (b) 40%, (c) 80% CAV penetration rate density heatmaps of the managed scenario simulated on the Network #2 and created with a traffic demand of 1400 vehicle/hour/lane and an incident duration of 900 seconds. 52

Figure 4.17. (a) Unmanaged, (b) managed case density vs. time plots comparing different CAV penetration rates of the scenario simulated on the Network #2 and created with a traffic demand of 1400 vehicle/hour/lane and an incident duration of 900 seconds. 52

LIST OF TABLES

Table 2.1. Summary of the conducted literature review. 12

Table 3.1. Mean, standard deviation, and SND threshold values of Networks #1 and #2. 16

Table 3.2. EC C-ITS scenario categorization [55]. 18

Table 3.3. C2C-CC C-ITS scenario categorization (Day 1 scenarios) [56]. . . . 19

Table 3.4. C2C-CC C-ITS scenario categorization (Day 2 and Day 3+ scenarios) [56]. 20

Table 4.1. A cross-section of the data set obtained after the simulation study. 34

Table 4.2. Vehicle type characteristic feature descriptions. 35

Table 4.3. Values assigned to vehicle type characteristic parameters [67]. . . 36

Table 4.4. Values assigned to vehicle type parameters. 36

Table 4.5. Characteristic parameter values of CAV and human-driven vehicle types. 36

Table 4.6. Scenario variables and their values. 41

Table 4.7. Comparison of average speed and density values recorded from the whole network based on different CAV penetration rates for managed and unmanaged cases considering the simulations conducted on the Network #1 with a traffic demand of 2400 vehicle/hour/lane and an incident duration of 600 seconds. 42

Table 4.8. Comparison of average speed and density values recorded in the incident region based on different CAV penetration rates for managed and unmanaged cases considering the simulations conducted on the Network #1 with a traffic demand of 2400 vehicle/hour/lane and an incident duration of 600 seconds. 43

Table 4.9. Comparison of average speed and density values recorded from the whole network based on different CAV penetration rates for managed and unmanaged cases considering the simulations conducted on the Network #2 with a traffic demand of 1400 vehicle/hour/lane and an incident duration of 900 seconds. 48

Table 4.10. Comparison of average speed and density values recorded in the incident region based on different CAV penetration rates for managed and unmanaged cases considering the simulations conducted on the Network #2 with a traffic demand of 1400 vehicle/hour/lane and an incident duration of 900 seconds. 49

LIST OF SYMBOLS

k	Traffic Density
L	Length
N	Number of Vehicles
q	Traffic Flow
t	Time
x	Vehicle Speed
ω	Shockwave Speed

LIST OF ACRONYMS/ABBREVIATIONS

C-ITS	Cooperative Intelligent Transportation System
C-V2X	Cellular Vehicle-to-Everything
CAV	Connected Autonomous Vehicle
CLT	Central Limit Theorem
CPI	Crash Potential Index
DSRC	Dedicated Short-Range Communications
GLOSA	Green Light Optimized Speed Advisory
ITS	Intelligent Transportation System
LCS	Lane Control Signs
OBU	On-Board Unit
RSU	Roadside Unit
SND	Standard Normal Deviation
SUMO	Simulation of Urban Mobility
SWSCAV	Shockwave Speed Connected Autonomous Vehicles
TraCI	Traffic Control Interface
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VMS	Variable Message Signs
VSL	Variable Speed Limits

1. INTRODUCTION

In the last decades, more developed cities all over the world have started inhabiting bigger populations [1]. Dense populations in metropolitan cities have negative effects on numerous sectors such as the transportation sector. The number of people residing in a city is correlated with the number of registered vehicles [2]. Therefore, as the population size increases, it highly affects the severity of traffic congestion faced by the drivers [3]. This has many outcomes such as economic costs, increased emissions, and more frequent traffic incidents [4]. Since safety is one of the most important aspects of transportation systems, traffic incident management methods, which mainly aim to reduce fatalities and increase traffic safety and efficiency, have gained importance.

There are many traffic incident management methods, which are being used in real-time traffic networks, such as Variable Message Signs (VMS), Lane Control Signs (LCS), and Variable Speed Limits (VSL) [5–7]. However, the rapid development in communication technologies increased the extent of benefits that can be obtained from traffic incident management methods. In recent history, the Cooperative Intelligent Transportation System (C-ITS) has become an attraction point for authorities. This novel system mainly relies on the communication of transportation entities such as vehicles, infrastructure, pedestrians, and networks [8]. The overall communication at which vehicles are capable of receiving data from and transmitting data to each transportation entity is called a vehicle-to-everything (V2X) communication system. This technology has several sub-branches, which are vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. The goal of C-ITS applications is to inform vehicles related to real-time events and increase their awareness [9]. Since one of the main causes of traffic incidents is human error, utilization of C-ITS in the context of traffic incident management is theoretically very useful [10]. With increased awareness, drivers have the potential to regulate their behavior regarding the received information and sudden encounters with incidents such as accidents, pedestrians and/or obstacles on the road, downstream congestion, etc. can be eliminated. Thus, the involvement of human error in the occurrence of secondary incidents can be reduced greatly.

In addition to C-ITS, connected autonomous vehicle (CAV) technologies are another novel innovation, which has the potential to increase the effectiveness of traffic incident management methods. Utilization of CAVs in traffic incident management methods is a topic, which is highly researched and seen as a revolutionary integration. However, the integration of CAVs and C-ITS can enhance the outcomes of traffic incident management methods to a greater extent. The reason behind this enhancement relies on C-ITS messages being mainly advisory messages such as speed and lane change advisory, and drivers having the option to overlook the information and advice given to them. Therefore, utilization of CAVs in C-ITS applications is promising in terms of being able to control these vehicles and reach an obedience rate of 100%. In conclusion, combining CAVs with C-ITS traffic incident management methods is a novel field, which can mitigate the effects of incidents on traffic conditions.

1.1. Goals and Objectives

The goal of this thesis is to develop and evaluate a C-ITS traffic incident management implementation using CAVs. This goal is achieved by the following objectives:

- To model a C-ITS traffic incident management scenario using SUMO Traffic Simulation software.
- To test the C-ITS scenario using two traffic demands, and six CAV penetration rates with or without traffic incident management implementation on two different simulation networks.
- To analyze and evaluate these scenarios using density heatmaps, speed vs. time, and density vs. time plots and tables to visualize the effects in detail.

1.2. Contributions of the Thesis

Since traffic incidents are inevitable and cause great economic costs, traffic safety risks and traffic efficiency reductions, implementation of traffic incident management methods is essential. Advanced technologies such as CAVs and C-ITS are seen as revolutionary technologies, which can be used in and increase the effectiveness of inci-

dent management. In this thesis, a novel incident management method is integrated with C-ITS using CAVs. Therefore, results of this study have the potential to provide guidance for incident management authorities in the future when CAVs and C-ITS become fully applicable.

1.3. Outline of the Thesis

This thesis comprises 5 sections. In the first section, which is "Introduction", the reasons behind increased traffic incident rates and the importance of managing these incidents using different technological novelties such as C-ITS and CAVs are explained. In the second section, named "Literature Review", studies related to the outcomes of implementing C-ITS, incident management methods, CAVs, and the integration of these three concepts are thoroughly researched. In the "Theory" section, detailed information regarding the used technologies and methods in the simulation studies is present. The fourth section, which is "Methodology", contains a detailed explanation of simulation modeling, and the analysis of simulation results using different plots and tables. In the "Conclusion" section, a summary of this thesis is presented, and the outcomes of the simulation studies are given in detail.

2. LITERATURE REVIEW

A literature review is an essential part of many studies since past and present trends regarding the research subject can be analyzed using the studies in the literature. In addition, positive or negative outcomes of the researched technological implementation can be investigated to acquire a general understanding of the concept and its uses.

In this section of the thesis, studies in literature are thoroughly investigated. This investigation is conducted on 3 different topics, which are "Cooperative Intelligent Transportation Systems", "Incident Management Systems" and "Integration of CAVs into C-ITS Traffic Incident Management Systems".

2.1. Cooperative Intelligent Transportation Systems

C-ITS has many uses ranging from decreasing the severity of congestion and improving the sustainability aspect of the traffic to increasing traffic safety [11–13]. Thus, many researchers and authorities have focused on observing these outcomes on various platforms and environments such as simulations and pilot projects. This increased the number of studies related to the application of C-ITS scenarios in literature.

With the increasing population in cities, the number of vehicles and severity of traffic congestion have also increased proportionally [14]. This led to an increase in traffic incidents since one of the causes of incidents is the number of vehicles in traffic and the level of traffic congestion [15]. Therefore, improving the safety aspect of the traffic has become an important topic. One of the main contributions of C-ITS applications is the increase in driver awareness due to the informative messages [16]. Thus, increased awareness leads to drivers being more careful before facing unexpected incidents or disruptions in traffic conditions, which has the potential to increase traffic safety [17]. In a study, which is based on a pilot project in South Korea, driver behaviors are investigated in the presence of C-ITS applications [18]. This investigation

is conducted utilizing a unique analytical method, using parallel processing and paired t-tests. The results of the study indicate that when a C-ITS application is introduced and drivers are given C-ITS warning messages, a decrease in hard braking and severe deceleration is noticed directly. After four months of continuous service, a reduction in excessive speeding is also observed. Therefore, it is possible to say that drivers become more aware of dangerous situations and drive in a more regularized manner due to C-ITS, which increases traffic safety.

In a different study, the improvements in traffic safety due to C-ITS applications are analyzed quantitatively [19]. To do it, a multi-agent driving simulation is used, which can investigate the traffic means of crash risks. The analysis is done using the Crash Potential Index (CPI), which gives an idea regarding the magnitude of rear-end traffic crash risks. Results of the study show that, in the presence of C-ITS applications, CPI decreases at a rate of 55.81%. Also, the analysis includes driver compliance rates to the C-ITS warning messages as a simulation variable. As the compliance rate increases, CPI reduces further. At full compliance, CPI is seen to decrease by 67.86%.

Various C-ITS scenarios can be implemented on traffic networks. In a previous study, seven C-ITS application scenarios were evaluated based on their effectiveness in reducing fatalities [20]. These scenarios are "In-vehicle signage, speed limit", "Weather Warning", "Warning of emergency braking ahead", "Road works warning", "Traffic jam ahead warning", "Car breakdown warning" and "In-vehicle signage, child and pedestrian crossing ahead". All of these scenarios are known to be decreasing fatalities, but the analysis conducted in this study is to put these scenarios in order of their effectiveness. The results indicate that "In-vehicle signage, speed limit" is the most effective scenario, whereas "Weather warning" is the second most effective one. These scenarios are followed by "Warning of emergency braking ahead" and "Road works warning". The least effective ones are seen to be "Traffic jam ahead warning", "Car breakdown warning" and "In-vehicle signage, child and pedestrian crossing ahead". Even though these scenarios are determined to be the least effective ones, they are still effective in reducing fatalities and increasing safety.

C-MobILE is a C-ITS project in which various scenarios are applied in different countries all over Europe. In this project, scenarios are bundled under 4 main categories named urban efficiency, infrastructure-to-vehicle safety, traffic efficiency, and vehicle-to-vehicle safety. Bundles related to safety include scenarios such as "Road work warning", "Emergency vehicle warning", "Slow or stationary vehicle warning" and "Emergency brake light". In a study, these bundles are evaluated based on different cost and benefit criteria [21]. Results of this evaluation show that safety-related bundles are beneficial in means of improving roadway safety conditions, reducing accidents, and decreasing fatalities and injuries.

In addition to traffic safety benefits, C-ITS has the capability of improving traffic efficiency. In a study, which is regarding the implementation of "Cooperative speed harmonization", simulations are conducted to evaluate the effectiveness of C-ITS scenarios on traffic efficiency [22]. Results of the simulations show that the application of the "Cooperative speed harmonization" scenario increases the average speed at a rate of 14%, reduces the average travel time of all vehicles by 16%, and additionally, lowers the CO_2 emissions by 11%. Therefore, it is possible to say that C-ITS is a beneficial system for increasing traffic efficiency.

In a different study, the effects of a lane-change distribution advisory scenario on the traffic congestion building up at a weaving section due to immediate and irregular lane change behavior of drivers as they enter this section are investigated [23]. This C-ITS application aims to give lane-changing advice to drivers to extend the lane change concentration to the full length of the weaving section and regularize lane changes. The study is carried out on AIMSUN microscopic simulation software. Results of the simulation studies indicate that the proposed C-ITS lane-change advisory scenario is beneficial in means of significantly reducing delays.

Green Light Optimized Speed Advisory (GLOSA) is a different C-ITS scenario, which aims to inform the drivers on the current signal phase at the next downstream traffic signal and advises them to speed up or slow down to a calculated optimum speed. This application is to make drivers arrive at the traffic signal at the right

time, so they don't join in on the stop-and-go motion, which usually occurs at traffic signal locations [24]. In a study, a C-ITS scenario, very similar to GLOSA, named "Traffic Light Assistance", is evaluated by performing theoretical studies in a lab-controlled environment [25]. Results of the evaluation studies show that the applied "Traffic Light Assistance" scenario can increase traffic efficiency, reduce emissions, and decrease waiting times at the traffic signal location.

The increasing number of vehicles in traffic is not only the cause of traffic safety and efficiency degradations but also the cause of sustainability problems. As the number of vehicles increases, emissions related to transportation systems increase as well [26]. This leads to an increased propagation of global warming threat. In the recent conditions related to countries aiming to minimize their emissions in each sector, the sustainability aspect of transportation system applications become very important [27]. In a thesis, it is stated that C-ITS is a transportation system, which provides environmental sustainability utilizing reducing emissions, increasing air quality, and decreasing noise pollution [28].

Compass4D is a C-ITS project, which has pilot applications in 7 different European countries. A study in the literature, which is based on this project, presents both the pilot application and microscopic simulation study results for governments and road operators to assess before taking action related to applying C-ITS scenarios [29]. According to this study, heavy vehicles are subject to better emission and efficiency improvements compared with light vehicles. Even though the improvements are higher for heavy vehicles, light vehicles show positive outcomes in means of emissions too.

In a different study, the effect of GLOSA application at signalized intersections is investigated [30]. It is also stated that stop-and-go motions are frequent at traffic signal locations, and this increases travel times, fuel consumption, and emissions. Then, a simulation study of the GLOSA application is conducted to evaluate the benefits of this scenario. Results of the simulations indicate that GLOSA can reduce fuel consumption and emissions in the signalized intersection region by 5 to 12%.

In conclusion, according to the results of the studies in the literature, C-ITS is capable of improving traffic safety, efficiency, and sustainability. However, the benefits that can be gained by this system are not limited to its application alone since C-ITS has the potential to be integrated into different systems such as traffic incident management methods.

2.2. Incident Management Systems

Traffic incidents are inevitable events, which harm traffic safety and efficiency [31]. These events include all types of cases that disrupt the normal flow of the traffic such as traffic accidents, road works, obstacles on the road, and vehicle breakdowns [32]. According to a study in which traffic incidents with different durations are simulated, it is observed that long-duration traffic incidents cause an increase in travel times by 18% [33]. An additional increase of 8% is seen when a short-duration incident is simulated alongside a long-duration incident. Therefore, there is a need for applications to reduce the negative effects of traffic incidents on safety and traffic efficiency. In the literature, there are several traffic incident management methods utilized to achieve this aim.

In a study, different traffic incident management methods are simulated on a large-scale microsimulation software [34]. The study aims to evaluate the effects of these incident management methods. Results of the simulations indicate that the application of the VMS incident management method yields a reduction in traffic delays at a rate of 8.8%, in number of stops by 22%, and in travel times by 3.3%. Additionally, the VSL management method is seen to increase traffic efficiency by 11% and improve traffic safety.

In addition to the traditional traffic incident management methods, integration of C-ITS into incident management has the potential to increase the general effectiveness. One way this integration aids incident management is by the utilization of communication systems of C-ITS, which are V2V and V2I communication. These communication systems allow vehicles to communicate with each other and the sur-

rounding environment. According to a study, the level of congestion, which is due to an incident, increases with delayed response [35]. In a different study, it is stated that the collection of data through V2I has the potential to reduce the duration of incident detection [36]. In the study, two different novel incident detection algorithms are proposed and simulated. Results show that the proposed methods are effective in fast detection and utilization of these methods decreases the length of peak queues by 25% and dissipation duration by 20%.

Aside from fast incident detection, V2X communication can inform drivers of the existence of an incident and make them aware and careful. According to a study regarding the use of V2X communication in incident management, simulation studies are carried out using VISSIM and Python to evaluate this implementation [37]. Simulation results show that the usage of V2X technology in incident management reduces travel times by 6%, average stop delay by 9% and vehicle stops by 27%.

Road works are a form of traffic incident since they disrupt the normal flow of traffic. In C-ITS, a "Road works warning" is a scenario in which drivers are informed regarding the location of the road work [38]. This application aims to improve traffic safety and efficiency by increasing awareness. In a study regarding the implementation of road works warning in a simulation environment, the benefits of the scenario are revealed [39]. Results show that, as the penetration rate of connected vehicles increases, the reduction in delay also increases with the highest reduction in delay recorded to be 8.66%. Also, due to drivers being aware of the location and lane of the road work, they tend to change their lane from a road work lane to an open lane before reaching the incident location. Therefore, the average speed on the road work lane increased to around 10 km/h. In addition, the average time in queue decreased by around 60 seconds at high penetration rates on the open lane and 25 seconds on the road work lane.

Studies in the literature reveal that C-ITS is a beneficial system to be used in traffic incident management. However, increasing the benefits further is still possible by integrating CAVs into C-ITS applications.

2.3. Integration of CAVs into C-ITS Traffic Incident Management Systems

In recent years, research and development studies regarding CAV technologies have increased substantially. This has accelerated the process of integrating CAVs into real traffic. This integration has the potential to provide numerous benefits in means of traffic efficiency and safety since CAVs are expected to reduce human error [40, 41].

In the literature, there are many studies investigating the potential outcomes of deploying autonomous vehicles into real-time traffic. In a study, the effect of autonomous vehicles on urban network capacity is investigated [42]. To analyze this effect, simulation studies are done with different autonomous vehicle penetration rates. According to the results, as the autonomous vehicle percentage increases, network capacity increases too. In a different study, the benefits of integrating CAVs into traffic are analyzed through simulation studies [43]. In this research, various CAV percentages are simulated. The outcomes of the study show that at 20% and 40% CAV penetration rates, traffic efficiency increases to its maximum level. However, traffic safety increases with increasing penetration rates. In a similar research, a stability analysis is conducted by simulating different CAV penetration rates in a simulation environment [44]. It is observed that CAVs positively affect string stability. According to another study, increased string stability improves throughput and mitigates traffic shockwaves [45]. Therefore, it is possible to say that when CAVs are deployed in real-time traffic, they are beneficial in terms of increasing traffic efficiency and safety.

In addition to the benefits of normal traffic flow, CAVs are also very advantageous when utilized in the case of an incident. According to a study, which investigates the effects of CAVs on incident cases, simulation studies with different CAV penetration rates and incident variables are conducted [46]. Results of the study show that when an incident with a duration of 900 seconds occurs and an 80% CAV penetration rate is present in the traffic flow, average travel times reduce at a rate of 20%. In a different study, the integration of autonomous vehicles into traffic incident management methods is investigated [47]. The analysis is done on the proposed incident management

algorithm using different CAV penetration rates. Results of the simulations, which are done on MATLAB, indicate that the proposed strategy has the potential to improve the recovery stage of the traffic after an incident and increase the stability of the traffic. It is also stated that CAV technologies are very promising in means of being utilized in incident management in the future mixed traffic environment.

Studies in the literature demonstrate that CAVs improve traffic conditions when deployed with or without incident management methods under incident cases. As communication and computation technologies developed further, a novel Intelligent Transportation System (ITS), named C-ITS, has become a focal point for many researchers and authorities. C-ITS has many application areas and scenarios such as informing the drivers, managing traffic, and incident management. Therefore, the integration of CAVs into C-ITS systems to manage incident cases more effectively has also become an attractive topic. In a study, 4 different C-ITS scenarios are tested, which are accident warning, traffic jam ahead warning, and 2 human presence on the road warnings (children and cyclists), in the presence of CAVs [48]. These scenarios aim to reduce the speeds of the vehicles, which are located in the upstream direction so that vehicles can arrange their behavior safely with reduced speeds at the incident location. Speed reduction is conducted in different ways for different types of vehicles. For human-driven vehicles, dynamic speeds are presented on electronic traffic boards, whereas for the CAVs, dynamic speeds are given directly to the vehicles. The analysis is done using the speed data of autonomous vehicles. According to the results, when CAVs are utilized in C-ITS incident management applications, the effectiveness of the applications increases further.

According to the literature review, there are studies analyzing the integration of CAVs and incident management methods, but there is a lack of studies considering the utilization of these vehicles in C-ITS incident management scenarios. Therefore, in this study, the quantitative analysis of using CAVs in C-ITS incident management is conducted on traffic efficiency metrics such as average speed, density and flow through microsimulation studies with different CAV penetration rates and traffic variables.

In Table 2.1, a summary of the conducted literature review is present.

Table 2.1. Summary of the conducted literature review.

Reference	Country	Method	Data Type
[11]	United Kingdom	Qualitative analysis	Expert surveys
[13]	Netherlands and United Kingdom	Benefit analysis using COBRA + tool	Results of the previous projects
[14]	Poland	Correlation and regression analysis	Real world data on number of vehicles, business entities and traffic demand
[15]	United States	Simple linear regression	Real world data on number of vehicles, fatal crashes, injuries, and fatalities
[16]	Belgium	Practical experimentation	Real world test data
[17]	European Union countries	Qualitative analysis	Information regarding previous C-ITS projects
[18]	South Korea	Unique analytical method, employing parallel processing techniques and a paired t-test	Pilot project data
[19]	South Korea	Multi-agent driving simulation	Traffic simulation data
[20]	European Union countries	Safety impact assessment using Power Model and expert opinions	Historical traffic crash data
[21]	Greece	Cost-Benefit Analysis	C-ITS applications in C-MobILE project
[22]	Russia	Simulation studies	Traffic simulation data
[23]	Australia	Microscopic simulation in AIMSUN	Traffic simulation data
[25]	Austria	Simulation studies	Traffic simulation data
[26]	China	COPERT IV model	Emission data in Yunnan province
[28]	Sweden	Qualitative analysis	Expert surveys and literature review
[29]	Seven European cities	Microscopic traffic simulations and Compass4D project field trials	Both simulation and field trial results
[30]	Italy	Simulation studies	Traffic simulation data
[31]	Australia	Tobit model	Historical traffic incident data
[32]	United States	Literature review on publications, standards, and guidelines	Literature review outcomes
[33]	Germany	Simulation studies	Real-world traffic data and simulation results
[34]	Australia	Simulation studies	Traffic simulation data
[35]	United States	Simulation studies	Traffic simulation data
[36]	-	Simulation studies	Traffic simulation data
[37]	Oman	Simulation studies on VISSIM	Traffic simulation data
[38]	Australia	Field operational tests	Collected data during field operational tests
[39]	Italy	Simulation studies	Traffic simulation data
[40]	Jordan and Yemen	Research on cyber security, technology, and improvements related to autonomous vehicles	Research outcomes
[41]	-	Discussion on the expert interviews	Expert interviews
[42]	Hungary	Simulation studies on SUMO, generalized additive model	Traffic simulation data
[43]	Greece	Simulation studies	Traffic simulation data
[44]	United States	Simulation studies	Traffic simulation data
[45]	-	Developing a networked Control System modelling framework, experiments performed with Cooperative Adapative Cruise Control equipped prototype vehicles	Data collected from the prototype vehicles
[46]	United States	Simulation studies	Traffic simulation data
[47]	-	Simulation studies	Traffic simulation data
[48]	Spain	Project field tests conducted in AUTOCITS C-ITS project	Field test results

3. THEORY

In this section, the details of each method, concept, and technology used in the development of the C-ITS incident management method are given. The working mechanism of the C-ITS incident management method is given in the flowchart below.

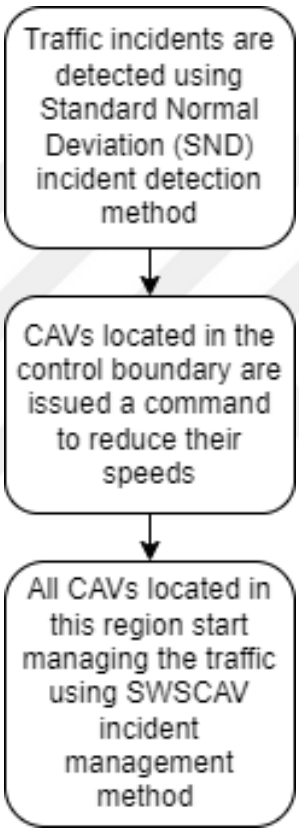


Figure 3.1. C-ITS incident management method.

According to the flowchart, there are 3 algorithmic components of the incident management method, which are the Standard Normal Deviation (SND) incident detection method, C-ITS, and SWSCAV incident management method. In this section, these components are explained in detail.

3.1. Standard Normal Deviation (SND) Incident Detection Method

SND is a statistical automatic detection method, which utilizes the mean and standard deviation of historical data. This algorithm is constructed by placing the mean and standard deviation pre-measurements of an important traffic parameter, which is highly affected by the occurrence of an incident, into the Central Limit Theorem (CLT). The equation used in the SND method is expressed as

$$SND = \frac{x(j,t) - \bar{x}(j,t)}{s} > T_{SND}, \tag{3.1}$$

where $x(j,t)$ refers to the value of the used traffic parameter at location j and time t, $\bar{x}(j,t)$ refers to the mean value of the used traffic parameter at location j and time t, S refers to the standard deviation value of the used traffic parameter at location j and time t, and T_{SND} refers to the SND threshold value.

In this thesis, the traffic parameter used in the SND incident detection method is traffic density since this parameter is highly affected by incidents and reliable in means of detecting incident occurrences due to the change in its instantaneous values. Therefore, this selection in the traffic control parameter of the SND method yields high accuracy in incident detection. In the process of constructing the algorithm, base run simulations at which there is no incident are conducted on both simulation networks of the study. Since the SND algorithm aims to detect anomalies in the traffic flow, the algorithm is constructed on the mean and standard deviation values of normal traffic flow, which are acquired using base run results. In the case of an incident, bottlenecks occur and density values in the region of this incident increase up to a level, which is rarely observed in normal traffic flow conditions.

To determine the SND threshold value, the mean and standard deviation values of density values recorded during the base run simulations are calculated for each network. Using these values and each density value recorded from each sensor at each time step of the simulation, density values are converted into SND values. In Figure 3.2, the SND value frequency distribution of Network #1, and in Figure 3.3, the SND value frequency distribution of Network #2 is present.

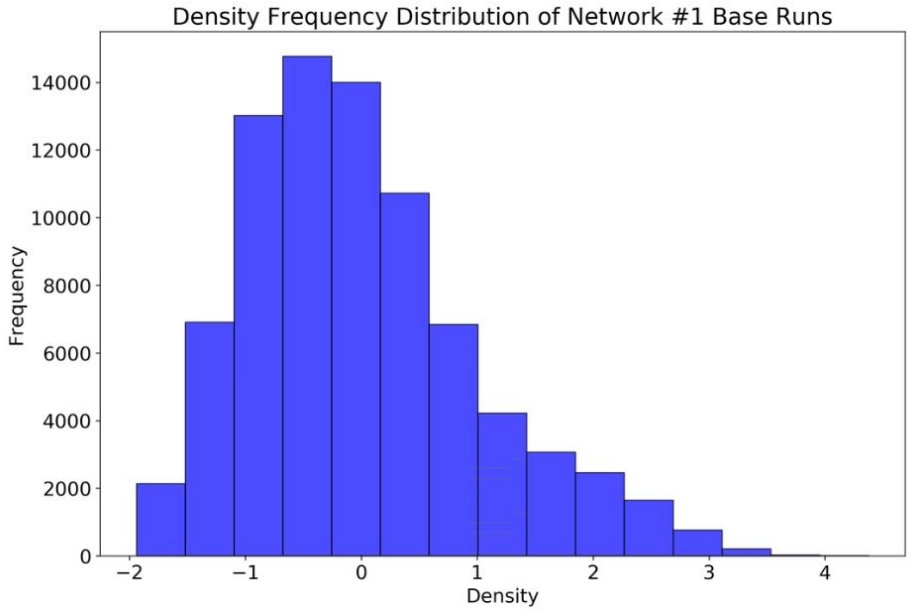


Figure 3.2. SND value frequency distribution of Network #1 base run.

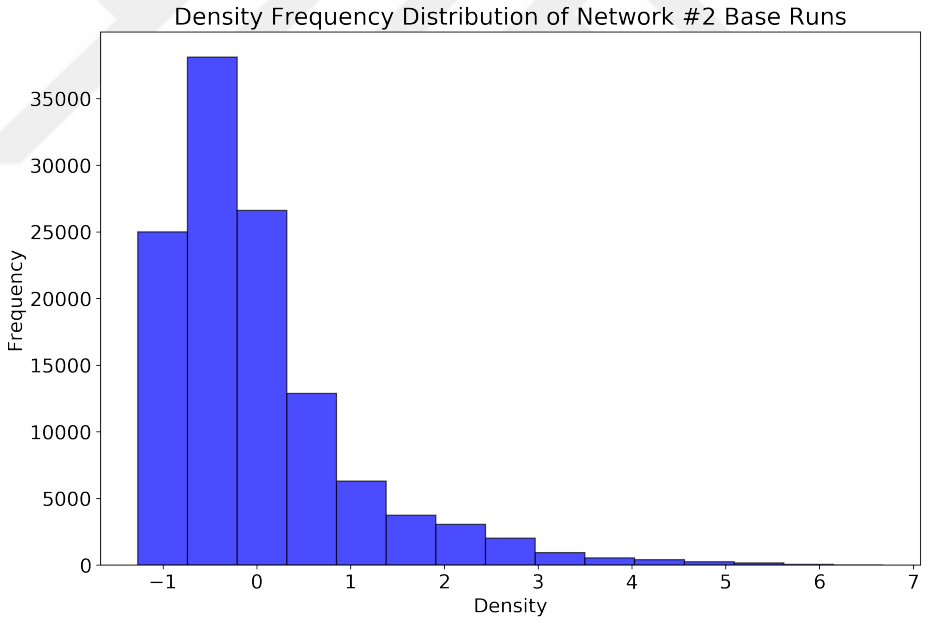


Figure 3.3. SND value frequency distribution of Network #2 base run.

Analyzing Figure 3.2 and 3.3, the SND threshold values are determined. This process is done by obtaining the SND threshold value at which 99% of the recorded SND values are below this threshold. Thus, SND values, which are located above these thresholds can be considered to be collected in the presence of an incident. In Table 3.1, the mean, standard deviation, and SND threshold values of each simulation network are given.

Table 3.1. Mean, standard deviation, and SND threshold values of Networks #1 and #2.

Network	Mean Density Value (veh/km)	Standard Deviation	SND Threshold Value
Network #1	9.5	4.89	3.5
Network #2	5.05	3.97	4.5

3.2. Cooperative Intelligent Transportation Systems

C-ITS is the technology that enables vehicles to connect with other vehicles, infrastructure, pedestrians, traffic control centers, etc. to transmit and receive data [49]. Through this connection, vehicles are informed regarding various situations, which include incidents, speed limits, and traffic signalization phases so that drivers receive the necessary information to make the right decisions and do not face any unexpected encounters.

In C-ITS implementations, there are various technologies used such as Roadside Units (RSU), On-Board Units (OBU), and communication technologies to be able to establish the connection between vehicles and other components of traffic.

RSUs are the devices, which are embedded in the infrastructure, that provide the capability of real-time data exchange between these devices and vehicles. Whereas OBUs are the devices, which are embedded in the vehicles, that connect with the RSU for data exchange. For this connection to be possible, different C-ITS communication technologies can be used [50].

In the current C-ITS studies, the most commonly used communication technologies are called Dedicated Short-Range Communications (DSRC) and Cellular Vehicle-to-Everything (C-V2X) [51–53]. These technologies differ based on their technical properties. For instance, DSRC has a lower transmission range, but higher transmission throughput compared to C-V2X [54]. Therefore, the selection of the communication technology is done according to the needs of the project.

In addition to these, numerous C-ITS scenarios can be implemented in transportation systems. These scenarios are classified based on different categorical systems by two institutions, which are the European Commission (EC) and the Car 2 Car Communication Consortium (C2C-CC). According to EC's classification, C-ITS scenarios are grouped under 2 classes, namely Day 1 and Day 1.5. Scenarios, that have higher benefit-cost ratios and need to be implemented earlier to increase the benefits of C-ITS applications, are gathered under Day 1 class. The rest of the scenarios are classified as Day 1.5 scenarios. In Table 3.2, EC classification and the corresponding C-ITS scenarios are present.

The other categorization is conducted by C2C-CC. In this categorization system, C-ITS scenarios are distributed under 3 categories, namely Day 1, Day 2, and Day 3+. Even though both systems include Day 1, the definitions of these categories are different. Based on the C2C-CC classification system, the definition of each category is given below.

- Day 1 (Awareness Driving): In this C-ITS scenario category, vehicles and infrastructure exchange data related to their status such as vehicle dynamics for vehicles and information regarding tolling stations. In addition to status information, vehicles are informed about unexpected events like hazardous locations (road works, incident zones, etc.) and adverse weather conditions.
- Day 2 (Sensing Driving): In this category, informative services are extended by the inclusion of informing vehicles regarding unexpected events, which are detectable by only on-board sensors such as cameras, lidars, and radars. This extension is beneficial in means of increasing the awareness of drivers on events, which are not locally detectable.
- Day 3+ (Cooperative Driving): The main difference provided by Day 3+ category is the inclusion of automated driving capabilities in C-ITS scenarios. Thus, drivers are aided in various phases of driving such as parking, steering, accelerating, etc. by different automation technologies.

C-ITS scenarios corresponding to Day 1 category are given in Table 3.3 and scenarios corresponding to Day 2 and Day 3+ categories are given Table 3.4.

Table 3.2. EC C-ITS scenario categorization [55].

Scenario Category	C-ITS Scenarios
Day 1	Emergency brake light
	Emergency vehicle approaching
	Slow or stationary vehicle(s)
	Traffic jam ahead warning
	Hazardous location notification
	In-vehicle signage
	In-vehicle speed limits
	Probe vehicle data
	Shockwave damping
	Road works warning
	Weather conditions
	Green Light Optimal Speed Advisory (GLOSA)
	Signal violation/Intersection safety
	Traffic signal priority requests by designated vehicles
Day 1.5	Off-street parking information
	On-street parking management and information
	Zone access control management
	Park & Ride information
	Information on AFV fuelling & charging stations
	Traffic information and smart routing
	Loading zone management
	Vulnerable road user protection (pedestrians and cyclists)
	Cooperative collision risk warning
	Motorcycle approaching indication
	Wrong way driving

Table 3.3. C2C-CC C-ITS scenario categorization (Day 1 scenarios) [56].

Scenario Category	C-ITS Scenarios
Day 1	Co-operative Glare Reduction
	Dangerous Situation Warning for Electronic Emergency Break Light (EEBL)
	Electric Vehicle Charging Spot Notification
	Animal or Person on the Road
	Alert Wrong Way Driving
	Accident Zone
	Emergency Vehicle Approaching
	Emergency Vehicle in Intervention
	Obstacles on the Road
	Public Transport Vehicle Crossing
	Public Transport Vehicle at a Stop
	Railway Level Crossing
	Stationary Vehicle
	Traffic Jam Ahead
	Temporarily Slippery Road
	Unsecured Blockage of a Road
	Weather condition Warning
	Intersection Collision Warning
	Free Text
	Traffic Signs
	Motorcycle Approaching Information
	Pre-crash Sensing Warning
	Event Data Collection
	Vehicle Data Collection
	Lane Closure
	Road Closure
	Road Works Mobile
	Road Operator Vehicle Approaching
	Road Operator Vehicle in Intervention
	Winter Maintenance
	Emergency Vehicle Priority
	Green Light Optimum Speed Advisory (GLOSA)
	Imminent Signal Violation Warning
	Signal Phase and Timing Information
	Traffic Light Prioritization
	Slow Vehicle Warning

Table 3.4. C2C-CC C-ITS scenario categorization (Day 2 and Day 3+ scenarios) [56].

Scenario Category	C-ITS Scenarios
Day 2	Advanced Intersection Collision Warning
	Advanced Motorcycle Approaching Information
	Advanced Pre-crash Sensing Warning
	Advanced Slow Vehicle Warning
	Blind Spot Assistant
	Cooperative ACC
	Cooperative ACC String
	Cooperative Emergency Brake Assistance
	Collective Perception Service for AD
	Hazardous Location Notification – Vehicle Assistance
	Platoon Support Information
	Motorcycle Approaching Warning or Protection
	Overtaking Vehicle Warning
	Road Work Warning
	Vulnerable Road User Protection
Day 3+	Advanced Cooperative ACC (String)
	Cooperative ACC String Management
	Automated Green Light Optimum Speed Advisory
	Automated GLOSA with Negotiation
	Cooperative Automated Parking
	Cooperative Lane Change
	Co-operative Merging Assistance
	Cooperative Overtaking
	Collective Perception Service for Highly AD
	Cooperative Transition of Control
	Improved Vulnerable Road User Protection
	Multi-Car Collision Avoidance
	Optimized Traffic Light Information with V2I
	Platooning
	Target Driving Area Reservation
	Transition of Control Notification

In this thesis, the studied C-ITS scenario is “slow or stationary vehicle warning”. This scenario is in the Day 1 category for both EC and C2C-CC classification systems as seen in both Table 3.2 and Table 3.3. Thus, both institutions evaluate this scenario to be a prioritized C-ITS implementation, so it is essential to analyze this scenario both

in real-life applications and simulation studies. As a novelty provided by this thesis, the aim of the implemented scenario is not to inform the drivers but to manage the CAVs in the presence of real-time communication capability using C-ITS infrastructure.

3.3. SWSCAV (Shockwave Speed Connected Autonomous Vehicles) Incident Management Method

Traffic shockwave refers to the formation of bottlenecks related to sudden and crucial traffic incidents, which disrupt the normal flow of traffic and show its effect in the form of a wave [57]. In the presence of bottlenecks, traffic congestion occurs in a direction according to the type of shockwave. Due to shockwaves, traffic parameters such as flow, average speed, and density, show differences through the effect of the wave-like impact. These traffic parameters are place and time-dependent variables. Therefore, changes in these parameters create boundaries, which differentiate the state of the traffic flow. For instance, in the presence of a traffic incident, if a region has relatively lower density and speed values compared to another region located downstream, the interaction between these regions affects the upstream region by reducing the region's density, speed, and flow parameters, which can be referred to as a shockwave. Thus, traffic incidents such as accidents, car breakdowns, and slow or stationary vehicles create differences in traffic parameter values in the incident region. This creates traffic shockwaves. In Figure 3.4, the interaction between two different regions with different flow and speed values and the shockwave emerging due to this interaction is illustrated.

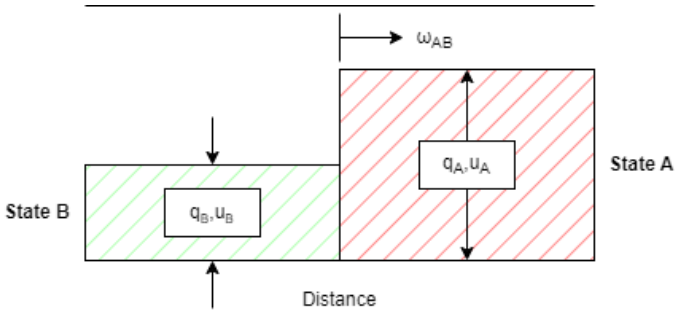


Figure 3.4. The diagram of a shockwave [58].

In Figure 3.4, q_A and u_A represents the flow and average speed of state A respectively, whereas q_B and u_B represent the flow and average speed of state B. Also, ω_{AB} is the shockwave speed, which occurs between state A and B. The equation used in shockwave speed calculation is expressed as

$$\omega_{AB} = \frac{q_A - q_B}{k_A - k_B}, \tag{3.2}$$

where ω_{AB} refers to the shockwave speed, which occurs between States A and B, q_A refers to the traffic flow value of State A, q_B refers to the traffic flow value of State B, k_A refers to the traffic density value of State A and k_B refers to the traffic density value of State B.

The incident management method used in this thesis, named SWSCAV, utilizes the calculated shockwave speeds. SWSCAV is a dynamic management method, which uses multiple mechanisms at the same time [59]. This method is activated once a shockwave is detected. After shockwave detection is completed, CAVs are informed regarding the incident, and a command is issued for them to decrease their speeds. CAVs, which are included in the management are determined by the control boundary. The length of this boundary is incident-specific and changes according to the location of the upstream shockwave boundary and control distance. The upstream shockwave boundary refers to the location further away from the incident at which the effects of the shockwave are seen. Control distance is the distance that extends the control region further from the upstream shockwave boundary. Thus, the control boundary is the area starting from the incident location and ending at a control distance away from the upstream shockwave boundary. In Figure 3.5, this boundary is visualized.

CAVs located in the control boundary have a 100% obedience rate to the speed reduction commands. Therefore, once a shockwave is detected, speeds are reduced and the number of vehicles reaching the incident location is minimized to increase safety and discharge efficiency. The speed, which is given as a command to CAVs, is the shockwave speed. Thus, after the boundaries of the shockwave are detected, shockwave speed is calculated dynamically. Then, CAVs located in the control boundary are informed and these vehicles reduce their speeds to the calculated shockwave speed.

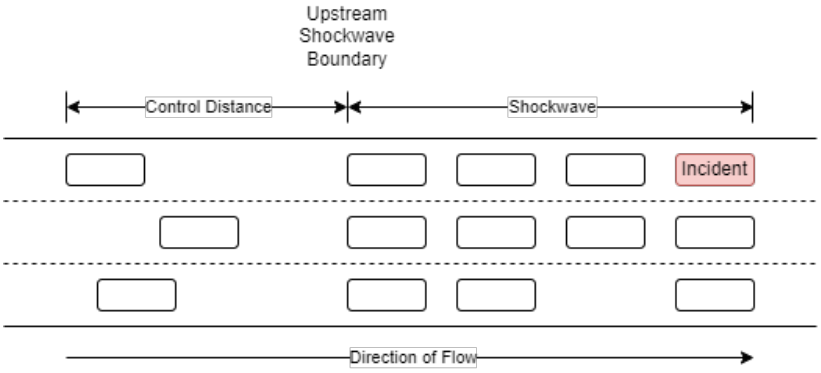


Figure 3.5. The sketch of a SWSCAV control boundary.

In this study, the assumptions made while modeling the SWSCAV incident management method are as follows:

- CAVs are capable of receiving information from the infrastructure continuously.
- CAVs are aware of their location accurately at all times.
- CAVs apply the commands given to them by SWSCAV as fast as possible.
- CAVs reduce their speeds linearly and once their speed is equal to the dynamically calculated shockwave speed, their speed is fixed.
- Instantaneous traffic density data, which is measured locally, shows wave properties.
- Vehicles do not exceed the speed limit. Also, even if the calculated shockwave speed is below 10 km/h, CAVs do not lower their speeds below this threshold.

In conclusion, the working mechanism flow chart of the SWSCAV incident management method is given in Figure 3.6.

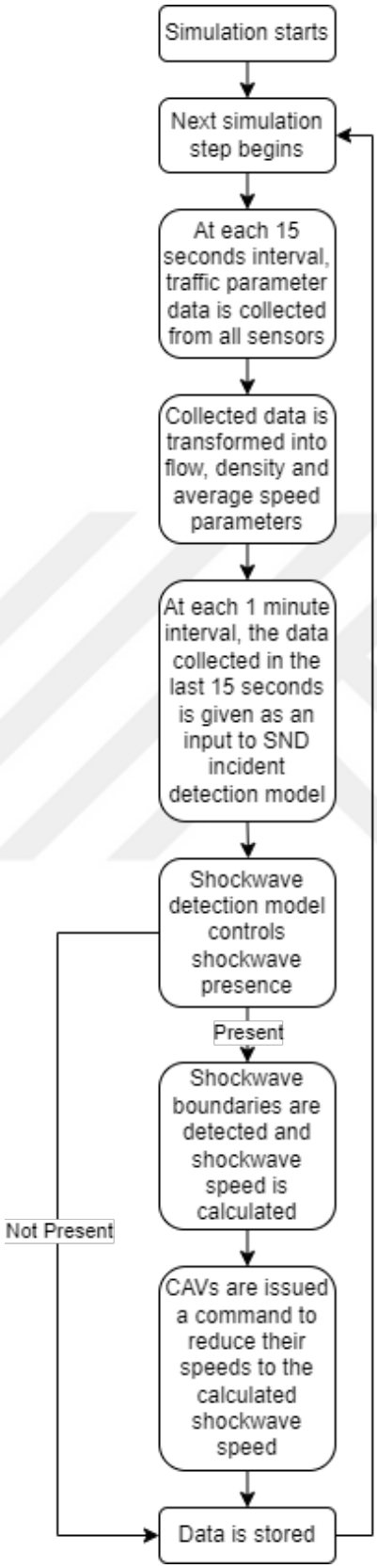


Figure 3.6. The working mechanism flow chart of the SWSCAV incident management method [59].

4. METHODOLOGY

In this section, the software used in the simulation studies, design of the simulation networks, distribution, and location of sensors throughout the networks, modeling of simulation components such as vehicles and sensors, data collection, simulation scenarios, and measure of effectiveness parameters are explained in detail. In addition to these, simulation results are visualized and evaluated.

4.1. Simulation of Urban Mobility (SUMO) Traffic Simulation Software

In this thesis, SUMO Traffic Simulation Software is used to simulate the determined scenarios. SUMO is an open-source, microscopic, and continuous traffic simulation package, which is developed to conduct simulation studies on networks created in virtual environments. This software is developed by the Institute of Transportation Systems at the German Aerospace Center [60]. SUMO has been available as an open-source package since 2001 and became an Eclipse Foundation project in 2017.

Simulation studies, which are carried out on SUMO, are time-dependent and each timestep is 1 second long. The length of this simulation timestep can be decreased down to 1 millisecond. The maximum allowed duration for a simulation is 49 days. Simulations conducted on SUMO are space-continuous and the location of each vehicle is defined by their lane and their distance from the starting point of the network. Vehicle speeds are determined dynamically considering the used car-following models. In these models, speeds are mostly calculated using algorithms, which take the speed of the vehicle located in front and the distance between these two vehicles into account. The default car following the model of SUMO is developed by Stefan Krauß and is a stochastic model [61]. This model is selected as default due to its simplicity and application speed. Various studies in the literature compared the Krauß model with the different car-following models to evaluate the validity of the model and according to these studies, the Krauß model is a valid and applicable car-following model [62,63].

In SUMO simulation studies, each vehicle given as input to the network is defined by various features such as vehicle ID, movement time, route, physical parameters, driving parameters, and car following model parameters. In addition to these features, current lane, speed, and location are also included in the vehicle definition.

SUMO enables the procurement of various outputs on the simulation study results. These results are obtained via sensors, which are capable of conducting measurements on short distances and work by induction loop concept. In addition to these sensors, SUMO also includes systems that can provide instantaneous and wide-range measurements across the simulation network.

In 2006, the extent of the possible simulation studies was increased by the addition of a connection socket, which enables online interaction with the simulations. This socket, which is named Traffic Control Interface (TraCI), was developed by Axel Wegener and his colleagues at Lübeck University [64]. After the simulation is loaded and the connection is established through TraCI, the client is responsible for starting the simulation, carrying the simulation further, and terminating the connection when the simulation ends. Using TraCI, it is possible to access each simulation component such as intersections, lanes, traffic signals, vehicles, and sensors. Through this access, the client has the opportunity to change the values of variables and conduct re-programming operations. In addition to these, it is possible to change the speed and lane of vehicles through TraCI. While establishing connections and accessing simulation components, a library, which is created in Python coding language is used.

SUMO simulation software provides advantages in many areas. One of these areas is applications where vehicle communication is established. Enabling online interaction with the TraCI library makes it possible to provide real-time information and guidance to vehicles through the collected data from vehicles or infrastructure. Thus, V2V and V2I applications, which are within the context of V2X and C-ITS, can be modeled and tested on SUMO. Therefore, SUMO's fast execution and online interaction feature provided by TraCI makes this program an effective simulation software for testing both traffic management applications and V2X systems [65].

Before starting simulation studies on SUMO, the network, vehicles, and traffic demand must be modeled. This process is included in the flow chart in Figure 4.1.

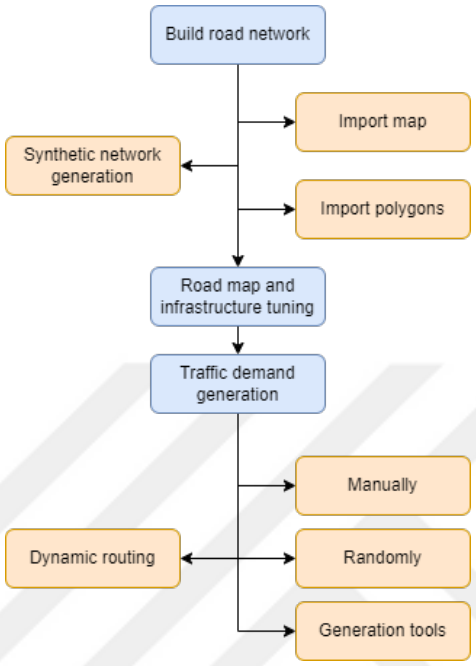


Figure 4.1. Flow chart followed when creating simulation networks and traffic demands.

Within the scope of this scheme, network modeling is conducted initially. Road networks used in SUMO simulation studies are created and edited via an internal program, named NetEdit. The construction of the road network can be carried out in three different ways, which are synthetic network generation, importing maps, and importing polygons. The most significant difference between importing map and polygon methods is the data and file format used. After the road network is created, infrastructure elements (sensors, traffic lights, bus stops, etc.) are integrated into the road network. Then, the traffic demand to be given to the road network needs to be modeled. At this stage, vehicle modeling is done. Every vehicle in the simulation is defined by its physical features, the route to be followed, and the vehicle type. In this definition, characteristic features such as acceleration, deceleration, and maximum speed are also included. After vehicle modeling is completed, the vehicle type and the route they will follow are assigned to the traffic flows created. Routes can be created in four different ways.

- Creation of the route by manually selecting each road section one by one.
- Creation of the route randomly.
- Usage of the route generation tools of SUMO.
- Adding the feature to vehicles to change their routes dynamically with a function within SUMO and determining the routes dynamically in this context [66].

4.2. Simulation Modelling

C-ITS incident management applications have become an important topic for many institutions and researchers. Since these applications require the usage of novel and advanced technologies such as low latency and fast communication technologies, connected vehicles, and hardware equipment such as OBUs and RSUs, the effects of these applications should be initially observed through simulation studies to avoid safety risks arising from directly implementing these technologies into real-time traffic. One other aspect of the examined C-ITS incident management application in this thesis is that it involves the deployment of CAVs. Thus, it becomes more important to initially investigate the effects of implementing this method in simulation environments.

In simulation studies conducted to evaluate the examined C-ITS incident management method, there are several models to be done before running the simulations. These are simulation network, infrastructure, and vehicle modellings.

4.2.1. Simulation Network Modelling

In this study, two different networks are created to be used in the simulation of the determined scenarios. Since incident management methods show different effects on different road network types, it is important to investigate the examined C-ITS incident management method on different networks.

The length of Network #1 is 10.4 kilometers. The first 200 meters of this 10.4 kilometers are defined as the entrance and the last 200 meters are defined as the exit

sections of the road network. While the entrance part is the area where vehicles join the road network, the exit part is the area where vehicles leave the road network. When the entrance and exit sections are not taken into account, the remaining 10 kilometers are considered to be the main road section. The road network continues with 3 lanes along the entire road length. The lane width is fixed and 3.2 meters. The road network is created using the NetEdit program. A representation of this road network is available in Figure 4.2.

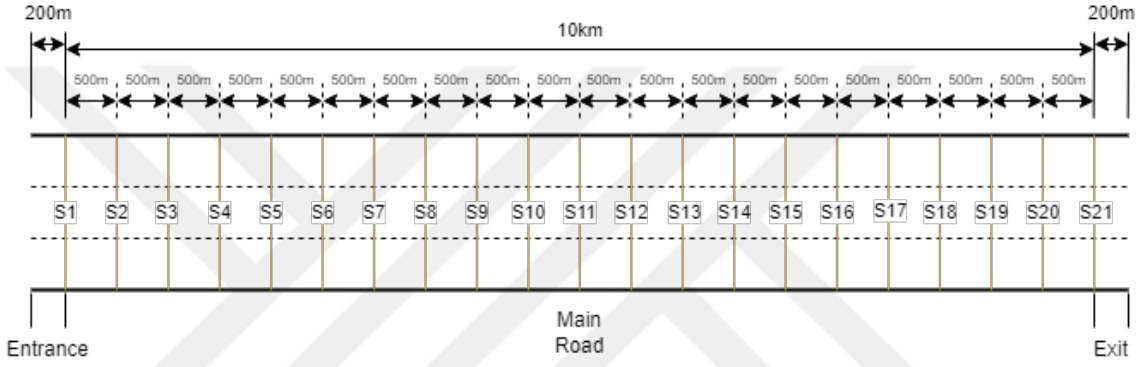


Figure 4.2. Illustration of the Network #1.

In the simulation studies carried out within this road network, sensors were used to collect data. The sensors used are "E1 Induction Loop" sensors and there is a distance of 500 meters between each sensor. As seen in Figure 4.2, there are 21 sensors in total throughout the road network.

The main reason why this road network is chosen as one of the used road networks is that there are no elements that can affect the traffic flow along the network. Thus, the effects of the implemented C-ITS incident management application can be observed more clearly.

On the other hand, the length of Network #2 is 20.4 kilometers in total. As in Network #1, there are entrance and exit sections, which have a length of 200 meters each. There are 43 sensors along the road network. While 41 of these sensors are on the main road section, 2 of these sensors are on the ramp section. While the distance between the sensors on the main road is 500 meters, sensors located on the ramp

section are 100 meters apart from each other. A representation of this road network is available in Figure 4.3.

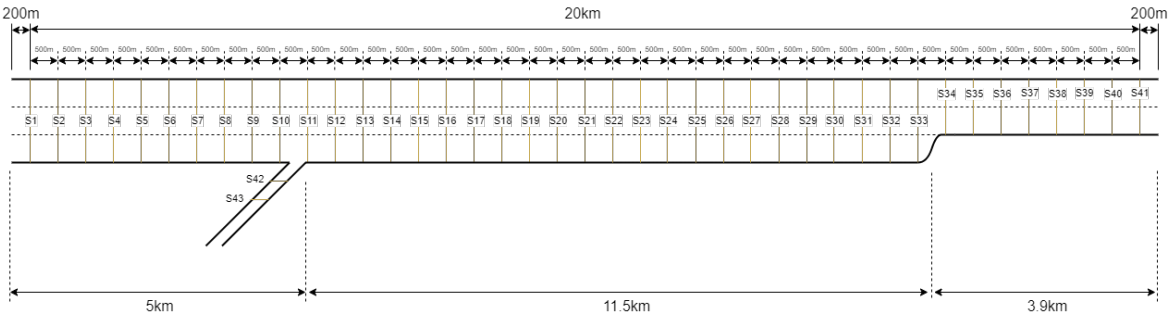


Figure 4.3. Illustration of the Network #2.

When Figure 4.3 is examined, it is seen that the ramp section is located at the 5th kilometer. Unlike the main road section, the ramp section contains only a single lane, and the width of this lane is the same as all lanes in the road network, which is 3.2 meters. In addition to the ramp section, at 16500th meter of the road network, the number of lanes decreases from 3 to 2 and the right lane joins the middle lane. The distance between the ramp section and the section where the change in the number of lanes takes place is 11.5 kilometers. The length of the two-lane road section is 3.9 kilometers.

The main reason why this road network is chosen as one of the used road networks is that different traffic elements such as intersections, ramps, and bottlenecks have different effects on the implemented incident management methods. Thus, by using Network #2, it is possible to evaluate the effects of the C-ITS incident management method under scenarios in which there is a ramp and bottleneck present.

Also, the reason behind making Network #2 longer than Network #1 is to move the ramp and bottleneck areas away from each other and to make the transition between these sections long enough to eliminate the possibility of these areas affecting each other due to the created traffic congestion. To efficiently observe the shock waves that will occur in the incident scenarios created, Network #2 is designed to be 10 kilometers longer than the other road network.

4.2.2. Simulation Infrastructure Modelling

In simulation studies, the sensor type named “E1 Induction Loop” is used to collect data. This sensor type is one of the built-in sensor types of SUMO simulation software. The illustration of these sensors on the road network is given in Figure 4.4.

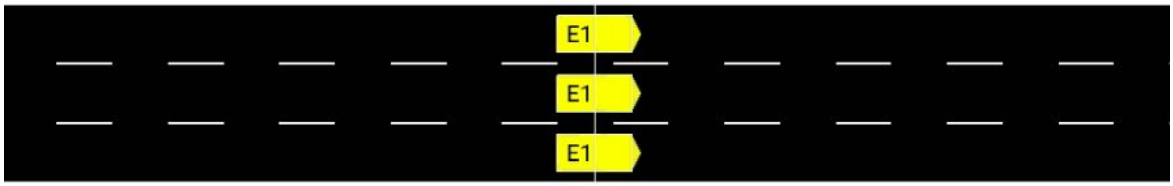


Figure 4.4. Illustration of the sensors on the road network.

These sensors are distributed throughout the road network at equal intervals. The detection area of this type of sensor is 4 meters. These sensors, which use induction loops as their working principle, detect the presence of a vehicle when a vehicle enters its detection area and increases the induction in the circuit. Thus, detection occurs as soon as a vehicle enters the 4-meter detection area. The data output by these sensors is available in Figure 4.5.

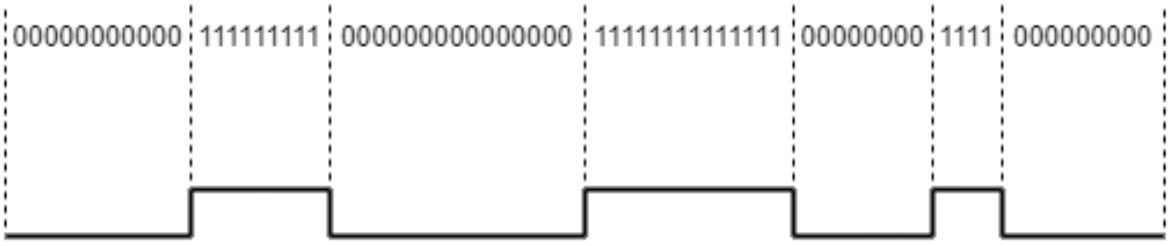


Figure 4.5. Output format of the induction loop sensors.

The 0 (zero) values in the output data indicate that there is no induction in the circuit, which also shows that there is no vehicle in the detection area. The 1 (one) values in this data represent that there is induction in the circuit and there is a vehicle in the detection area. The 0 and 1 values in the output are time-continuous and each measurement takes place within the measurement frequency of the sensor type. Thus, the length of the consecutive continuity of the output values is related to the long or short durations of vehicle presence or no presence. For instance, if the length of

consecutive 1 values is long, the sensor detection area is occupied for a long duration. If the length of consecutive 0 values is long, there is no vehicle present in the detection area for a long duration. Through these sensors, the number of vehicles, vehicle speed, and occupancy rate data can be collected.

Throughout the simulation studies, sensors collect data every second. To make the collected data meaningful and analyzable, the data collected at the end of every 15 seconds is processed according to the data type. The processed data is then inserted into the main dataset as a single data line. Therefore, every 15-second interval is defined as 1 data processing frequency.

The algorithms and formulas used by these sensors when converting the collected data into the desired data format are available below.

- Number of vehicles: When the sensor output data is examined, it can be detected if a vehicle is present in the detection area. Thus, at each second, it is known if a vehicle is recorded by the sensor or not. Using this data, the number of vehicles that pass through each sensor is measured for each 15-second interval and is inserted into the main dataset.
- Vehicle speed: Analyzing the sensor output data, it is possible to measure the duration it takes for a specific vehicle to enter and leave the detection area of a sensor. Therefore, the equation used in vehicle speed calculation is expressed as

$$\dot{x_n} = \frac{L_n + L_D}{(t_{occ})_n}, \tag{4.1}$$

  where $\dot{x_n}$ refers to the speed of the vehicle, L_n refers to the length of the vehicle, L_D refers to the length of the detection area of the sensor, and $(t_{occ})_n$ refers to the duration of the vehicle n occupying the detection area. Vehicle speed data is kept every second throughout the simulation, and the average value is calculated for each 15-second interval and is inserted into the dataset. Thus, average vehicle speed data collected from each sensor at each 15-second interval is obtained.
- Occupancy rate: Occupancy rate is the ratio of the duration any vehicle occupies the sensor detection area to the measurement period. This ratio is an important

parameter used in traffic density calculations. The equation used in occupancy rate calculation is expressed as

$$OCC\% = \frac{\sum_{n=1}^{N}(t_{OCC})_n}{T} x100, \tag{4.2}$$

where $OCC\%$ refers to the occupancy rate, N refers to the number of vehicles detected in time T, and T refers to the duration of measurement.

Occupancy rate data is calculated by dividing the time the sensors are occupied during each 15-second interval by 15 seconds. After this rate is calculated, it is inserted into the dataset and the occupancy rate of the next 15-second interval begins to be calculated.

The collected number of vehicles, vehicle speed, and occupancy rate data are then converted into flow, density, and average speed data by using conversion formulas. The application of these conversions and the formulas used in the process are given below.

- Conversion of occupancy rate into traffic density: The equation used to convert the occupancy rate data collected from each sensor at each 15-second interval into density data is expressed as

$$k = \frac{10}{\bar{L_v} + L_D} OCC\%, \tag{4.3}$$

where k refers to traffic density, $\bar{L_v}$ refers to average vehicle length, and L_D refers to sensor detection area length.

- Conversion of number of vehicles into traffic flow: The number of vehicles data collected from each sensor at each 15-second interval represents the number of vehicles passing through each sensor in 15-second intervals. Multiplying this by 240, the number of vehicles passing through each sensor in 1 hour, which is traffic flow, can be calculated. The equation used for this conversion is expressed as

$$Q = Q_{15} x240, \tag{4.4}$$

where Q refers to traffic flow, and Q_{15} refers to traffic flow for 15-second intervals.

- Conversion of vehicle speed into average vehicle speed: In this study, the speeds of vehicles passing through the sensors are recorded every second. These speeds

are then averaged at the end of each 15-second interval. Thus, the average vehicle speeds measured from each sensor at each 15-second interval are inserted directly into the main dataset.

An example cross-section of the dataset obtained after the simulation study is completed is available in Table 4.1.

Table 4.1. A cross-section of the data set obtained after the simulation study.

Data Processing Frequency	Sensor	Flow (vehicle/hour)	Density (vehicle/km)	Average Speed (km/h)
243	1	2080	12.49	48.6
243	2	1360	4.68	96
243	3	1920	8.18	77.24
243	4	1200	4.42	98.28
243	5	2160	9.12	78.94
243	6	1360	6.6	98.84
243	7	1680	9.46	84.6
243	8	1920	12.16	86.4
243	9	1040	5.33	94.5
243	10	1920	9.35	94.91
243	11	1040	3.79	93.09
243	12	80	0.65	68.4
243	13	880	4.82	86.91
243	14	1440	6.75	101.13
243	15	2720	12.8	84.74
243	16	960	3.64	98.4
243	17	1600	9.14	99.51
243	18	800	4.42	86.4
243	19	1440	7.79	90.9
243	20	960	3.96	102.6
243	21	1200	6.66	98.18

4.2.3. Vehicle Modelling

After modeling the road networks and sensors, vehicle modeling takes place. In SUMO simulation software, a different vehicle type can be assigned to each vehicle. These vehicle types differ in the values assigned to their characteristic parameters.

Different values assigned to the features given in Table 4.2 construct the vehicle types and change the behaviors of vehicles in traffic.

Table 4.2. Vehicle type characteristic feature descriptions.

Characteristic Feature	Description
Acceleration (m2/s)	The maximum acceleration value that the vehicle type can reach during the simulation
Deceleration (m2/s)	The maximum deceleration value that the vehicle type can reach during the simulation
Length (m)	Vehicle length
Maximum Speed (m/s)	The maximum speed value that the vehicle type can reach during the simulation
Sigma	One of the most distinctive parameters that distinguish vehicle types from each other is the sigma value. It is also called driver imperfection. Sigma is one of the parameters used by the Krauss car following model and it directly affects the awareness of the vehicles regarding their surroundings. It regulates the acceleration and deceleration behavior of vehicles, and it takes a value between 0 and 1. The Sigma value being equal to zero indicates that the driver is perfect, awareness of the environment is at the highest level, and acceleration and deceleration behaviors are in accordance with the theoretical assumptions of the Krauss car following model. The Sigma value being equal to 1 indicates that driver imperfection is at the highest level.
Speed Deviation	This parameter is the standard deviation of standardized speed distributions. The autonomous vehicles used in this study show a more homogeneous speed distribution and therefore, their speed deviation value is lower.
Speed Factor	Speed factor is a variable assigned to vehicle types that determines how much these vehicles can exceed speed limits. This variable is multiplied by the speed limit, and the value obtained within this multiplication determines the maximum speed that each vehicle type can reach.
Minimum Gap	It determines the minimum distance between the vehicle in front and the vehicle following.

In this simulation study, there are two vehicle types, which are human-driven vehicles and CAVs. In the process of determining the values to be assigned to each characteristic parameter, a thorough literature review is conducted. In Table 4.3, the values assigned to human-driven and autonomous vehicles in a different study are presented.

Table 4.3. Values assigned to vehicle type characteristic parameters [67].

	Minimum Gap (m)	Acceleration (m2/s)	Deceleration (m2/s)	Emergency Deceleration (m2/s)	Sigma
Human-driven vehicle	1.5	3.5	4.5	8	0.5
Autonomous vehicle	0.5	3.8	4.5	8	0

In different studies, different values are assigned to these parameters. In Table 4.4, the values assigned to acceleration and deceleration parameters in previous studies are given.

Table 4.4. Values assigned to vehicle type parameters.

	Acceleration (m2/s)	Deceleration (m2/s)	Reference
Human-driven vehicle	3	9	[68]
Human-driven vehicle	3	5	[69]
Autonomous vehicle	2	3	[70]

Considering the literature review, the characteristic parameter values of the human-driven vehicles and CAVs used in this study are determined. These values are given in Table 4.5.

Table 4.5. Characteristic parameter values of CAV and human-driven vehicle types.

	CAVs	Human-driven vehicles
Accelaration (m/s2)	2.6	2.7
Deceleration (m/s2)	4.5	4.5
Length (m)	4.5	4.5
Maximum Speed (m/s)	17	17
Sigma	0.05	0.4
Speed Factor	0.9	0.7
Speed Deviation	0.1	0.35
Minimum Gap (m)	1.5	1.5

4.3. Scenarios

In this thesis, an evaluation of the implemented C-ITS incident management method is done through the conducted simulations. To be able to observe the outcomes of applying this method to various traffic situations, different scenarios are created and

simulated. The extent of the scenario set is determined by scenario variables, which are the simulation network, traffic demand, CAV penetration rate, incident duration, and management status.

As explained previously, two different simulation road networks are modeled and used in the simulation study of this thesis, namely Network #1 and Network #2. The set of values assigned to CAV penetration rate, incident duration, and management status variables are the same for each network. However, since the capacity of Network #1 and Network #2 are different due to geometric design, different traffic demand values for each network are used. In the process of selecting these traffic demand values, preliminary simulation studies are done to be able to detect the capacity of each network. This is done by simulating base scenario runs at which there is no CAV and incident present. It should also be noted that different sections of a network have different capacities due to geometric properties. For instance, analyzing Network #2, it can be stated that the bottleneck section has a lower capacity compared to the 3-lane continuous section due to the decrease in the number of lanes. Therefore, in the process of detecting the capacity of a network, critical regions such as ramp and bottleneck sections should be analyzed, and the least capacity should be selected as the network capacity.

Initially, the capacity of Network #1 is analyzed by running the base run scenario with a traffic demand of 2200 vehicle/hour/lane. Since the geometry of Network #1 is the same in each section, there is no critical region to be assessed while analyzing the capacity of the network. Thus, the data recorded from the sensor located in the middle and marked with a black box is used, which is also shown in Figure 4.6.

After the base run simulation is concluded, using the density and flow data measured from the 11th sensor at each 15-second interval, a flow vs. density fundamental diagram is created. This diagram is given in Figure 4.7.

The best-fit line present in Figure 4.7 is used in the detection of network capacity. The highest flow value observed on this best-fit line represents the capacity value, which

is 2555.49 vehicle/hour/lane. Therefore, the traffic demand values to be used in the simulations of Network #1 are selected to be 1800 and 2400 vehicle/hour/lane, which indicate low and high traffic demands.

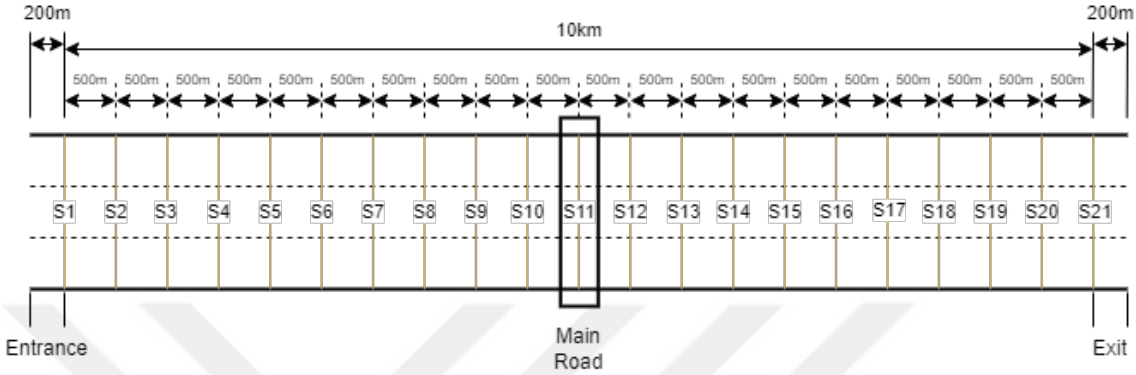


Figure 4.6. Sensor used to detect the capacity of Network #1.

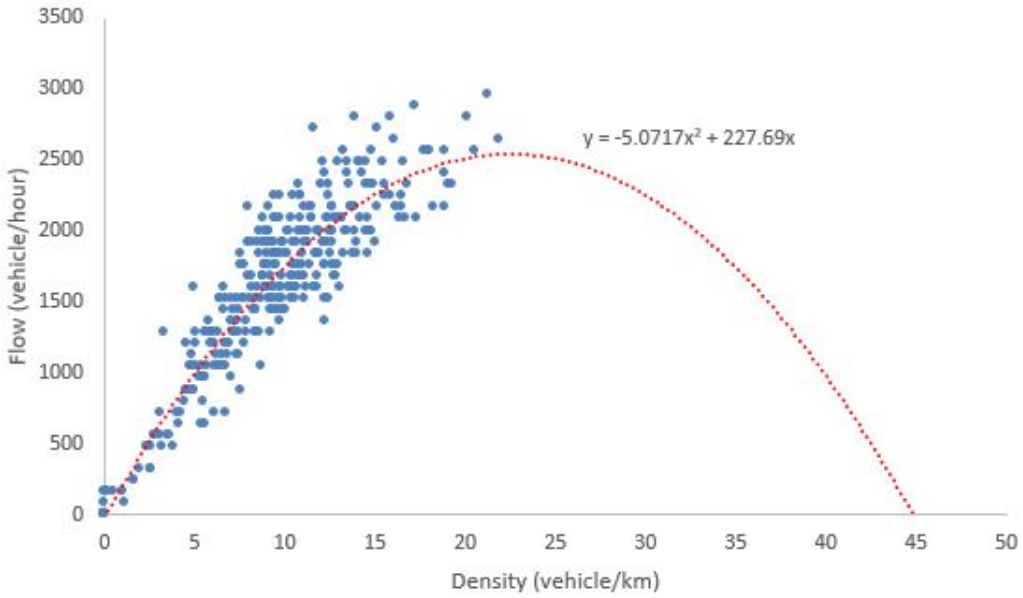


Figure 4.7. Flow vs. density diagram of the Network #1 base run simulated with a traffic demand of 2200 vehicle/hour/lane.

In the process of capacity detection for Network #2, the base scenario is simulated with a traffic demand of 1250 vehicle/hour/lane. Since this network contains a ramp, an additional traffic demand of 120 vehicle/hour/lane is given into the network via the ramp. Also, unlike Network #1, Network #2 includes ramp and bottleneck sections. Therefore, it is known that the least capacity values are observed around

these sections. In Figure 4.8, the sensors, which are located at the regions of least capacity are marked with black boxes, and these sensors are used in the detection of network capacity.

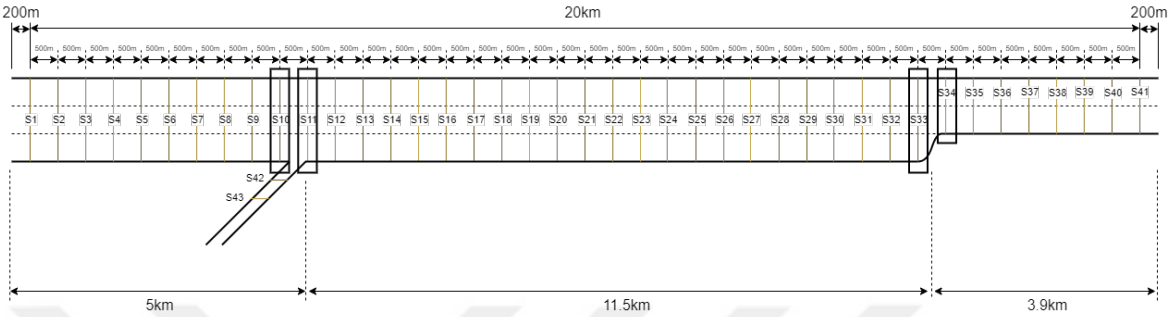


Figure 4.8. Sensors used to detect the capacity of Network #2.

After the simulation is concluded, using the density and flow data recorded from the 10th, 11th, 33rd, and 34th sensors at each 15-second interval, flow vs. density fundamental diagrams are created. These diagrams are given in Figure 4.9. Analyzing Figure 4.9, it is seen that the least capacity is detected at the flow vs. density diagram created by the data recorded from the 33rd sensor, which is 1882.07 vehicle/hour/lane. Thus, the values assigned to Network #2 traffic demand variables are selected to be 1250 and 1400 vehicle/hour/lane.

Considering the CAV penetration rate variable, it is important to assess the effects of deploying both low, medium, and high penetration rates to be able to observe the change in the effectiveness of the C-ITS incident management method according to changing CAV penetration rates. Thus, 6 different penetration rates are selected, which are 0%, 20%, 40%, 60%, 80%, and 100%.

Since the applied method is an incident management method, incidents are created in the simulations. It is important to evaluate the effects of incident situations on the C-ITS incident management method. Thus, incident duration is selected to be a scenario variable. The values assigned to this variable are chosen to be 300 seconds, 600 seconds, and 900 seconds, which simulate short-term, mid-term, and long-term incidents.

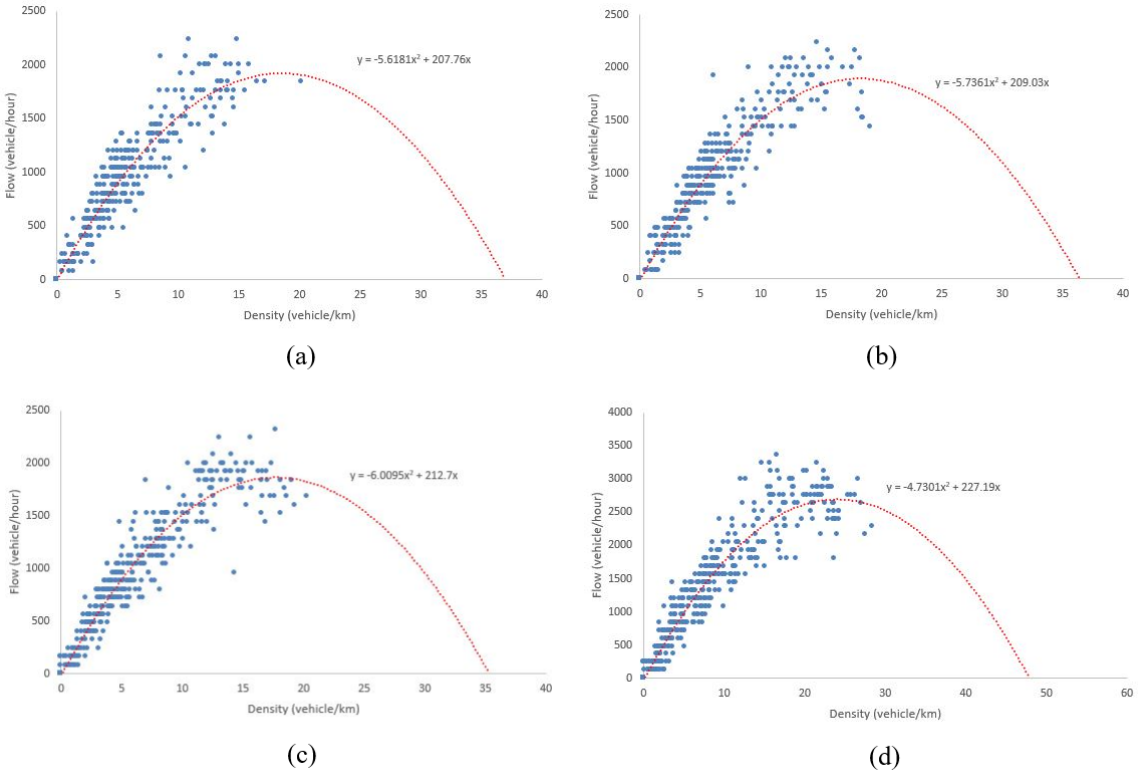


Figure 4.9. (a) The 10th sensor, (b) the 11th sensor, (c) the 33rd sensor, (d) the 34th sensor flow vs. density diagrams of Network #2 base runs simulated with a traffic demand of 1250 vehicle/hour/lane.

Each scenario of the simulation study is simulated with the C-ITS incident management method being applied and not applied. Since the study aims to evaluate the outcomes of implementing the examined C-ITS incident management method, named "Slow or Stationary Vehicle Warning", it is essential to have the results of both managed and unmanaged incident cases.

In conclusion, the scenario variables and values assigned to these variables are given in Table 4.6. Considering this table, it is seen that there are 6 CAV penetration rates, 2 traffic demands, 3 incident durations, and 2 management status values, which makes a total of 72 scenarios for each network. In total, there are 144 scenarios in the simulation study.

On the other hand, randomness in simulation studies is an issue that can greatly affect the results. To eliminate the randomness effects, each scenario is simulated

again with a specific simulation seed set. In this way, the effects of randomness can be eliminated to a high extent. In this study, each scenario is simulated multiple times with the same simulation seed set. There are 3 different simulation seeds in the created set, and the values assigned to these seeds are chosen randomly. Therefore, each scenario is simulated again with 3 different seeds, making a total of 432 simulation runs.

Table 4.6. Scenario variables and their values.

Variable	Value
CAV Penetration Rate (%)	[0, 20, 40, 60, 80, 100]
Traffic Demands (vehicle/hour/lane)	Network #1: [1800, 2400] Network #2: [1250, 1400]
Incident Duration (s)	[300, 600, 900]
Incident Location (m)	Network #1: [7050] Network #2: [5800]
Incident Lane	[Left]
Management Status	[Present, Not Present]

4.4. Simulation Results

After the simulation studies are completed, analysis of the simulation results is done. In the analysis stage, collected traffic data is used to visualize the effects of the C-ITS incident management method and the effects of scenario variables on the applied method. The analysis is conducted for each network type separately.

4.4.1. Simulation Results of the Network #1

In Table 4.7, average values of speed and density data collected from each sensor of the Network #1 when the simulations are done using a traffic demand of 2400 vehicle/hour/lane and an incident duration of 600 seconds are present. Thus, this table contains the average of the data collected from the whole network. Analyzing the table, it is observed that, as CAV penetration rate increases, average density

values show a decreasing trend and average speed values show an increasing trend. Therefore, CAVs have a positive effect on traffic efficiency. Also, comparing managed and unmanaged cases, it is observed that the C-ITS incident management method increases average density values and decreases average speed values. Since the aim of the implemented method is to slow down the CAVs in the incident region to increase safety rather than increasing traffic efficiency, an increase in densities and decrease in speeds was expected. Comparing the results of managed and unmanaged cases based on different CAV penetration rates, the effects of the method is observed the most at 40% CAV penetration rate since percent change values are the highest at this rate.

Table 4.7. Comparison of average speed and density values recorded from the whole network based on different CAV penetration rates for managed and unmanaged cases considering the simulations conducted on the Network #1 with a traffic demand of 2400 vehicle/hour/lane and an incident duration of 600 seconds.

CAV Penetration Rate	Avg. Density for Unmanaged Case (vehicle/km/lane)	Avg. Density for Managed Case (vehicle/km/lane)	% Change	Avg. Speed for Unmanaged Case (km/hour)	Avg. Speed for Managed Case (km/hour)	% Change
0%	12.92	12.92	0	63.81	63.81	0
20%	12.25	13.34	8.94	68.71	61.39	-10.67
40%	11.17	12.68	13.53	75.64	65.75	-13.08
60%	10.4	11.56	11.19	81.7	72.95	-10.71
80%	9.91	10.36	4.56	86.73	83.54	-3.68
100%	8.53	8.7	1.94	94.57	93.45	-1.18

Also, utilizing the two-way ANOVA test, which is used to analyze if the collected data considering two different scenario variables are statistically different and significant, data presented in Table 4.7 is tested. In the applied ANOVA test, alpha value is determined to be 0.05. According to the results, both management status and CAV penetration rate variables have p-values below the alpha value, which is 0.05. Also, F-values of these variables are over the critical F values. Therefore, results presented in the table are statistically different and significant.

In Table 4.8, the same comparison is made for only the incident region rather than the whole network. Analyzing the results given in this table, it is observed that

increases in CAV penetration rates decrease both average speeds and densities. Since the applied method reduces the speeds of vehicles located in the upstream direction of the incident, the rate of number of vehicles reaching the incident region decreases, which also decreases the average densities in the incident region. Also, because CAVs are slowed down, average speeds decrease directly. Based on these outcomes, it is possible to say that the implemented C-ITS incident management method achieved its goal of increasing the safety aspect of traffic in the incident region by decreasing vehicle densities. On the other hand, examining the effects of different CAV penetration rates on the comparison between managed and unmanaged cases, it is observed that 60% CAV penetration rate is the optimum rate since the average density value decreases highly, which increases safety, but the average speed value decreases at a very low rate. Therefore, at 60% CAV penetration rate, the implemented C-ITS incident management method increases safety to a great extent, but does not reduce average speed as much.

Table 4.8. Comparison of average speed and density values recorded in the incident region based on different CAV penetration rates for managed and unmanaged cases considering the simulations conducted on the Network #1 with a traffic demand of 2400 vehicle/hour/lane and an incident duration of 600 seconds.

CAV Penetration Rate	Avg. Density for Unmanaged Case (vehicle/km/lane)	Avg. Density for Managed Case (vehicle/km/lane)	% Change	Avg. Speed for Unmanaged Case (km/hour)	Avg. Speed for Managed Case (km/hour)	% Change
0%	15.28	15.28	0	58.71	58.71	0
20%	26.23	23.63	-9.9	38.91	40.15	3.19
40%	26.46	23.53	-11.09	46.18	42.78	-7.36
60%	32.75	27.47	-16.12	37.01	36.75	-0.72
80%	30.8	26.86	-12.8	42.42	36.77	-13.33
100%	40.52	38.48	-5.04	34.98	31.35	-10.38

In Figure 4.10, the density heatmaps of unmanaged and managed cases considering the scenario created with a traffic demand of 2400 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 20% are given. These density heatmaps are constructed by using density data collected from each sensor at each 15-second interval. X-axis of the heatmaps represent sensor locations and y-axis represents the time of the simulation. The legend located at the right sides of the heatmaps specify the color range assigned to density values. Therefore, light yellow

represents low densities and dark blue represents high densities. The heatmaps given in the figure are created using the data collected from the simulation of the scenario at which each variable is kept the same except management status. Comparing these heatmaps, it is observed that the implemented C-ITS incident management method reduces the area, where high density values are observed. Also, it is seen that the length of queue is decreased significantly. Therefore, it is possible to say that the C-ITS incident management method is very useful in terms of dissipating high density regions originating due to the incidents and increasing the efficiency of the traffic flow in the incident region.

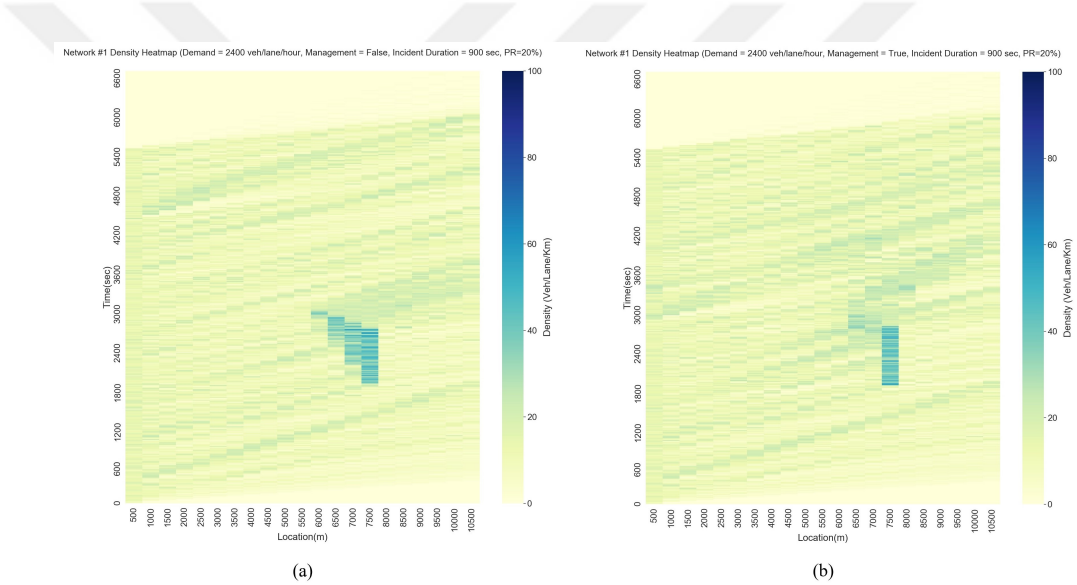
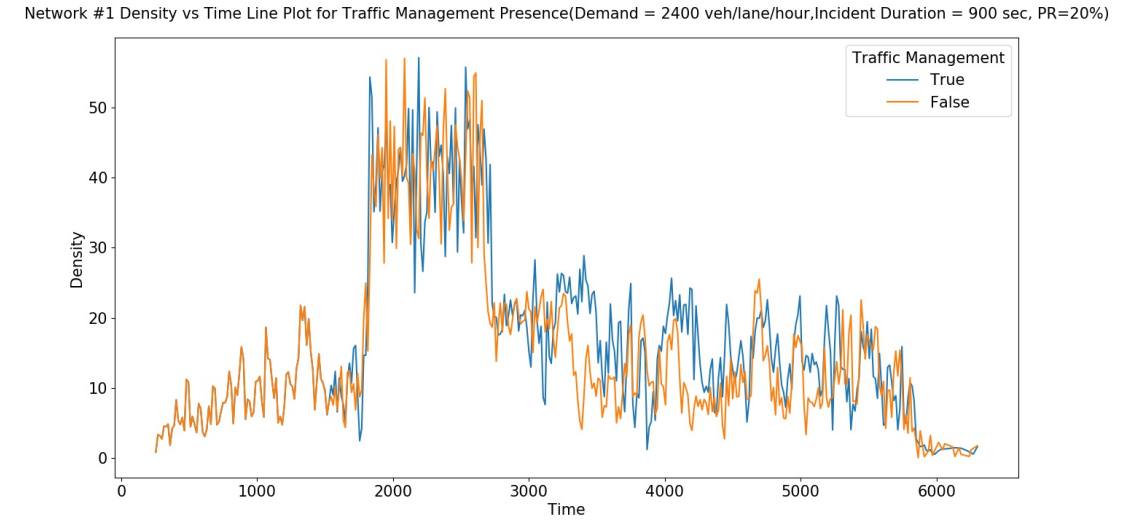


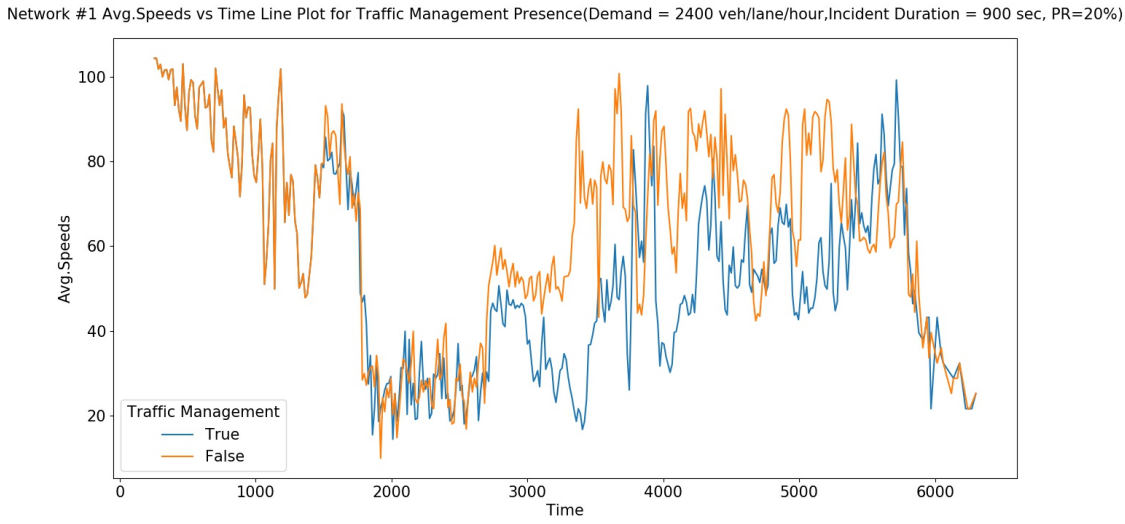
Figure 4.10. (a) Unmanaged, (b) managed case density heatmaps of the scenario simulated on the Network #1 and created with a traffic demand of 2400 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 20%.

In Figure 4.11, density vs. time, and average speed vs. time plots of the scenario created with a traffic demand of 2400 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 20% are given. As it is also seen, both graphs include the plots of managed and unmanaged cases. These figures are constructed using the data collected from the sensor closest to the incident region in the upstream direction. Thus, the analysis done on this figure is a local analysis. As the figure is investigated, it is observed that average speeds decrease, and densities increase after

the incident. However, in the Average Speed vs. Time plot, average speeds decrease further in the managed case compared to unmanaged case, which indicates an increase in traffic safety aspect. Even though average speeds decrease more, density values do not increase proportionally considering the managed case. Therefore, throughput is decreased slightly. This shows that the implemented C-ITS incident management method increases traffic safety by slightly reducing traffic efficiency.



(a)



(b)

Figure 4.11. (a) Density vs. time, (b) average speed vs. time plots comparing managed and unmanaged cases of the scenario simulated on the Network #1 and created with a traffic demand of 2400 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 20%.

In Figure 4.12, the density heatmaps of 0%, 60% and 100% CAV penetration rate cases considering the managed scenario created with a traffic demand of 2400 vehicle/hour/lane and an incident duration of 900 seconds are given. Analyzing these heatmaps, it is possible to say that as the CAV penetration rate increases, the size of the area having high density values decreases. Therefore, the efficiency of the implemented C-ITS incident management method increases with increasing CAV penetration rate.

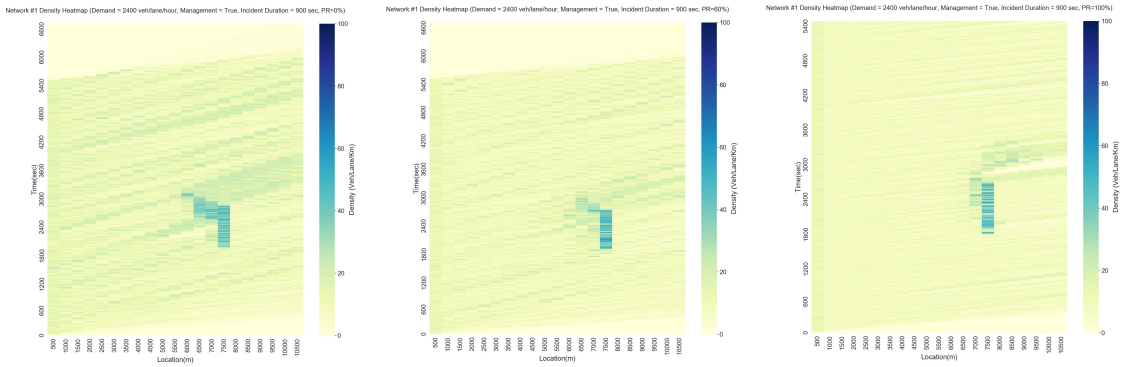


Figure 4.12. (a) 0%, (b) 60%, (c) 100% CAV penetration rate density heatmaps of the managed scenario simulated on the Network #1 and created with a traffic demand of 2400 vehicle/hour/lane and an incident duration of 900 seconds.

In Figure 4.13, Density vs. Time plots of both managed and unmanaged cases are present considering the scenarios created with a traffic demand of 2400 vehicle/hour/lane and an incident duration of 900 seconds. As it is seen, density plots of different CAV penetration rates are given in the graphs. Analyzing this figure, it is observed that at high CAV penetration rates, density values increase faster as the incident takes place and recover faster after the incident is concluded in both managed and unmanaged cases. In addition, at 60% CAV penetration rate, densities recover faster in the managed case compared to unmanaged case. Thus, it is possible to say that the C-ITS incident management method increases the traffic efficiency aspect of 60% CAV penetration rate case.

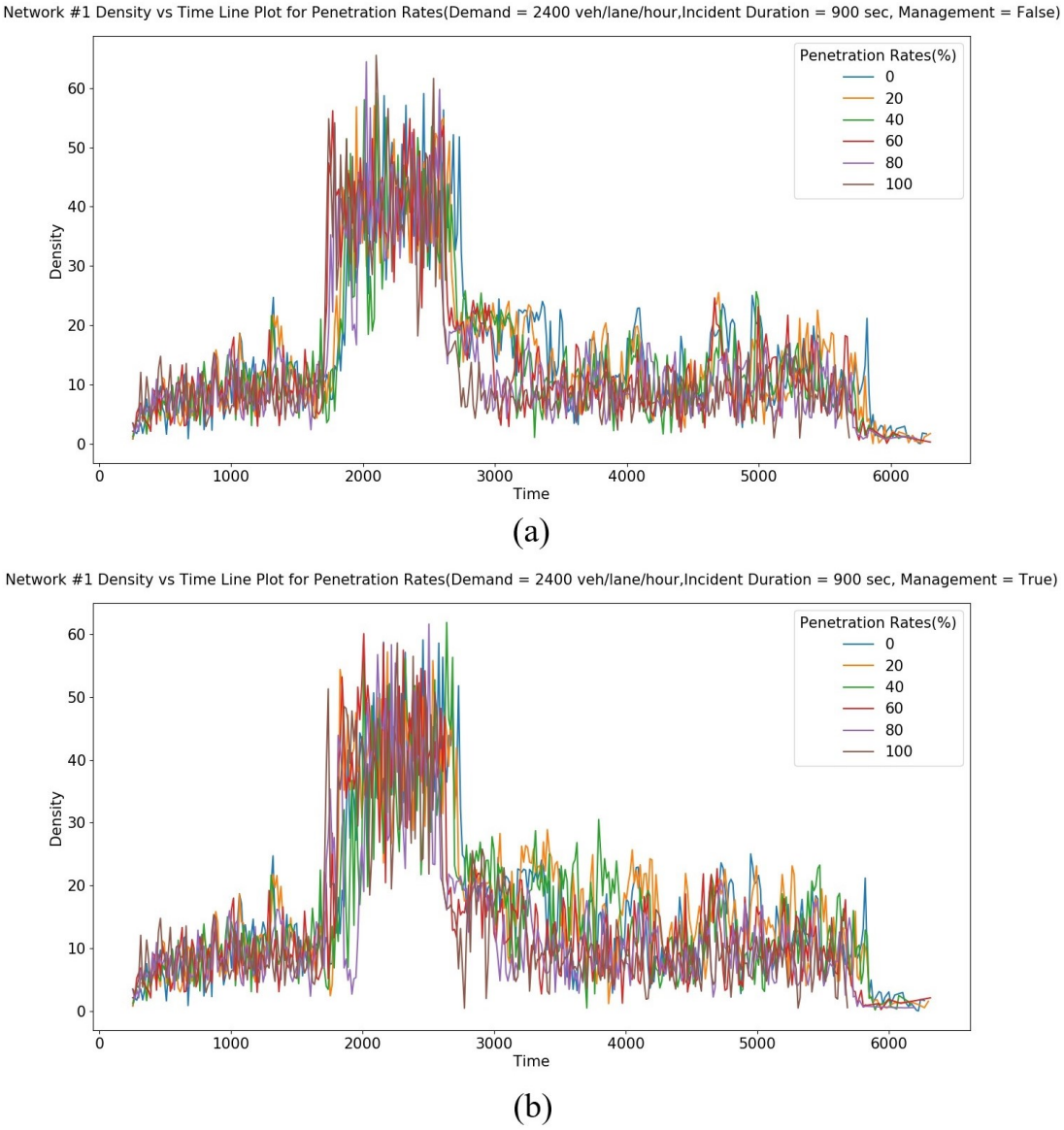


Figure 4.13. (a) Unmanaged, (b) managed case density vs. time plots comparing different CAV penetration rates of the scenario simulated on the Network #1 and created with a traffic demand of 2400 vehicle/hour/lane and an incident duration of 900 seconds.

4.4.2. Simulation Results of the Network #2

In Table 4.9, average values of speed and density data collected from each sensor of the Network #2 when the simulations are done using a traffic demand of 1400 vehicle/hour/lane and an incident duration of 900 seconds are present. Analyzing the table, it is observed that as the CAV penetration rate increases, average density values

decrease, and average speed values increase for both managed and unmanaged cases. On the other hand, comparing average speed and density values of managed and unmanaged cases, in the managed case average speeds are lower and average densities are higher since CAVs are slowed down in the management process. Comparing these two cases based on CAV penetration rate, it is observed that as the penetration rate increases, the percent change in average density decreases and percent change in average speed increases. Thus, it is possible to say that the implemented management method performs better at higher CAV penetration rates.

Table 4.9. Comparison of average speed and density values recorded from the whole network based on different CAV penetration rates for managed and unmanaged cases considering the simulations conducted on the Network #2 with a traffic demand of 1400 vehicle/hour/lane and an incident duration of 900 seconds.

CAV Penetration Rate	Avg. Density for Unmanaged Case (vehicle/km/lane)	Avg. Density for Managed Case (vehicle/km/lane)	% Change	Avg. Speed for Unmanaged Case (km/hour)	Avg. Speed for Managed Case (km/hour)	% Change
0%	8.15	8.15	0	53.97	53.97	0
20%	7.58	8	5.53	58.71	53.98	-8.05
40%	7.23	7.51	3.88	62.73	59.31	-5.46
60%	6.78	7.02	3.63	67.92	64.43	-5.14
80%	6.61	6.85	3.57	80.2	76.42	-4.71
100%	6.03	6.2	2.69	91.69	89.51	-2.38

In Table 4.10, the same comparison is made for only the incident region rather than the whole network. Analyzing the results given in the table, considering average speeds, the implemented C-ITS incident management method performs better at higher CAV penetration rates since percent change values increase as the penetration rate increases. However, considering average densities, percent change values are the lowest at 40% and 60% CAV penetration rates. Since the average density values given in this table represent the number of vehicles in the incident region, lower densities provide an increase in the safety aspect. Therefore, it is possible to say that 60% CAV penetration rate is the optimum rate due to a higher percent change in average speeds compared to 40% penetration rate case.

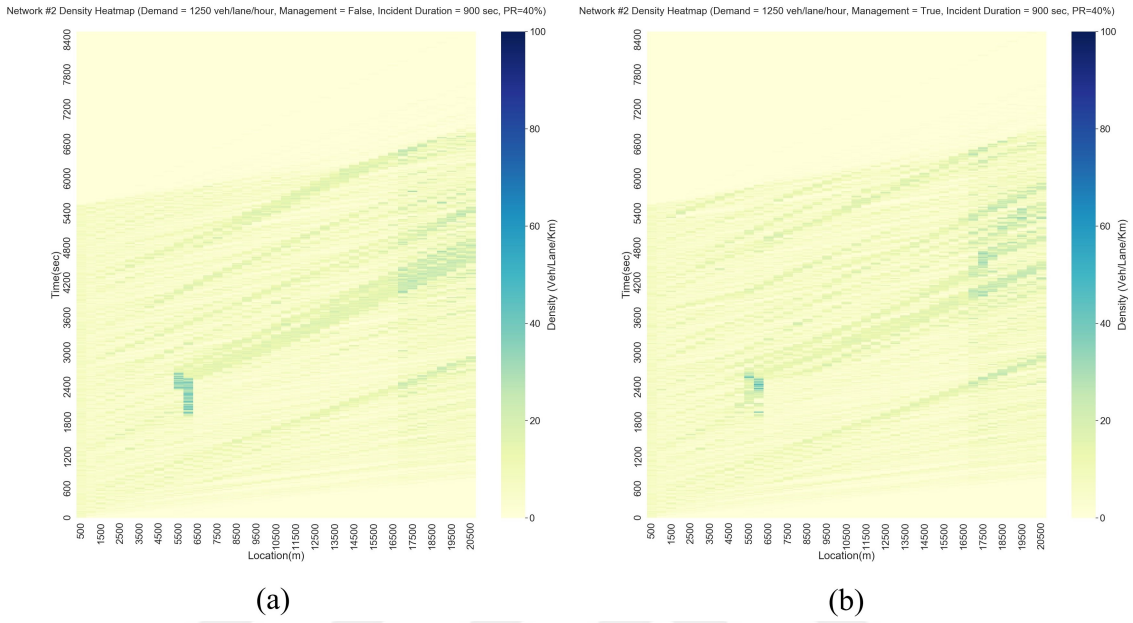
Table 4.10. Comparison of average speed and density values recorded in the incident region based on different CAV penetration rates for managed and unmanaged cases considering the simulations conducted on the Network #2 with a traffic demand of 1400 vehicle/hour/lane and an incident duration of 900 seconds.

CAV Penetration Rate	Avg. Density for Unmanaged Case (vehicle/km/lane)	Avg. Density for Managed Case (vehicle/km/lane)	% Change	Avg. Speed for Unmanaged Case (km/hour)	Avg. Speed for Managed Case (km/hour)	% Change
0%	8.9	8.9	0	55.58	55.58	0
20%	8.58	8.9	3.63	62.86	57.54	-8.46
40%	8.24	8.46	2.7	67.2	63.08	-6.12
60%	7.89	8.1	2.7	74.43	70.39	-5.42
80%	7.4	7.63	3.11	83.99	79.81	-4.97
100%	6.43	6.64	3.22	91.01	88.44	-2.82

In Figure 4.14, the density heatmaps of unmanaged and managed cases considering the scenario created with a traffic demand of 12500 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 40% are given. Analyzing the heatmaps, it is observed that the size of the area including high density values is smaller in the managed case. Thus, the implemented C-ITS management method increases traffic efficiency in the incident region. On the other hand, since density values are decreased, which indicates decreased number of vehicles in the incident region, traffic safety is improved.

In Figure 4.15, density vs. time, and average speed vs. time plots of the scenario created with a traffic demand of 1250 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 80% are given. As it is also seen, both graphs include the plots of managed and unmanaged cases. Examining average speed vs. time plot, it is observed that the average speed values of the managed case are lower compared to unmanaged case. This indicates that the speeds of human-driven vehicles are lower in the managed case compared to unmanaged case and due to this fact, these vehicles will reach the incident location at lower speeds and react to the incident more safely. Thus, safety aspect of the traffic is increased. Even though average speeds decrease more, density values do not increase proportionally considering the managed case. Therefore, throughput is decreased slightly. This shows that the implemented

C-ITS incident management method increases traffic safety by slightly reducing traffic efficiency.



(a) (b)

Figure 4.14. (a) Unmanaged, (b) managed case density heatmaps of the scenario simulated on the Network #2 and created with a traffic demand of 1250 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 40%.

In Figure 4.16, the density heatmaps of 0%, 40% and 80% CAV penetration rate cases considering the managed scenario created with a traffic demand of 1400 vehicle/hour/lane and an incident duration of 900 seconds are given. Analyzing these heatmaps, it is possible to say that as the CAV penetration rate increases, the size of the area having high density values decreases. Therefore, the efficiency of the implemented C-ITS incident management method increases with increasing CAV penetration rate.

In Figure 4.17, density vs. time plots of both managed and unmanaged cases are present considering the scenarios created with a traffic demand of 1400 vehicle/hour/lane and an incident duration of 900 seconds. As it is seen, density plots of different CAV penetration rates are given in the graphs. Analyzing this figure, it is observed that at high CAV penetration rates, density values increase faster as

the incident takes place and recover faster after the incident is concluded in the unmanaged case. However, in the managed case, at 60% CAV penetration rate, density values increase later than other penetration rates. This indicates an increase in traffic efficiency. Thus, it is possible to say that the C-ITS incident management method increases the traffic efficiency aspect of 60% CAV penetration rate case.

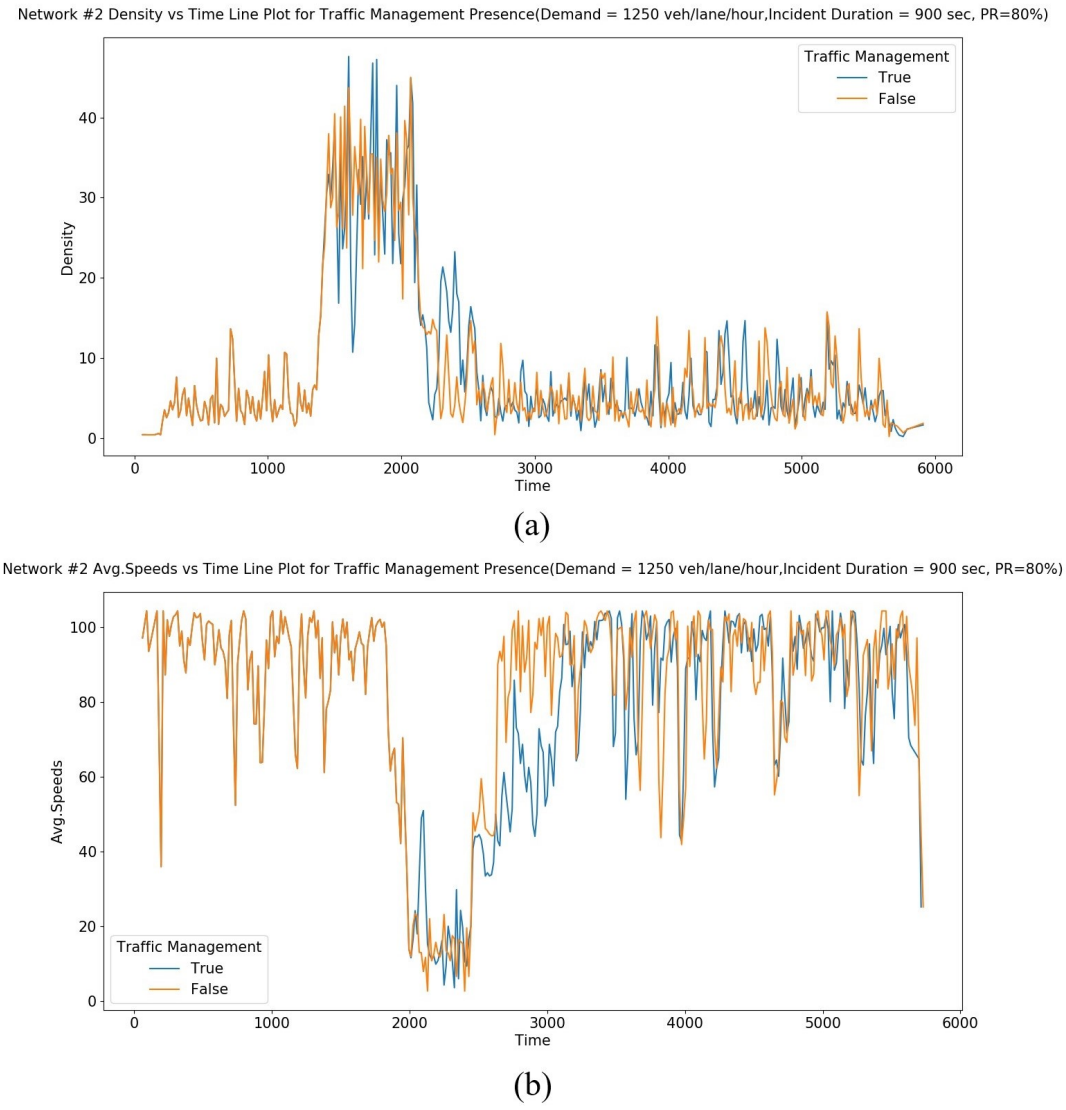
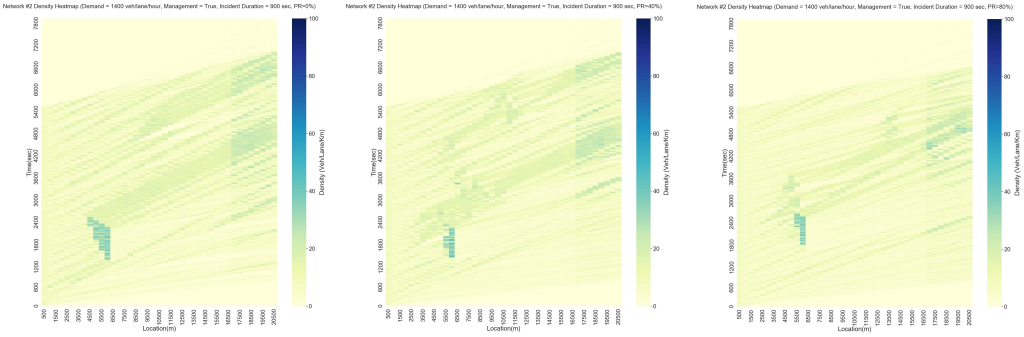
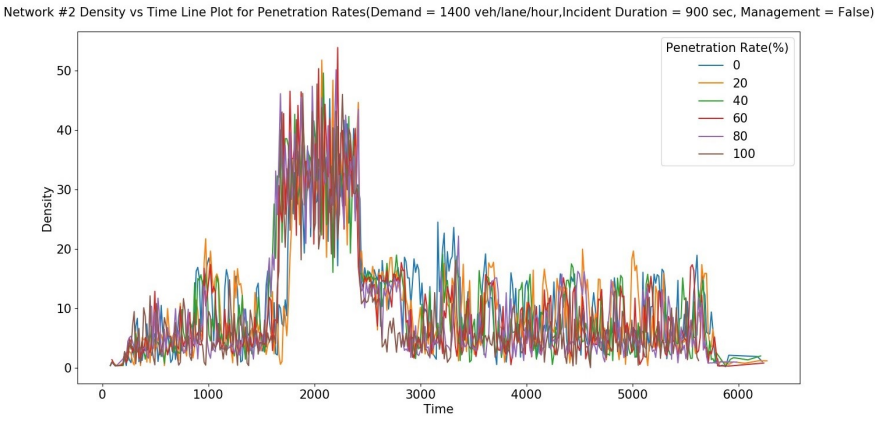


Figure 4.15. (a) Density vs. time, (b) average speed vs. time plots comparing managed and unmanaged cases of the scenario simulated on the Network #2 and created with a traffic demand of 1250 vehicle/hour/lane, an incident duration of 900 seconds and a CAV penetration rate of 80%.

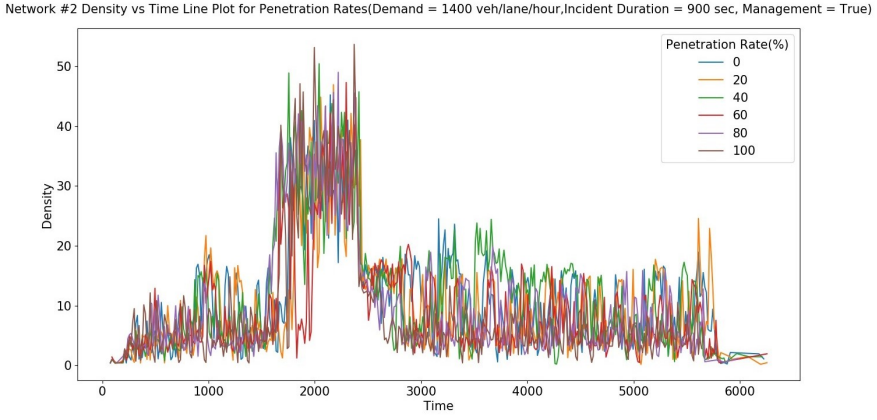


(a) (b) (c)

Figure 4.16. (a) 0%, (b) 40%, (c) 80% CAV penetration rate density heatmaps of the managed scenario simulated on the Network #2 and created with a traffic demand of 1400 vehicle/hour/lane and an incident duration of 900 seconds.



(a)



(b)

Figure 4.17. (a) Unmanaged, (b) managed case density vs. time plots comparing different CAV penetration rates of the scenario simulated on the Network #2 and created with a traffic demand of 1400 vehicle/hour/lane and an incident duration of 900 seconds.

5. CONCLUSION

In this thesis, a novel incident management method is created by integrating the C-ITS scenario, named "Slow or Stationary Vehicle Warning" with CAVs. The working principle of the method is to control the speeds of CAVs in the presence of an incident. By doing so, traffic safety and efficiency aspects are aimed to be increased. To be able to evaluate and analyze the created C-ITS incident management method, simulation studies are conducted on SUMO Simulation Software. In order to thoroughly analyze the method, different simulation scenarios are created using various scenario variables, namely simulation networks, traffic demands, CAV penetration rates and incident durations. Simulations are carried out on two different networks. The Network #1 is a 10.4 kilometers long continuous network, which does not include any ramp or bottleneck sections. The Network #2 is a 20.4 kilometers long network at which one ramp and one bottleneck section are present. To be able to determine the traffic demands to be given to the networks, capacity analysis is conducted through the data collected from preliminary simulations, which does not include CAVs and incidents. For the Network #1, 1800 and 2400 vehicle/hour/lane traffic demands are used, whereas for the Network #2, 1250 and 1400 vehicle/hour/lane traffic demands are used. At each network, 6 different CAV penetration rates are used, which are 0%, 20%, 40%, 60%, 80% and 100%. Since this method is an incident management method, incidents are created in simulation studies. 3 different incident durations are used, which are 300 seconds, 600 seconds, and 900 seconds. Combining these variables, 144 scenarios are created in total.

To be able to simulate these scenarios, necessary simulation modelling, including networks, sensors, and vehicle types, is done. Initially, the Network #1 and the Network #2 are modelled using the built-in program of SUMO Simulation Software named NetEdit. After modelling the networks, sensor modelling, and vehicle type modelling is completed. In this thesis, two different vehicle types are used, which are human-driven vehicles and CAVs. After modelling these components, created scenarios are run with 3 different seeds, making 432 simulation runs in total.

After the simulations of the scenarios are completed, the collected data is visualized, and the C-ITS incident management method is evaluated. According to the simulation results, this incident management method decreased average densities and increased average speeds considering the whole network. This indicates an increase in traffic efficiency. However, when the data collected from only the incident region is analyzed, average densities and average speeds both decreased in the Network #1. This shows an increase in traffic safety since the number of vehicles in the incident region decreases and the vehicles located in this region move slowly.

Comparing the results collected from each network based on CAV penetration rates, the optimum CAV penetration rate at which the C-ITS incident management method shows the best performance is seen to be 60%. Considering the results of Network #1, densities recover faster after the incident is over at 60% CAV penetration rate in the managed case compared to unmanaged case. Also, analyzing the results of the Network #2, it is observed that at 60% CAV penetration rate, density values increase later than other CAV penetration rate cases. This supports the outcome of 60% CAV penetration rate being the optimum rate for each network.

It is also observed that this management method decreases the length of queues originating due to incidents. This improvement enhances with increasing CAV penetration rate. On the other hand, analyzing the density heatmaps of managed cases, the size of the areas, where high density values are observed, decreases as the CAV penetration rate increases. This indicates an increase in traffic efficiency and safety since the number of vehicles located in the incident region decreases.

Considering the average speed vs. time plots, created using the data collected from the sensor, which is closest to the incident location, the C-ITS incident management method is seen to be decreasing the average speed values further compared to unmanaged cases. The reason for this is that CAVs are controlled and slowed down by the incident management method. However, the density vs. time plots reveal that densities do not increase in proportion with the decreasing average speeds in the managed case. This indicates an increase in safety and a slight reduction in throughput.

In addition to the results acquired from the simulation studies, there are also various policy implications related to the implementation of the C-ITS incident management method analyzed in this thesis. Since CAVs are utilized in the application of the management method, and legislations related to the accountability of these vehicles in traffic accidents are not fully constituted, legislative works on CAVs need to be completed before putting this incident management method into practice. On the other hand, C-ITS implementations are prone to creating traffic safety risks in the presence of late, false, or manipulated informative services. Thus, authorities responsible for monitoring and inspecting the deployment phase should determine a set of requirements related to the communication technologies used, which should contain clauses on cyber security, latency, speed, and coverage.

On the other hand, even though the examined C-ITS incident management method is evaluated to be beneficial in terms of increased traffic efficiency and safety, the limitations related to this study may affect the generalizability and applicability of the method. Initially, even if the used vehicle type characteristic parameter values are close to reality, it is impossible to model each vehicle type fully realistically. This limitation can be averted once real-life applications using the C-ITS incident management method take place. Also, there are different assumptions of the thesis related to the used communication technologies such as vehicles being able to receive information instantly and communication technologies working continuously. Thus, the applicability of the C-ITS incident management method must be assessed in real-life with the current communication technologies.

There are numerous other C-ITS scenarios except the one used in the implemented C-ITS incident management method, named “Slow or Stationary Vehicle Warning”. For future works, other C-ITS scenarios can be integrated into the management method and the extent of the study can be improved further.

REFERENCES

1. Buch, T., S. Hamann, A. Niebuhr and A. Rossen, "What Makes Cities Attractive? The Determinants of Urban Labour Migration in Germany", *Urban Studies*, Vol. 51, No. 9, pp. 1960–1978, 2013.

2. Ramanathan, R., "Link Between Population and Number of Vehicles", *Cities*, Vol. 17, No. 4, pp. 263–269, 2000.

3. Samal, S. R., P. Gireesh Kumar, J. Cyril Santhosh and M. Santhakumar, "Analysis of Traffic Congestion Impacts of Urban Road Network Under Indian Condition", *IOP Conference Series: Materials Science and Engineering,* India, Vol. 1006, No. 1, p. 012002, 2020.

4. Afrin, T. and N. Yodo, "A Survey of Road Traffic Congestion Measures Towards a Sustainable and Resilient Transportation System", *Sustainability*, Vol. 12, No. 11, p. 4660, 2020.

5. Amiri, H. and H. Li, "Paper the Resilience of ITS: Variable Message Signs Contribution to Road Network Resilience Under Incident and High Congestion Conditions: A State of the Art Review", *World Journal of Engineering and Technology*, Vol. 10, No. 01, pp. 1–27, 2022.

6. Farrag, S., M. Y. El-Hansali, A. Yasar and E. M. Shakshuki, "Simulation-Based Evaluation of Using Variable Speed Limit in Traffic Incidents", *Procedia Computer Science*, Vol. 175, pp. 340–348, 2020.

7. Zhang, Y., M. Quinones-Grueiro, W. Barbour, C. Weston, G. Biswas and D. Work, "Quantifying the Impact of Driver Compliance on the Effectiveness of Variable Speed Limits and Lane Control Systems", *2022 IEEE 25th International Conference on Intelligent Transportation Systems (ITSC),* China, pp. 3638–3644, 2022.

8. Maaloul, S., H. Aniss, M. Kassab and M. Berbineau, "Classification of C-ITS Services in Vehicular Environments", *IEEE Access*, Vol. 9, pp. 117868–117879, 2021.

9. Faiz, S., N. Achir and K. Boussetta, "On the Benefits of Increased Vehicles Perception to Cooperative Communications: A Performance Evaluation Study", *Proceedings of the ACM MobiArch 2020 The 15th Workshop on Mobility in the Evolving Internet Architecture,* United States, pp. 16–21, 2020.

10. Lang, N., M. Rüssmann, T. Dauner, S. Komiya, X. Mosquet, X. Doubara and A. Mei-Pochtler, "Self-Driving Vehicles, Robo-Taxis, and the Urban Mobility Revolution", 2016, https://www.bcg.com/publications/2016/automotive-public-sector-self-driving-vehicles-robo-taxis-urban-mobility-revolution, accessed on December 15, 2023.

11. Li, S., S. Edwards, M. O. Isik, Y. Zhang and P. T. Blythe, "Qualitative Examination of Cooperative-Intelligent Transportation Systems in Cities to Facilitate Large-Scale Future Deployment", *Sensors*, Vol. 22, No. 21, p. 8423, 2022.

12. Group, C.-I. D., "With C-ITS Towards Safer Roads in Europe", 2021, https://c-its-deployment-group.eu/news-events/news/2021-06-04-c-roads-saferoads/, accessed on December 17, 2023.

13. Malone, K. M. and A. M. Soekroella, "Estimating Benefits of C-ITS Deployment, When Legacy Roadside Systems are Present", *IET Intelligent Transport Systems*, Vol. 13, No. 5, pp. 915–924, 2019.

14. Koźlak, A. and D. Wach, "Causes of Traffic Congestion in Urban Areas. Case of Poland", *SHS Web of Conferences,* Poland, Vol. 57, No. 01019, p. 9, 2018.

15. Onyeneke, C., "Modeling the Effects of Traffic Congestion on Economic Activities - Accidents, Fatalities and Casualties", *Biomedical Statistics and Informatics*, Vol. 3, No. 2, p. 7, 2018.

16. Charpentier, V., N. Slamnik-Krijestorac and J. Marquez-Barja, "Latency-Aware C-ITS Application for Improving the Road Safety with CAM Messages on the Smart Highway Testbed", *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS),* United States, pp. 1–6, 2022.

17. Botte, M., L. Pariota, L. D'Acierno and G. N. Bifulco, "C-ITS Communication: An Insight on the Current Research Activities in the European Union", *International Journal of Transportation Systems*, Vol. 3, pp. 52–63, 2018.

18. Kang, J., S. Tak and S. Park, "Analyzing the Impact of C-ITS Services on Driving Behavior: A Case Study of the Daejeon–Sejong C-ITS Pilot Project in South Korea", *Sustainability*, Vol. 15, No. 16, p. 12655, 2023.

19. Ko, J., J. Jang and C. Oh, "Assessing the Safety Benefits of In-Vehicle Warning Information by Vehicle Interaction Analysis in C-ITS Environments", *Journal of Korean Society of Transportation*, Vol. 39, No. 1, pp. 1–13, 2021.

20. Rämä, P. and S. Innamaa, "Safety Assessment of Local Cooperative Warnings and Speed Limit Information", *IET Intelligent Transport Systems*, Vol. 14, No. 13, pp. 1769–1777, 2020.

21. Mitsakis, E. and A. Kotsi, "Costs and Benefits of Bundled C-ITS Services. The C-MobILE Approach", *Smart Cities and Mobility as a Service International Conference,* Greece, pp. 1–8, 2017.

22. Englund, C., L. Chen and A. Voronov, "Cooperative Speed Harmonization for Efficient Road Utilization", *2014 7th International Workshop on Communication Technologies for Vehicles (Nets4Cars-Fall),* United States, pp. 19–23, 2014.

23. Mai, T., R. Jiang and E. Chung, "A Cooperative Intelligent Transport Systems (C-ITS)-Based Lane-Changing Advisory for Weaving Sections", *Journal of Advanced Transportation*, Vol. 50, No. 5, pp. 752–768, 2016.

24. Portal, C. U. M., "Green Light Optimal Speed Advisory (GLOSA)", 2021, https://co-ump.eu/glosa/, accessed on December 18, 2023.

25. Olaverri-Monreal, C., J. Errea-Moreno and A. Díaz-Álvarez, "Implementation and Evaluation of a Traffic Light Assistance System Based on V2I Communication in a Simulation Framework", *Journal of Advanced Transportation*, Vol. 2018, pp. 1–11, 2018.

26. Lv, W., Y. Hu, E. Li, H. Liu, H. Pan, S. Ji, T. Hayat, A. Alsaedi and B. Ahmad, "Evaluation of Vehicle Emission in Yunnan Province from 2003 to 2015", *Journal of Cleaner Production*, Vol. 207, pp. 814–825, 2019.

27. Yüksel, S. and A. Mikhaylov, *Clean Energy Investments for Zero Emission Projects - The Effect of the Carbon Tax to Minimize Emission*, pp. 1–11, Springer International Publishing, Germany, 2022.

28. Tägtström, N., *Impact of C-ITS on Mobility and Society*, Ph.D. Thesis, KTH Royal Institute of Technology, Sweden, 2023.

29. Edwards, S., G. Hill, P. Goodman, P. Blythe, P. Mitchell and Y. Huebner, "Quantifying the Impact of a Real World Cooperative-ITS Deployment Across Multiple Cities", *Transportation Research Part A: Policy and Practice*, Vol. 115, pp. 102–113, 2018.

30. Pariota, L., L. D. Costanzo, A. Coppola, C. D'Aniello and G. N. Bifulco, "Green Light Optimal Speed Advisory: A C-ITS to Improve Mobility and Pollution", *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe),* Italy, pp. 1–6, 2019.

31. Tavassoli Hojati, A., L. Ferreira, S. Washington, P. Charles and A. Shobeirinejad, "Modelling the Impact of Traffic Incidents on Travel Time Reliability", *Transportation Research Part C: Emerging Technologies*, Vol. 65, pp. 49–60, 2016.

32. Islam, M. A., "A Literature Review on Freeway Traffic Incidents and Their Impact on Traffic Operations", *Journal of Transportation Technologies*, Vol. 09, No. 04, pp. 504–516, 2019.

33. Kaddoura, I. and K. Nagel, "Using Real-World Traffic Incident Data in Transport Modeling", *Procedia Computer Science*, Vol. 130, pp. 880–885, 2018.

34. Dia, H., W. Gondwe and S. Panwai, "Traffic Impact Assessment of Incident Management Strategies", *2008 11th International IEEE Conference on Intelligent Transportation Systems,* China, pp. 441–446, 2008.

35. Wirtz, J. J., J. L. Schofer and D. F. Schulz, "Using Simulation to Test Traffic Incident Management Strategies: The Benefits of Preplanning", *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1923, No. 1, pp. 82–90, 2005.

36. Popescu, O., S. Sha-Mohammad, H. Abdel-Wahab, D. C. Popescu and S. El-Tawab, "Automatic Incident Detection in Intelligent Transportation Systems Using Aggregation of Traffic Parameters Collected Through V2I Communications", *IEEE Intelligent Transportation Systems Magazine*, Vol. 9, No. 2, pp. 64–75, 2017.

37. Farrag, S. G., F. Outay, A. U.-H. Yasar, D. Janssens, B. Kochan and N. Jabeur, "Toward the Improvement of Traffic Incident Management Systems Using Car2X Technologies", *Personal and Ubiquitous Computing*, Vol. 25, No. 1, pp. 163–176, 2020.

38. Elhenawy, M., A. Bond and A. Rakotonirainy, "C-ITS Safety Evaluation Methodology Based on Cooperative Awareness Messages", *2018 21st International Conference on Intelligent Transportation Systems (ITSC),* United States, pp. 2471–2477, 2018.

39. Agriesti, S. A. M., L. Studer, G. Marchionni, P. Gandini and X. Qu, "Roadworks Warning—Closure of a Lane, the Impact of C-ITS Messages", *Infrastructures*,

Vol. 5, No. 3, p. 27, 2020.

40. Khoury, M. A. and F. A. Hussein, "Efficiency and Safety: The Impact of Autonomous Controls on Transportation", *International Journal of Information and Cybersecurity*, Vol. 7, No. 1, pp. 13–39, 2023.

41. Kyriakidis, M., J. C. F. de Winter, N. Stanton, T. Bellet, B. van Arem, K. Brookhuis, M. H. Martens, K. Bengler, J. Andersson, N. Merat, N. Reed, M. Flament, M. Hagenzieker and R. Happee, "A Human Factors Perspective on Automated Driving", *Theoretical Issues in Ergonomics Science*, Vol. 20, No. 3, pp. 223–249, 2017.

42. Lu, Q., T. Tettamanti, D. Hörcher and I. Varga, "The Impact of Autonomous Vehicles on Urban Traffic Network Capacity: An Experimental Analysis by Microscopic Traffic Simulation", *Transportation Letters*, Vol. 12, No. 8, pp. 540–549, 2019.

43. Gueriau, M. and I. Dusparic, "Quantifying the Impact of Connected and Autonomous Vehicles on Traffic Efficiency and Safety in Mixed Traffic", *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC),* Greece, IEEE, 2020.

44. Talebpour, A. and H. S. Mahmassani, "Influence of Autonomous and Connected Vehicles on Stability of Traffic Flow", *Transportation Research Board 94th Annual Meeting,* United States, p. 16, 2015.

45. Oncu, S., J. Ploeg, N. van de Wouw and H. Nijmeijer, "Cooperative Adaptive Cruise Control: Network-Aware Analysis of String Stability", *IEEE Transactions on Intelligent Transportation Systems*, Vol. 15, No. 4, pp. 1527–1537, 2014.

46. Samimi Abianeh, A., M. Burris, A. Talebpour and K. Sinha, "The Impacts of Connected Vehicle Technology on Network-Wide Traffic Operation and Fuel Consumption Under Various Incident Scenarios", *Transportation Planning and Tech-*

nology, Vol. 43, No. 3, pp. 293–312, 2020.

47. Yue, W., C. Li, S. Wang, N. Xue and J. Wu, "Cooperative Incident Management in Mixed Traffic of CAVs and Human-Driven Vehicles", *IEEE Transactions on Intelligent Transportation Systems*, Vol. 24, No. 11, pp. 12462–12476, 2023.

48. Naranjo, J. E., F. Jimenez, A. Gomez, A. Valle, J. Gonzalez and A. Cruz, "Integration of C-ITS in Autonomous Driving", *2020 IEEE Intelligent Vehicles Symposium (IV),* United States, pp. 27–32, IEEE, 2020.

49. Portal, C. U. M., "Why C-ITS?", 2021, https://co-ump.eu/why-c-its/, accessed on December 22, 2023.

50. Jaiswal, S. and F. Shaikh, "Infrastructure to Enable Connected Vehicles", 2021, https://www.telematicswire.net/infrastructure-to-enable-connected-vehicles/, accessed on December 22, 2023.

51. Costandoiu, A. and M. Leba, "Convergence of V2X Communication Systems and Next Generation Networks", *IOP Conference Series: Materials Science and Engineering,* Bosnia and Herzegovina, Vol. 477, p. 012052, 2019.

52. Maglogiannis, V., D. Naudts, S. Hadiwardoyo, D. van den Akker, J. Marquez-Barja and I. Moerman, "Experimental V2X Evaluation for C-V2X and ITS-G5 Technologies in a Real-Life Highway Environment", *IEEE Transactions on Network and Service Management*, Vol. 19, No. 2, pp. 1521–1538, 2022.

53. Sattiraju, R., D. Wang, A. Weinand and H. D. Schotten, "Link Level Performance Comparison of C-V2X and ITS-G5 for Vehicular Channel Models", *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring),* Belgium, pp. 1–7, 2020.

54. Haque, K. F., A. Abdelgawad, V. P. Yanambaka and K. Yelamarthi, "LoRa Architecture for V2X Communication: An Experimental Evaluation with Vehicles on the Move", *Sensors*, Vol. 20, No. 23, p. 6876, 2020.

55. Asselin-Miller, N., M. Biedka, G. Gibson, F. Kirsch, N. Hill, B. White and K. Uddin, *Study on the Deployment of C-ITS in Europe: Final Report*, Technical Report, Ricardo Energy & Environment, United Kingdom, 2016.

56. Consortium, C. . C. C., *Guidance for Day 2 and Beyond Roadmap*, Technical Report, CAR 2 CAR Communication Consortium, Germany, 2021.

57. Motamedidehkordi, N., M. Margreiter and T. Benz, "Shockwave Suppression by Vehicle-to-Vehicle Communication", *Transportation Research Procedia*, Vol. 15, pp. 471–482, 2016.

58. May, A. D., *Traffic Flow Fundamentals*, Prentice Hall, New Jersey, 1990.

59. Gokasar, Ilgın, "Baglı Otonom Araclarla Kesintisiz Trafik Akımında Kaza-Olay Yonetimi", https://www.tubitak.gov.tr/en, 2022, hibe Numarasi: 120M574, TUBITAK 2. Ara Rapor.

60. SUMO, "SUMO User Documentation", https://sumo.dlr.de/docs/index.html, accessed on December 25, 2023.

61. Krauss, S., *Microscopic Modeling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics*, Technical Report, German Aerospace Center, Germany, 1998.

62. Brockfeld, E., R. D. Kühne and P. Wagner, "Calibration and Validation of Microscopic Models of Traffic Flow", *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1934, No. 1, pp. 179–187, 2005.

63. Brockfeld, E. and P. Wagner, "Testing and Benchmarking of Microscopic Traffic Flow Models", *WCTR04 - 10th World Conference on Transport Research,* Turkey, pp. 775–776, 2002.

64. Wegener, A., M. Piórkowski, M. Raya, H. Hellbrück, S. Fischer and J.-P. Hubaux, "TraCI: An Interface for Coupling Road Traffic and Network Simulators", *Proceedings of the 11th Communications and Networking Simulation Symposium,* Canada,

pp. 155–163, 2008.

65. Krajzewicz, D., E. Brockfeld, J. Mikat, J. Ringel, C. Feld, W. Tuchscheerer, P. Wagner and R. Woesler, "Simulation of Modern Traffic Lights Control Systems Using the Open Source Traffic Simulation SUMO", *3rd Industrial Simulation Conference 2005,* Germany, pp. 299–302, 2005.

66. Barbecho Bautista, P., L. Urquiza-Aguiar and M. Aguilar Igartua, "Evaluation of Dynamic Route Planning Impact on Vehicular Communications with SUMO", *Proceedings of the 23rd International ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems,* Spain, pp. 27–35, 2020.

67. Lu, Q., T. Tettamanti, D. Hörcher and I. Varga, "The Impact of Autonomous Vehicles on Urban Traffic Network Capacity: An Experimental Analysis by Microscopic Traffic Simulation", *Transportation Letters*, Vol. 12, No. 8, pp. 540–549, 2019.

68. Song, J., Y. Wu, Z. Xu and X. Lin, "Research on Car-Following Model Based on SUMO", *The 7th IEEE/International Conference on Advanced Infocomm Technology,* China, pp. 47–55, 2014.

69. Ibrahim, A., M. Cicic, D. Goswami, T. Basten and K. H. Johansson, "Control of Platooned Vehicles in Presence of Traffic Shock Waves", *2019 IEEE Intelligent Transportation Systems Conference (ITSC),* New Zealand, pp. 1727–1734, 2019.

70. Do, W., O. M. Rouhani and L. Miranda-Moreno, "Simulation-Based Connected and Automated Vehicle Models on Highway Sections: A Literature Review", *Journal of Advanced Transportation*, Vol. 2019, pp. 1–14, 2019.