AUTONOMOUS VEHICLES: EVALUATION OF TRAFFIC MANAGEMENT STRATEGIES IN THE CASE OF AN INCIDENT

by

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ABSTRACT

AUTONOMOUS VEHICLES: EVALUATION OF TRAFFIC MANAGEMENT STRATEGIES IN THE CASE OF AN INCIDENT

Since the invention of the first automobile, many inventions and innovations relevant to the automobiles and automobile technologies have been made in the automotive sector. As the traffic congestion becomes a worldwide problem, many studies have been conducted to determine and improve the issues. Autonomous vehicle technology is a breakthrough idea of 2000's. Since the technology was invented, investments and developments on this subject are made continuously. Autonomous vehicles are expected to change the traffic models completely in the near future. In this thesis, it is aimed to determine the benefits and the disadvantages of autonomous vehicles where they are in a network under traffic management strategies in the case of an incident, which causes a lane to be closed for a given period. PARAMICS, the program used for the simulation model, is a microscopic traffic simulator that enables to input different calibration properties for vehicles and routes. A simulation model was specifically created for this research where Lane Control Signals (LCSs) at 2 different locations are present. It evaluates the average travel times and average speeds of the vehicles in the case of an incident for 90 different scenarios while also introducing autonomous vehicles into the system. In the simulation model, the best improvements are observed when the traffic demand is 3000 vehicle/hour for three lanes of the network. As the autonomous vehicle ratio changes from %0 to %100 on the network, without a LCS implementation, which is the best scenario, autonomous vehicles improve the average travel time by %20.26 and the average speed by %25.38. In the best scenario, where human-driven vehicles are evaluated only, LCS improves the average travel time by %16.05 and the average speed by %19.08. When LCS and autonomous vehicles are simultaneously introduced to the network, in the best scenario, which is also the best scenario among all the scenarios of the simulation model, the average travel time reduces by %21.33 and the average speed increases by %27.08.

ÖZET

SÜRÜCÜSÜZ ARAÇLAR: BİR TRAFİK KAZASI DURUMUNDA TRAFİK YÖNETİM STRATEJİLERİNİN DEĞERLENDİRİLMESİ

Dünyada ilk otomobil icat edildiğinden beri, arabalara ve araba teknolojilerine ilişkin birçok buluşlar ve inovasyonlar otomotiv sektöründe yapılmıştır. Trafik sıkışıklığının dünya çapında bir problem olması ile bu durumun sebeplerini gözlemlemek ve bu durumu geliştirmek için pek çok sayıda araştırma yapılmaktadır. Otonom araç teknolojisi 2000'li yılların en büyük buluş düşüncelerinden birisidir ve fikir ortaya atıldığından beri, bu konu üzerine yatırımlar ve geliştirmeler durmadan devam etmektedir. Otonom araçların yakın gelecekte trafik modellerini tamamen değiştirmesi beklenmektedir. Bu tezde, otonom araçların trafik yönetim stratejileri altında bulunan bir ağda bulunduğunda otonom araçların yararları ve dezavantajlarının belirlenmesi hedeflenmektedir Simülasyon modeli için kullanılan program, PARAMICS, araçların ve yolların farklı kalibre özelliklerinin girilmesini sağlayan bir mikroskobik trafik benzetim yazılımıdır. Bu araştırma için 2 farklı noktada Şerit Kontrol Sinyalleri bulunan bir benzetim modeli kurulmuştur. Bu model bir trafik kaza durumunda, ağa otonom araç katılımı sağlayarak, 90 farklı senaryo için araçların ortalama seyahat sürelerini ve hızlarını değerlendirmiştir. Simülasyon modelinde, en iyi iyileştirmeler trafik talebinin ağın üç şeridi için 3000 araç/saat olduğu durumda gözlemlenmiştir. ŞKS uygulaması olmadığı durumlarda, otonom araç oranı %0'dan %100'e doğru değiştikçe, en iyi otonom araç senaryosunda, otonom araçlar ortalama seyahat süresini %20.26 oranında ve ortalama hızı %25.38 oranında iyileştirmiştir. Otonom araçların bulunmadığı en iyi senaryoda, ŞKS ortalama seyahat süresini %16.05 ve ortalama hızı %19.08 oranında iyileştirmiştir. ŞKS ve otonom araçlar aynı anda ağa tanıtıldığında, aynı zamanda benzetim modelinin tüm senaryolarının en iyi senaryosu olan en iyi ŞKS ve otonom araç senaryosunda, ortalama seyahat süresi %21.33 oranında azalmıştır ve ortalama hız %27.08 oranında artmıştır.

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LIST OF ABBREVIATIONS

ACC	Adaptive Cruise Control
AGV	Autonomous Ground Vehicle
AV	Automated Vehicle
AVs	Automated Vehicles
CAVs	Connected and Autonomous Vehicles
CV	Connected Vehicle
CVs	Connected Vehicles
EBA	Emergency Break Assist
LGS	Lane Guard System
LCS	Lane Control System
PCE	Passenger Car Equivalent
VSL	Variable Speed Limit

1. INTRODUCTION

There have been many developments in the production technologies and important innovative breakthroughs since the invention of automobiles. The consumers have been introduced with different automobile concepts, such as driver-controlled automobiles with active support systems (e.g. Emergency Brake Assist-EBA, Adaptive Cruise Control-ACC and Lane Guard System-LGS), hybrid electric vehicles, and driverless (autonomous) automobiles. The latest and one of the most innovative progresses in the automotive field is the autonomous automobile progression, which is a recent developed technology [1]. Several major companies made investments in this field [2]. These autonomous cars are also called self-driving vehicles, driverless vehicles or robotic vehicles [3].

Autonomous vehicles can travel on roads without the need of a driver (control) by detecting the road, traffic flow and their surrounding by means of automatic control systems implemented on them. Technologies like radar, LIDAR, GPS, odometer and computer view, and some special techniques allow autonomous vehicles to detect the objects around them. First autonomous models were produced in 1980s [4]. Variety of automobiles were being manufactured which were controlled by driver intervention. Today vehicles have begun to be designed as partially autonomous, as level of automation [5]. In this respect Society of Automotive Engineers (SAE) defined 5 stages for automation at automobiles [6].

Autonomous vehicles can detect dangerous situations in traffic quicker and act faster than humans. Therefore, it is expected some likelihood benefits such as an increase in capacity of roads and intersections, reduced numbers of road accidents, reduced travel time, as well as fuel and energy efficiency [7]. The other contributions of autonomous vehicles include freedom of travel for young and old people or people with physical disability [4]. In addition to these, the economic investments to transportation will shift direction since the need for new road infrastructures will lower, and new traffic models will be needed for autonomous vehicles [5]. However there are still doubts in people's minds due to the uncertainty of the interaction between autonomous and non-autonomous vehicles in the traffic. System failure and the risk of system hacking are some of the concerns. The economic affordability to buy and repair is also another public worry that needs to be solved when autonomous vehicles become more common [8].

A simulation study on comparable characteristic features of manned and autonomous cars by evaluating traffic management strategies (Lane Control Signals) is performed. As autonomous vehicles become more common in traffic, it is aimed to evaluate the impact of autonomous vehicles in a network by observing 90 scenarios in the case of an incident.

1.1. Problem Statement

The influence of autonomous vehicles to a section of a road network must be inspected in detail in order to use autonomous vehicles in traffic in the most efficient way. Also to have a solid solution for the traffic congestion problem, especially in case of an accident, the intelligent transportation system infrastructures between autonomous and human-driven vehicles must work in perfect harmony to be as effective as possible. To understand how these autonomous vehicles act in a network section, in the case of an accident where there are lane control signs, the study shows a significant evaluation.

1.2. Goal and Objectives

The main goal of the thesis is that in the light of the qualitative and quantitative data of features of autonomous vehicles, gathered by literature review, to find the benefits or the disadvantages of autonomous vehicles where they are in a network under traffic management strategies, in the case of an incident. Although, it is aimed to observe the contribution of autonomous vehicles, there are also several objectives to be researched in the study:

- Evaluating the impact of LCS, on the section of a road network with LCS, by observing the performance measures (average speed and travel time) of a road section under various scenarios.

- Evaluating the impact of autonomous vehicles, on the section of a road network without LCS, by observing the performance measures (average speed and travel time) of a road section such as under various scenarios.

- Evaluating the impact of autonomous vehicles, on the section of a road network with LCS, by observing the performance measures (average speed and travel time) of a road section under various scenarios.

1.3. Thesis Outline

In the introduction chapter, by giving prior knowledge on the subject the related concepts/terms are explained. Moreover, the scope of the research, its aim and objectives are explained, and a roadmap followed during the research is given.

In the second chapter, the literature is focused on the studies of autonomous vehicles and Lane Control Systems is reviewed. In the literature review, first aspect is to bring the findings about the comparable characteristic features, qualitative and quantitative data of autonomous vehicles with manned vehicles and then to show the current and simulated examples for the use of LCSs.

In the third chapter, autonomous cars are searched by concept/definition, content/scope, implementation stages, general properties, advantages and disadvantages of these cars. A theoretical background is also presented for LCS.

In the fourth chapter, a network is simulated in PARAMICS, a microscopic traffic simulation software package, to compare the section of a road networks' performance in the case of an incident that causes a lane to be closed for 20 minutes. By generating different scenarios, with include introducing autonomous vehicles and LCSs into the network separately and simultaneously; the effects of autonomous vehicles and LCSs on the network are evaluated.

2. LITERATURE REVIEW

2.1. Autonomous Vehicles

Many researchers develop real AVs based on behaviors [5]. Efforts on developing AVs continue today, as the wireless connectedness studies in different technology areas has come to a great level. Wireless connection technology supports the development in the area of connected vehicle technology and changes the direction of autonomous vehicles improvements. While initial studies on AVs focused on making these cars possible to operate without a driver, nowadays the efforts has shifted to increasing the level of autonomous driving which currently rose to upper levels (Level 4 and Level 5). As the researches have reached to these levels, they show us that in near future autonomous (driverless) vehicles will take part in traffic besides the manned cars [7]. However, because driverless cars are mainly at the idea stage, not used in every day lives and a recently developed technology, lower user acceptance to autonomous vehicles makes it difficult to conduct researches. In a study, by Van der Laan *et al.* (1997) it was stated that informative systems, which gives information to drivers without restricting their control, are most likely to be accepted rather than the systems, which restrict their control. On the other hand, in a public survey among 5000 respondents by Kyriakidis *et al.* (2014), it is found out that 69% of the respondents believe that autonomous vehicles will have 50% of the market share until 2050's, and also 33% of the respondents think that they would prefer using autonomous vehicles. In another research, by Schoettle and Sivak (2015), a questionnaire is prepared, and 505 licensed drivers in the U.S.A. are asked about their preferred level of automation and their concerns about self-driving vehicles. It is indicated that the most preferred level is no self-driving vehicle by 43.8%. While 40.6% preferred a partially automated car, and 15.6% of respondents preferred a completely self-driving car. It is also stated that 35.6% of the respondents are very concerned about the use of fully-automated vehicles, meanwhile 14.1% of the respondents are very concerned about the use of partially-automated vehicles. Relevant to this topic it's informed that research studies on the general opinions, concerns and acceptance of automated driving largely neglected systems at SAE Level 4 and 5 [5]. Since there is still time needed to achieve Level 4 and

Level 5 performances, in a study, by Isaac (2016), it is indicated that researchers do not think that autonomous vehicles will be presented on roads until 2025-2040. According to the estimates, Level 4 or 5 AVs will be at restricted usage in 2020s, and their wide usage will not be until the 2040s [13].

On the other hand, some studies focus on autonomous vehicle planning impacts. As it is predicted, AVs will have various impacts on transportation planning. In the period 2015-2025, it is expected that autonomous vehicles will become legal, so that it is required to prove that they function safe on public roads, by using data collected in the real tests. Between 2020 and 2040, as traffic density will grow due to the increase of autonomous vehicles and vehicle flow, it will be necessary to have such lanes for these connected vehicles. As autonomous vehicles will have several important impacts on traffic, there will also be several additional affects of autonomous vehicles until 2040s such as higher car sharing, and mobility for non-drivers. After 2040, until 2050s, it is expected that people with lower-income will have more chance of transportation with autonomous vehicles rather than public transportation, so that the need for the improvement of public transportation will decrease. In 2050-2060s period, traffic congestion is expected to decrease, so the need for planning new roads will be reduced. Meanwhile, since autonomous vehicles will replace human-driven vehicles, it will be important to plan the mixed traffic and then to follow with the restriction of human-driven vehicles [3].

In the related literature, some research studies have focused on performance expectancy from autonomous vehicles. Schoettle and Sivak (2014) analyzed public opinion (n=1,533) in the US, UK and Australia about the performance of autonomous vehicles, and found that respondents believe that autonomous vehicles will have an impact on crash reduction (70%), fewer emissions (64%) and fuel consumption (72%), improved traffic congestion (52%) or reduced travel time (57%). There are also concerns about riding AVs, as in a study by Kockelman *et al.* (2015), 347 respondents state that their concerns as equipment or system failure (50%), interactions to use self-driving vehicles (48%), and legal liability for drivers or owners (36%).

Besides performance expectancy, other determinants, such as socio-demographic features (gender, age, income, family situation e.g. number of children), trust, usability, predisposition or willingness to use new technologies, costs, willingness to pay, sensation seeking, pleasure, dominance, satisfaction, equity, social acceptability, and etc., can take effect on user acceptance. However the determinants of user acceptance of driverless vehicles are largely unknown. The determinants may be demographic, sociologic or originating from psychology and personality of an individual. Education level as a determinant factor is also influential on ability or willingness to use new technologies. Autonomous cars use connected technologies. It’s a newly developing area of technology. In relevance to tendency and willingness to use new technologies, according to a research conducted by HIS Automotive, it is estimated that the number of vehicles connected to the Internet worldwide will grow more than six times to 152 million until 2020 from 23 million in 2013 [15]. Therefore, the importance of tendency and ability of people to use new technologies will increase. The cost of AV cars will also be a significant influence on the opinion of the users. As it’s informed, various studies have estimated that shared autonomous vehicles will cost $0.20-0.40 per passenger-mile. Though, it is added that these are mostly lower-bound estimates that exclude some cost categories such as vehicle cleaning, administration and profits, use optimistic and occupancy assumptions, and ignore empty vehicle travel required for taxi services. It is ultimately stated that autonomous vehicle will increase carsharing and the cost range per vehicle-mile will be between $0.60-$1.00 including ownership, operation and administrative costs. For human-driven taxis, this cost range per vehicle-mile including ownership, ownership, operation and administration and labor costs is between $2.00-3.00 [3]. Determination of cost for these cars will depend to cost elements. So, cost factors gains importance. In the study, by Nordhoff et al. (2016), using the previous studies, Unified Theory of Acceptance and Technology Use (UTAUT), and Pleasure, Arousal and Dominance paradigm of effect (PAD) are linked together to create a conceptual model to explain, predict and develop user acceptance of autonomous vehicles.

All possible benefits expected from autonomous cars in a near future can be affected by user acceptance. In a survey, by Cox Automotive (2016), 2264 of U.S. residents between 12 and 64 years old stated the catalyst and barrier factors to purchase a fully autonomous vehicle (Level 5). The catalyst factors to buy an autonomous vehicle by the respondents are found out as; price in an affordable range (53%), proof of safety (51%), reduction of insurance rates (35%), chance to test for free (30%), tax breaks (28%), and standart autonomy in the desired vehicle (28%), respectively. On the other hand, respondents stated the barrier factors to purchase an autonomous vehicle as; high price to afford (50%), high cost of maintenance (48%), system failure (47%), system being hacked (44%), no switch option to take control (43%), belief of better driver ability (38%), concerns about interactions between AVs and human-driven vehicles (37%), connectedness failure (37%), and not feeling relaxed during the travel (27%) [16].

There are also studies of the impacts of autonomous vehicle on roads. In various ways the AVs can affect total vehicle travel. Relevant to their impacts on total vehicle travel trips, in many studies, since autonomous vehicles will make travels more suitable for more people, total travel trips are likely to increase. To avoid the increase of travel trips, specific demand management strategies such as higher road user fees may be implemented [3]. By researches made on this subject some estimations are shared. Trommer *et al.* (2016) used three different scenarios for three countries, U.S.A., Germany, and China, to project the use of autonomous vehicles in 2035, by taking the current and future trends of 2015 of these countries, and forecasted that the introduction of AVs into traffic are likely to increase total vehicle-kilometers travelled by 3-9% by 2035. There are several reasons for the increase of total vehicle travel trips. Since autonomous vehicles are driverless, passengers will be able to do what they want while traveling. Non-drivers, in a situation of being too young, old, disabled, lack of driver’s license and etc, will be able to travel, so this might increase travel demands by up to 11%. Besides these, less traffic congestion and costs will create more demand for travel. On the other hand, as car sharing and driverless-public transportation will be more common, people might decide to use their vehicles less and even not to own private vehicle. Also, autonomous vehicles might create an impact on pedestrian as reduced risks on walking [3].

Connectivity of autonomous vehicles is a developing technology to enable the vehicles to communicate to all the traffic conditions around them without any human contribution. There are four types to be improved for the connectivity of autonomous vehicles. AVs must always connect to the other vehicles in order to avoid any accident with them and also give the necessary reactions to maintain the flow. This technology is called V2V (Vehicle-to-Vehicle). AVs also must provide a connection to the environment of the network where they are moving, and it is called as V2I (Vehicle-to-Infrastructure).

These two improved and still being improved technologies of autonomous vehicles are considered as the differences comparing to human-driven vehicles. As the third connectedness, V2X (Vehicle-to-X) autonomous vehicles must also connect to others, such as the pedestrians and the bicyclists, in order to avoid any crash with them. Connection to 'Cloud' is indicated as getting information about traffic from a center by Internet and autonomous vehicle adapts their travels according to the information [18].

In a study, it is foreseen that these connectedness technology will change the existing traffic models. According to this assumption, since autonomous vehicles can interact with vehicles and environment, it is stated that new intersection concepts should be evaluated. Perception of autonomous vehicles compared to human-driven vehicles will be much higher at the intersections, and so the need for traffic lights and etc. will be less. Implementing new developed models considering autonomous vehicles will reduce travel times of trips. To create efficient intersections for autonomous vehicles, in the study, a simulation model is created. In the model, two policies at the intersections are introduced. First one is stated as "First Come, First Served" (FCFS), and it is implemented for the scenario where all the vehicles are autonomous. The second policy is described as FCFS-Light policy, and it is applied when there are also human-driven vehicles in the system. As a result of simulations, it is found out that for autonomous vehicles reservation system which avoids any stop when there is no cross-traffic reduces average delay compared to traffic light. It is also found out that if the policy is changed to FCFS-Light for human-driven vehicles, adoption of autonomous vehicles into the system reduces average delays at the intersection [7].

In a study of Abraham's (2015), the effect of autonomous vehicles for different percentages of autonomous vehicles on a straight road section is evaluated. In order to evaluate the impact, a model is simulated in MATLAB. In the simulation, it is aimed to observe the impact of Vehicle-to-Vehicle technology of autonomous vehicles. The comparable characteristic feature of autonomous vehicles is selected as reaction time, which is entered as 0 (zero) in the program, meanwhile for human-driven vehicles it is 0.8 s. It is found out that when 40% of total vehicles are autonomous vehicles on the network, traffic flow rate increases [19]. In a study by Le Vine *et al.* (2016), a model is simulated to show the efficiency of queue-discharge operations of autonomous vehicles at a signalized intersection. It is indicated that the required time for ten queued autonomous vehicles to pass the stop line is 25.4% lower than the time for human-driven vehicles' scenario. On the other hand, the results also showed that V2V communication which is able to allow the vehicles to move when the signal is green, the improvement in capacity is relatively lower compared to V2V communication which enables the vehicles to find alternative paths [20].

Autonomous vehicles' software will also adjust the speed and route of the vehicle accordingly by detecting the objects that appear on road with sensors, while vehicle is moving [21]. By shared information such as dangerous situations on roads and live traffic conditions, CAVs are able to optimize the speed of the car. As an example, when a dangerous situation occurs on the road, the car receives an instantaneous speed limit message. In the case of an autonomous vehicle, it is stated that in the simulations a virtual vehicle model behaves exactly same as a robotic vehicle in real life behaves, and the parameters to simulate a virtual vehicle are calculated using the robotic vehicle features. These features are such as acceleration rates, distances to decelerate, speed limits and suspension behavior [22]. Adaptive Cruise Control (ACC) technology, which is used in autonomous vehicles, also provides a safe following distance between vehicles by adjusting the speed of vehicle automatically [13]. Speed control, reducing or increasing speed, and threshold values determined for acceleration and deceleration momentums, is important in the case of AV's since dangers to walking, cycling and human-driven vehicles could occur. As it is informed, Level 5 AVs perform all driving functions on all normal road types, speed ranges and environmental conditions. However, some benefits like higher traffic speeds, reduced congestion and automated intersections require dedicated autonomous vehicle lanes [3]. Among the features of autonomous vehicles there is also driving at more consistent speeds, with less accelerating and braking [23]. Both acceleration and deceleration rate values of autonomous vehicles are determined by an upper and bottom threshold. For acceleration rate, the upper threshold (limit) as is 1,37 m/sec2 and the bottom threshold is 0,76 m/sec2; as for deceleration rate, the upper threshold is 3,35 m/sec2 and the bottom threshold is 1,83 m/sec2 for autonomous vehicles [24].

As it's known autonomous vehicles control vehicle steering, deceleration and acceleration [5]. In the related terminology autonomous vehicles are described as the vehicles during the operation of the vehicles, any direct driver input is necessary to control speed, acceleration and deceleration rates. Since there is no necessity of driver contribution during the travels, drivers do not have to keep track of vehicles and environment on the roadway. In the conducted researches on autonomous cars, it is found that slower acceleration and deceleration rates among autonomous cars may be required to enhance passenger comfort, but would lead the overall flow of the traffic to decrease [25]. As Le Vine *et al.* (2015) argued that for passengers who are more sensitive to comfort, to enjoy or to work during their travels than the drivers, autonomous vehicles should have slower acceleration and deceleration rates than human-driven vehicles. It is expected that the smooth speed changes of autonomous vehicles will reduce urban roadway capacity. In Level 1 AVs, human driver is assisted with either steering or acceleration/deceleration by the driver assistance system e.g. ACC. In Level 2 AVs driver assistance system undertakes steering and acceleration/deceleration using information about the driving environment, with the human driver performing all other tasks [22].

In a study, the interaction between occupant comfort and impact of it on capacity is are evaluated. To evaluate the interaction, 16 different scenarios where composition of traffic stream is 25% autonomous vehicles and 75% human-driven vehicles are compared to the baseline scenario where all the present vehicles on the network are human-driven vehicles. The scenarios are defined in two categories as High-Speed rail (HSR) and light rail transit (LRT) to observe how the passenger-comfort rate affects total delay and capacity at the intersection. Since acceleration and speed values are selected as lower for autonomous vehicles compared to human-driven vehicles, for both scenarios, it is observed that total delays are higher and capacities are lower at the intersection relatively to the baseline scenario. For light rail transit scenarios, which has higher acceleration and speed values for autonomous vehicles than High-Speed rail scenarios, total delays are lower and capacities are higher relatively to High-Speed rail scenarios. In the end, it is suggested that to achieve optimal results on occupant comfort and capacity, autonomous vehicles may have options which can be selected by passengers according to their comfort desire [26].

Just like manned cars, braking is among the main driving tasks in autonomous vehicles [6]. Braking is slowing down the vehicle by using a brake system or providing that the vehicle stopped. It is useful while a vehicle is under way to slow down its speed or stopping it; thereby is related with deceleration of vehicle and inversely related with acceleration of vehicle. The term deceleration means to lose speed after brake. When it's formulated; deceleration = speed/time; and by symbols a = v/t in m/s2. While (braking) deceleration is the term used for the reduction in speed, acceleration is the term used for the increase in speed [27]. As stated before, ACC allows a vehicle's cruise control system to adapt the vehicle's speed to the traffic environment. ACC system has a brake control module on it and decelerates the vehicle. The primary function of the brake control module is to determine vehicle speed via each wheel and to decelerate the vehicle by applying the brakes when requested by this module. Conversely ACC system also accelerates the vehicle by increasing the target speed sent to the engine control module. A radar system which is attached to the vehicles detects if a vehicle with a lower speed is on the path of the vehicle with the ACC system. When a slower vehicle is detected, ACC system decreases the speed of the vehicle and makes the vehicle move according to enough gap and time headway on the road. The system also enables to detect if the vehicle in front increases the speed and gets out of the path of the vehicle with ACC system. When it is detected, ACC system changes the speed of the vehicle unless it achieves the set cruise control speed. ACC vehicle is basically able to decelerate and accelerate according to traffic conditions by itself without any driver operation [28].

Previously the ACC system on AVs appropriate following distance between cars is provided [13]. In a study, by Le Vine *et al.* (2016), under set of parameters, autonomous vehicles' discharge at signalized intersections is simulated. Using scenario analysis, calculation of arc elasticities and Monte-Carlo methods, in the results it is observed that autonomous vehicles has following distance of 1,83m, max acceleration as 1,50 m/sec2 and max speeds as 13,9 m/h [29].

By causing a revolution in passenger car segment, autonomous automobiles seem to cause a big change in automotive sector. With the invention of future cars--the connected and autonomous cars--the need to clarify some related concepts become compulsory. A connectedness to a center of such type cars and from this center will be produced traffic information and making such an information use in the most efficient way also gains importance. By using technologies on connected and autonomous cars such a connectedness can be obtained. The mentioned connected car technologies will provide many benefits to car drivers, for instance safety on roads, reduced road accidents and deaths, reduced travel delay as well as fuel saving, etc. [30]. Autonomous vehicles will travel on roads by obeying the traffic rules [31]. Moreover, the autonomous vehicles are expected to have a positive impact on environment as well [25].

2.2. Lane Control Signals

Lane Control Signals (LCSs) is one of the traffic management technologies for managing lane use on freeways, by posting speed limits and vacating or changing a lane when necessary using a sign above each lane. It is accepted as one of the best solution for local incident management and is utilized all over the world. The drivers adapt to these systems and follow the signs that are displayed on the systems to improve their travel experiences [32]. In San Antonio, Lane Control Signals started to be used in late 1995 in traffic, and 80% of drivers has followed the signs to change their lanes while it was only 33% before LCSs [33].

The perception of the drivers spacing between lane control signals is an important parameter to consider. In an expert panel, consisting of personnel employed by TxDOT Districts and Divisions gathered by TTI Researchers, it was decided that the spacing between Lane Control Signals should be between 0.8 and 1.6 km, with the assumption of driver's perception to the status of lane is active in 30 to 60 seconds [34]. Three different performance measures; lane distribution, speed measurement, and in-vehicle driver responses can evaluate the effectiveness of the changeable message sign. In a case where the distance is 1.2 km in between, LCS got better lane distribution than the distance of 0.6 km. In the meantime, a reduction of speed at critical road locations approaching tapers was measured [35].

Simulations and studies are made in order to observe the advantages and shortcomings of these systems. In a simulation model of a network in California, an incident is created on the network, which closes a lane of the network. After the incident occurred, the impact of Lane Control Signals and Variable Speed Limit (VSL) control systems on this section were evaluated to observe the improvements on traffic mobility, safety and the environment. Although the average travel time was reduced by 27%, it was indicated that the bottleneck throughput is increased. Meanwhile, the number of stops was reduced by 81%, which is shown as the main contribution of lane change control [36]. In another study, where the same section is inspected, scenarios including lane control systems and variable speed limit control system are implemented separately; it was observed that when LCS is applied alone, the bottleneck discharge rate increased [37]. In another incident simulation of US290 was designed to see the impact of Changeable Lane Assignment System (CLAS) after an incident occurs for 7 different scenarios (1 AM, 3 mid-day and 3 PM). It was observed that except AM peak-period, CLAS improved the total delay, but it also showed that for some scenarios it might not help to improve the traffic flow [38].

In a study, 141 different scenarios were run to observe the impact of LCSs and it is found out that in the best scenario LCSs reduce the average travel times of vehicles by 16.76% and increase the mean speeds of vehicles by 20.19% in the case of an incident. On the network, there are two different dynamic tags. The first tag by a yellow arrow warns vehicles about the incident while the second tag, closer to the incident scene, by a red cross tells vehicles to change their lanes. The scenarios are selected to evaluate the importance of the locations of LCSs and the compliance rates to LCS. In the best scenario, the distance between the tags is 1123 m and the compliance rate of the vehicles to the tags is 30% and 100%, respectively [32].

3. THEORY

Autonomous vehicles and LCS are two different concepts, aimed to improve the current traffic conditions. An autonomous vehicle is a robotic technology, which is currently being developed, to avoid the failures of human drivers in traffic and to improve the conditions of passengers during travels. LCS is a dynamic signal feature on roads to regulate the existing traffic flow in cases where vehicles should be warned. In this chapter, these two concepts are theoretically reviewed.

3.1. Autonomous Vehicles

An autonomous car simply can be regarded as a robotic car. By robotic components and advanced technologies, an autonomous car can travel without any intervention by driver on roads. On the other hand, when it's encountered as an expression of autonomous vehicle, then a wide scope of vehicles are involved in it; such as trucks, buses and tractors [5] and other type possible vehicles. In general, vehicles that are able to drive partly or fully without human interaction are called autonomous [39]. In the literature an autonomous vehicle is defined and explained as follows;

- An autonomous vehicle is the vehicle that itself can move from one point to another without a driver intervention and remote control [7].
- An autonomous vehicle is fundamentally defined as a passenger vehicle that drives by itself [40].
- Autonomous vehicles are vehicles, which can drive themselves without human supervision or input.
- Autonomous vehicles can be defined as vehicles, which are controlled remotely by an operator, or autonomously operated. Autonomous vehicles are vehicles, which are capable of driving themselves. In order to do this, the vehicle must be able to perceive its environment, make decisions about where it is safe and desirable to move, and take action. It can also possible for a vehicle to be only partially

autonomous, so that some decisions are made by a human driver, and some by the vehicle itself [23].

- Broadly speaking, an autonomous vehicle is one equipped with technologies that facilitate aspects of its operations. Examples range from systems, which simply ease the driver’s task (such as self-parking) to self-driving vehicles that do not require a driver. This is the difference between automated-driver-assistance systems (ADAS) and the fully autonomous vehicle [21].

- As described by the Department for Transport’s (DfT) Code of Practice a fully autonomous vehicle is one in which a driver is not necessary. Which means that there will be people in the vehicle but they are not responsible for the driving [22].

An autonomous vehicle can travel on roads without need to a driver (control) by detecting the road, traffic flow and the surrounding by means of automatic control systems mounted on it.

In traffic an autonomous vehicle follows the traffic rules. Also due to the technologies mounted on and used by them, it can be foreseen that crashes will reduce in the traffic [4]. On autonomous vehicles some technologies like radar, LIDAR, GPS, odometer and computer view are mounted; in this way these vehicles can detect the road, objects and other vehicles on road, traffic flow and surrounding around them.

3.1.1. Some Terms Related to Autonomous Vehicles

Some associated terms related to autonomous vehicles, safety requirements, needed connected vehicle technologies, CVs, AVs and CAVs are explained in detail below.

3.1.1.1. Connected Vehicle Technologies for Vehicles. The reason why people need connected vehicles simply is safety, mobility and environment related requirements. On these vehicles, related connected vehicle technologies are present. By assistance of such technologies obtained benefits are as follows;

- Safety on roads,

- Reduced road accidents,
- Reduced death rates,
- Reduced travel delay,
- Green transportation,
- Efficient fuel usage.

Under the connected vehicle technologies safety on roads will increase, possible road accidents will be forecasted/detected beforehand and in this way the death rates in consequence of road accidents will be reduced. Connected vehicle mobility applications will enable car drivers to make smart choices for reducing travel delay. Also connected vehicle environmental applications will enable car drivers to make a green transportation choice by providing real time information to them with managing fuel using in the most efficient way [30].

As it is said, number of accidents will be reduced which may change the concept of vehicles. Traffic congestion reduction may lead to avoid maintenance costs and new infrastructure needs. As the vehicles will be robotics, travel time predictions will be much more accurate than the human-driven vehicles while passenger can be more productive during travels. As AV participation in traffic increase, it will lead to new business models such as new car ownership models and energy efficient and eco-friendly vehicles [41].

3.1.1.2. Connected and Autonomous Vehicles. AVs are defined as vehicles where aspects of a safety-critical control function such as steering, throttle control and braking will occur without direct driver input. Here defined AVs, is a developing technology. During the explanation of this technology it is pointed out that a vehicle with only driver safety warnings such as crash warning is not accepted as an autonomous vehicle. To be accepted as an autonomous vehicle, the vehicle should have also a control mechanism without any driver input need [42]. On the other hand, CVs are explained as vehicles that use any of a number of different communication technologies to communicate with the driver, other cars on the road (vehicle-to-vehicle [V2V]), roadside infrastructure (vehicle-to-infrastructure [V2I]), pedestrians, bicyclists (V2X) and vehicle to the "Cloud" [18]. The wireless technology is used on CVs. In this way additional safety is provided to vehicle and driver [43]. Like AVs this is a developing technology. Relevant to this technology it is asserted that it can be used to improve vehicle safety, and to improve vehicle efficiency and communication durations [44]. Technological capabilities of CVs are very large, for instance these vehicles will provide data for drivers that will give socially relevant information about people's behaviors in traffic [45].

AVs and CVs will change the traditional road transportation and the lifestyles of people. As it's reported AVs and CVs may improve safety, reduce emissions, and improve the efficiency and reliability of the transportation systems [46]. Relevant to these development areas, it is also pointed out that while the development of CVs and AVs is occurring largely independently, convergence of the two areas will be required to achieve full vehicle automation in the future [42]. On this two development areas, in the end CAVs come in sight. Progressions in the AVs area still continue today. In the coming years potential implementations can be seen.

AVs offer a partial or fully automated (i.e. autonomous) driving ability to drivers; and it is considered as the next innovation in the years to come [40]. AVs have got important features and superiorities within/on them. It is expected that in the near future AVs will communicate with each other, interact with smart infrastructure, drive themselves in traffic jams, highways, and park themselves [47]. Such superiorities of the AVs will attract people's attention to them and therefore they are coming with a loud noise. [7].

Together with these important inventions, however a general public acceptance and willingness to autonomous vehicles will be required to form in the society. It will be important to position these vehicles in the market. The results of recently made studies indicate that respondents expect fewer crashes as to be the primary benefit of autonomous vehicles [8]. Since it is expected that autonomous vehicles travel fairly (properly to the traffic rules) in the traffic [31]. Besides improving road safety, autonomous vehicles offer several other transportation changes, such as optimizing traffic flow, more efficient transportation, new mobility models, and additional comfort for drivers and passengers [45]. Such expectations of respondents on an autonomous vehicle are very important because these aspects will attract the population's attention and make them more inclined to accept the vehicles. In relation to acceptance, in the related literature Venkatesh *et al.* (2003) developed a unified model, called the Unified Theory of Acceptance and Use of Technology (UTAUT) [46]. It was formulated with four core determinants as of performance expectancy, effort expectancy, social influence and facilitating conditions [5].

There are several studies in the literature that searched user acceptance of driverless vehicles. For instance, Casley *et al.* (2013) searched and determined six key influences, which impact the desirability of autonomous cars, as three primary influences (safety, cost, and legal structure) and three secondary influences (productivity, efficiency, and environmental impact). In this study, following the data collection (by a conducted survey) and analyzation the researchers determined that although the secondary traits of autonomous cars were quite appealing, the primary influences were not acceptable. For this reason the researchers concluded that the technology and the laws regarding it must be further developed before the public is willing to accept this new car technology [2]. Nordhoff *et al.* (2016) developed a conceptual model that integrates a holistic and comprehensive set of variables to explain, predict and improve user acceptance of driverless vehicles. It is a five blocks and multiple components model. In this model there were external variables (socio-demographics, mobility characteristics, vehicle characteristics, contextual characteristics), psychological variables (locus of control, sensation seeking, trust), variables from the UTAUT (Unified Theory of Acceptance and Technology Use) model (performance expectancy, effort expectancy, social influence) the PAD framework (pleasure, arousal, dominance) and the acceptance construct (efficiency, effectiveness, equity, satisfaction, usefulness, willingness to pay, social acceptability, behavioral intention). Also this model assumed that there are relationships between the components of the model and between the variables within the components [5].

Concerning performance expectancy, in the literature, studies examine some advantages of automated vehicles relating to different dimensions of users' driving performance are traffic safety, productivity, traffic flow, and fuel and emission efficiency. Some other advantages or benefits of automated vehicles examined in the related literature mainly are crash reduction, improved traffic congestion or reduced travel time [5]. Here used term "automated" means that a vehicle is programmed to carry out specific tasks, using a predefined course of actions, in a set of known operating conditions [45]. In a study, Litman (2017) explored the impacts that autonomous vehicles will likely to have on travel demands and transportation planning, by exploring the benefits e.g. as independent mobility, reduced traffic and parking congestion, increased safety, energy conservation and pollution reduction, and also by regarding their costs [3]. Traveling by an automobile normally is perceived unsafe, costly and burdensome [8]. Herein traffic congestion is the most influential factor at perceiving it burdensome. However, it is expected that as the autonomous cars safety on roads will increase, the traffic congestion will be reduced. There is a relationship between road accidents and traffic congestion on roads. It's known that road accidents are one of the important causes of traffic congestion on roads [32]. Furthermore it is expected that autonomous cars will provide convenience, efficiency and increased mobility for some groups of society as well as economic benefits, and a positive impact on environment [25].

3.1.2. Advantages and Disadvantages of Autonomous Cars Compared to Manned Cars

Autonomous cars will provide some advantages to drivers. Advantages of autonomous cars can be summarized as follows;

- Increased safety on roads (by a capability to detect potential risks and accidents initially) [45],
- Reduced road accidents (by detecting potential risks and accidents initially and as a result of reduced traffic congestion) [32],
- In this way reduced death- and permanent disability events on roads,
- Avoiding human errors on roads [48].
- Reduced traffic congestion and optimized traffic flow (by informing the drivers on traffic flow, speed and lane status, and guidance), in this way,
- Reduced travel time and delays [5],
- More efficient transportation [45],

- Used connected and automated vehicle technologies on autonomous cars may improve the efficiency and reliability of the transportation system [46].
- Better accuracy in judging distance (btw the other cars) and velocities in traffic [7].
- New mobility models,
- Increased mobility, especially for the groups like young and old people or people with physical disability [4].
- Productivity,
- More productive in-vehicle time [47],
- Additional comfort for drivers and passengers [45],
- Convenience [25],
- Arriving somewhere on the dot,
- Less wasted time looking for parking [47],
- Reduced parking congestion,
- Fuel saving [30],
- Energy conservation [7]; it is informed that AVs using efficient, smooth acceleration will enable optimal energy use, and
- Reduced emissions [47],
- Pollution reduction [3].

On the other hand, there are some foreseen disadvantages of autonomous cars as well. Disadvantages of autonomous cars can be explained as follows;

- Equipment and system failures,
- Interactions with conventional vehicles,

- Affordability [8].

3.2. Lane Control Signals

Manual on Traffic Control Devices (MUTCD) defines Lane Control Signals (LCS) as regulatory signs. They are primarily used for closing lanes in order to effectively manage traffic incidents and work-zone areas in order to improve safety. LCSs are used to open/close lanes, restrict traffic (bus, truck etc.), limit the speed and signalize incident-lane. They are placed on acceleration-deceleration ramps, dangerous road sections, alternative bypass road exits, tunnels and toll plazas. Each LCS can be controlled as a standalone device or as part of a network that shares the same controller, power supply and communication unit. The controller and power supply unit can be located in a roadside cabinet with different interfaces that works for communication and integration control. It is composed of a green or a white arrow to indicate a lane is open and a red cross to indicate a lane is closed.

LCSs promptly close lanes during an incident that requires a lane closure to manage the safety of road users, crash victims and incident responders and to minimize the risk of secondary incidents, complementing traffic control during maintenance, changing lane allocations or functions during road works or incidents, and restricting lane use to facilitate safe enforcement operations where interception sites are provided this system achieves its goal.

LCS displays use variable speed limit (VSL) signs to advice speed limits too. VSL signs are used in order to decrease speed fluctuations of vehicles so that traffic flow is improved. A VSL sign’s objectives are to;

- Optimize traffic flow rates by managing operating speed and reducing probability of flow breakdown and congestion,

- Restore optimal flow rate as quickly as possible in case of congestion by adjusting operating speed of approaching and departing vehicles from the incident location,

- Improve safety and to prevent traffic flow breakdown by reducing speed difference between mainline traffic and entrance ramp traffic,
- Manage the traffic flow during poor weather or road conditions by reducing speed limit,
- Arrange the appropriate speed limit for present conditions [32].

In case of an incident, LCSs try to reduce backup queues by displaying the closed-lane and suggesting the use of open-lanes, which increases efficiency and safety. The system also comes into play when tough weather conditions and work zone areas are present. By providing information about the downstream to drivers, such as existence of an incident, a merging or crossroad, the drivers become aware and act accordingly. In the figure below a 4 lane LCS display is presented. The left-most display shows a red cross sign, which indicates a closed-lane and the speed limit signs advice drivers to maintain a speed below that value (Figure 3.1).

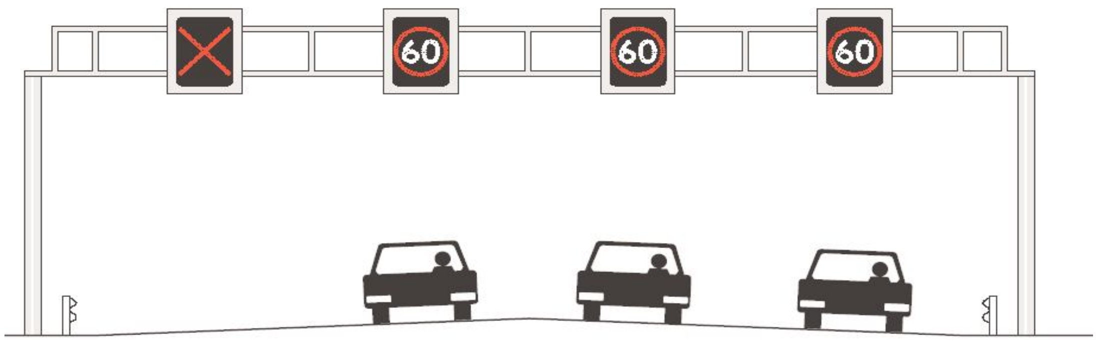

Figure 3.1. A 4-lane LCS display [50].

3.2.1. LCS Sight Distance Requirements

L is called the legibility distance, which is the distance where a driver begins to observe a LCS display, whereas R is called the reading distance, which is the distance where a driver is able to read a LCS display (TRUMM, 2010). The point which the driver can no longer read the display is defined by S*Cot(θ), where S is the height of the center of the display above the driver's eyes. θ angle is given as 5° for overhead mounted signs and 10° for side mounted signs. Figure 3.2 demonstrates the definitions on the sketch.

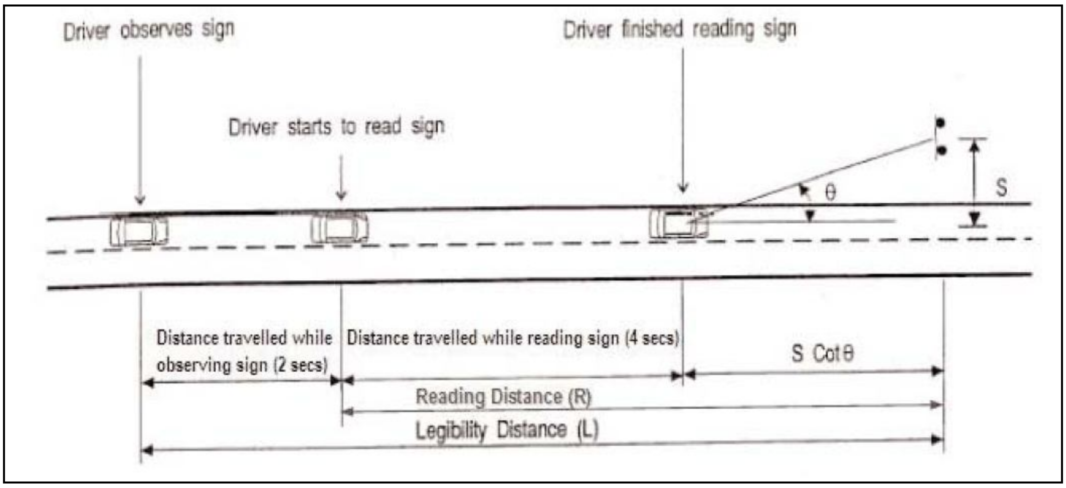

Figure 3.1. The legibility and reading distance of LCS [50].

It takes 2 seconds to read the sign and 4 seconds to recognize and understand the content, resulting in total of 6 seconds. For instance, a vehicle with 70 km/h speed would travel about 120 meters in 6 seconds.

3.2.2. LCS Spacing Requirements

Ramp spacing, location of other major driving decision point, available sight distance, and location of other information sources (guide signs, vms, etc.) are the criteria for the actual location of LCS, when legibility and spacing distances are considered. Cost considerations also do influence LCS locations. The expert decisions taken in a forum, assembled in Fort Worth/Texas in 1994 (FHWA, 1996), decided in principle that LCSs should be spaced between 0.8 up to 1.6 km apart to function adequately in urban areas.

3.2.3. LCS Mounting Requirements

The LCS displays must be visible and legible enough to compete with the other visual factors in the complex driving environments. Due to information sources such as VMS, guide signs and other distracting objects such as geometric features and certain structural elements, the visibility of LCS can suffer immensely. FHWA considers that a roadway information system is started to be an overload information system when it contains more than five information sources (FHWA, 1996). The laboratory research and field experience have both showed the importance of having entire LCS array visible for drivers so that they can evaluate the overall display and move to an appropriate lane if necessary (FHWA, 1996). A narrow LCS signal for wide urban freeways is a problematic example for a poor design. The LCS tag must include the following criteria (TRUMM, 2010):

- Minimum vertical clearance for heavy and oversize vehicles,
- A safety barrier if the overhead structure supports are located within the clear zone,
- In liaison with enforcement authorities, provision to mount and operate speed enforcement devices,
- Protection from vandalism and unwanted public access to equipment especially where signs are mounted on bridges with pedestrian access.

3.2.4. LCS Scenarios

LCS scenarios can be separated into three main categories:

- Congestion (1),
- Harsh weather conditions (e.g. snow, rain, fog) (2),
- Incident, work-zone and VSL (3).

The decision flow-chart in the figure below (Figure 3.3) is utilized when one or a combination of these categories are observed by the Traffic Control Center operators. The decision system checks potential conditions in the given order. If any of these conditions is detected, then the system activates the appropriate scenario to turn the traffic condition back to its normal status.

The LCS operators at the traffic control center are notified. They also focus on the problematic areas where there are sudden increases and decreases in real time traffic measurements. The LCS uses a software, which can work manually or automatically. Due to the automation logic it can be followed from the scenario chart. It is also important to arrange the inputs and outputs in a hierarchical order. The proposed scenarios should be tested on a user-friendly traffic simulation software. Finally, the system's hierarchy and integration has to be provided. A list of rules should be prepared in order to control the changes of signs flashed at correct LCS.

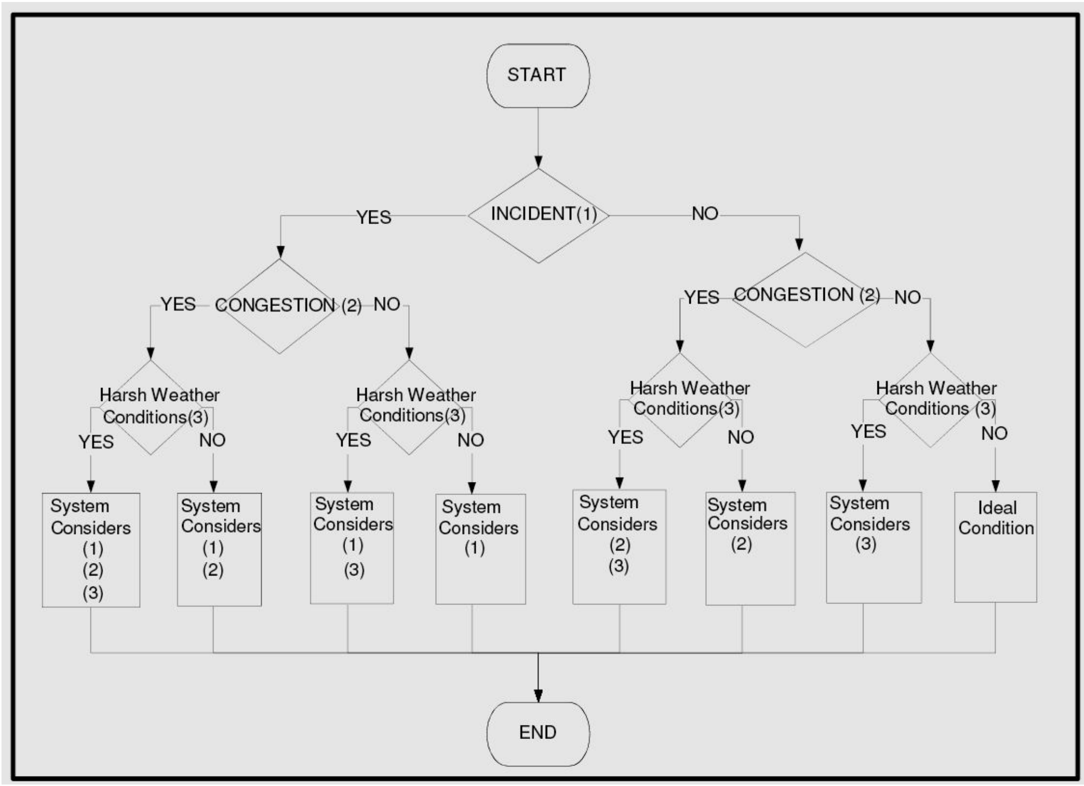

Figure 3.3. LCS scenarios [52].

4. A SIMULATION STUDY ON AUTONOMOUS VEHICLES: EVALUATION OF LANE CONTROL SIGNALS IN THE CASE OF AN INCIDENT

In this chapter, a network is simulated in PARAMICS, a traffic microsimulation software package program, to compare the characteristic features of autonomous vehicles and the use of Lane Control Signals in the case of an incident. In the comparison, the base scenario is accepted as the scenario, which has no autonomous vehicles and LCSs on the network. By generating different scenarios, while including autonomous vehicles and LCSs into the network separately and simultaneously, the effects of autonomous vehicles and LCSs on the network are evaluated.

4.1. Modeling and Simulation

In the study, the network is chosen as the highway, with a length of 2.5 km, starting from Çağlayan Interchange to the entrance of Mecidiyeköy, on D100 Highway, in Istanbul. The direction of the flow is from Çağlayan Interchange to the entrance of Mecidiyeköy. On the road, there are Lane Control Signals, which indicate lane changes for vehicles. The distances between the LCSs are not regular. Below, the sketch of the network, in the Figure 4.1, is given including LCSs locations, speed detector locations and incident location. There are 14 nodes on the network to be used for LCSs and speed measurements. The numbers, 109, 334 and etc., indicate these nodes. The incident occurs between the nodes 283 and 153, and in the sketch, it is indicated with a cross between these nodes. The numbers, 87, 93 and so on, indicate the distance between the nodes [32].

PARAMICS is a simulation program that enables to design a network as realistically as possible with the sufficient input options. PARAMICS is capable of creating incident scenarios and LCSs on networks. It has an option to close a lane and direct vehicles to other lanes. Meanwhile the compliance rate of the vehicles to the signal, closer to the incident, which states that the lane is closed, may be chosen. In PARAMICS, it is also possible to change characteristic features of vehicles, such as reaction time and time headway. The program gives output reports to see the average travel times and the mean speeds between specified locations [53].

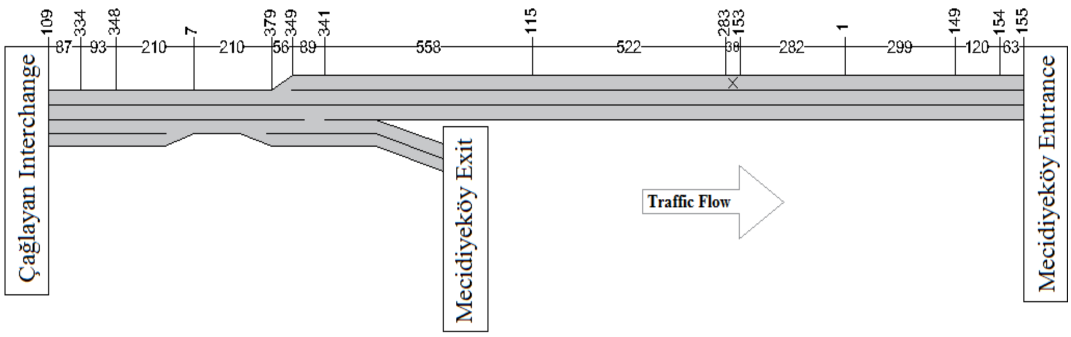

Figure 4.1. Sketch of the network [32].

In the model, mean reaction time and mean time headway are selected as the comparable characteristic features of autonomous vehicles. In a research, reaction time of AVs is taken as 0.5 second, while it is 1 second for human-driven vehicles. It is observed that as autonomous vehicle ratio increases, travel times always decrease. Even on a large-scale network, it helps to reduce travel times by %78 when there are %100 autonomous vehicles [54]. In another study, it is shown that autonomous vehicles, when reaction time is taken as 0 (zero) (meanwhile it is 0.8 s for manned vehicles), have improved the traffic density and flow rate [19]. Time headway is the other researched subject of autonomous vehicles; and it is found out that if time headway is taken as 0.5 s, the capacity of a lane and the current value can go from 2200 veh/h, to 3900 veh/h when all vehicles are purely autonomous vehicles on network [55]. Considering the literature, in the simulation model, the selected values in order to observe vehicles as autonomous vehicles are as 0.5 s for reaction time, and also 0.5 s for headway time.

Simulation scenarios of the model are produced to evaluate the objectives of the study;

- 5 different autonomous and human vehicles participation ratio on the network,
- 2 different LCS locations,

- 2 different compliance rules to the signal, closer to the incident, for vehicles are included in the simulation scenarios of the model.

In total, including the incident scenarios without any LCS and autonomous vehicle application and no incident scenarios, there are 90 scenarios. Below, in Table 4.1, a summary of the scenarios is given. In the first scenario, there is no accident and LCS. In the second scenario, an accident occurs, but LCS is not implemented in the network. The other scenarios are tested in the case of where the compliance rate to the LCS2, closer to the incident, is 80% and 100%, and in the case of where the distances between LCSs are 558 m and 1123 m. These scenarios are run for 3 different demands and 5 different vehicle ratios on the network. These demands are determined using 60% (2010 veh/h), 70% (2400 veh/h) and 90% (3000 veh/h) of the hourly vehicle data on the road network [5]. In order to evaluate the autonomous vehicles' contribution to traffic on the network, the vehicles ratios are chosen as 0%, 25%, 50%, 75%, and 100% autonomous vehicles.

Table 4.1. Summary of the scenarios.

Simulation Scenario	Accident	LCS	LCS1 Obediance	LCS2 Obediance	LCS1 Node	LCS2 Node	Distance Between LCS'	Between LCS1 and the incident
1	0	0	-	-	-	-	-	-
2	1	0	-	-	-	-	-	-
3	1	1	30 %	100 %	341	115	558 m	1080 m
4	1	1	30 %	80 %	341	115	558 m	1080 m
5	1	1	30 %	100 %	348	115	1123 m	1645 m
6	1	1	30 %	80 %	348	115	1123 m	1645 m

As in the sketch of the network, Figure 4.1, it can be observed that when an incident occurs on the left lane, between 283 and 153, Lane Control Signals gets active at two locations on the network for the vehicles to change their lanes. The nearest node to the incident is 115, 522 m away from the incident, and the second nodes are 341 and 348 and the distances of them to the first are 558 m and 1123 m, respectively. In the first signal, vehicles are warned about the incident and told that they should change their lanes soon by a yellow arrow directed to the next lane. In the second signal, which is closer to the incident, by a red cross, it is stated that vehicles must change the incident lane since the incident lane is closed. The locations are chosen to evaluate whether the distances to the incident location have importance on evaluation. In addition to this, the compliance rates to

LCS2 are chosen as 80% and 100%, while at LCS1 it is kept as 30%. All these scenarios are generated separately and examined by comparing the changes in the average travel time and the average links speeds between the detectors with the base scenario, where there is an incident and no autonomous vehicles and LCSs are applied in the network. The duration of scenarios is one hour. The time schedule is given below:

- at 00:00:00 the scenario starts.
- at 00:15:17 the incident occurs.
- at 00:20:00 LCSs warn vehicles to change their lanes.
- at 00:35:17 the incident lane is cleaned and starts to be operated.
- at 00:40:00 LCSs stop to show the lane change.
- at 01:00:00 the scenario finishes [5].

4.2. Simulation Results

All the simulations are tested for 3 different seed values for each scenario and the average values of these tests are given as the results.

In Figure 4.2, the results of the simulation scenarios are displayed according to the summarized scenarios in Table 4.1. The scenarios, 1-6, indicate where the vehicles' ratio on the network is as 100% human-driven vehicles. The scenarios, 7-12, are where autonomous vehicles participate to the road by 25%, in the scenarios, 13-18, they participate by 50%, and in the scenarios, 19-24, they are on the network by 75%. In the last scenarios, from 25 to 30, on the network there are all autonomous vehicles by 100%.

As in the Figure 4.2, it can be seen that third traffic demand level gives more significant results to evaluate the scenarios compared to the other demand levels, although it has the highest travel times. As the autonomous vehicle ratio on the road increases the average travel time decreases. LCSs have an impact on reducing the average travel time compared to the network where there is no LCS. The effect of the compliance rate of the vehicles differs for different scenarios, so it should be evaluated whether it is better that the vehicles obey to LCS2 by 100% or 80% for different scenarios, separately. The impact of the distance of the locations of LCSs to the incident scene is similar to the effect of the compliance rate.

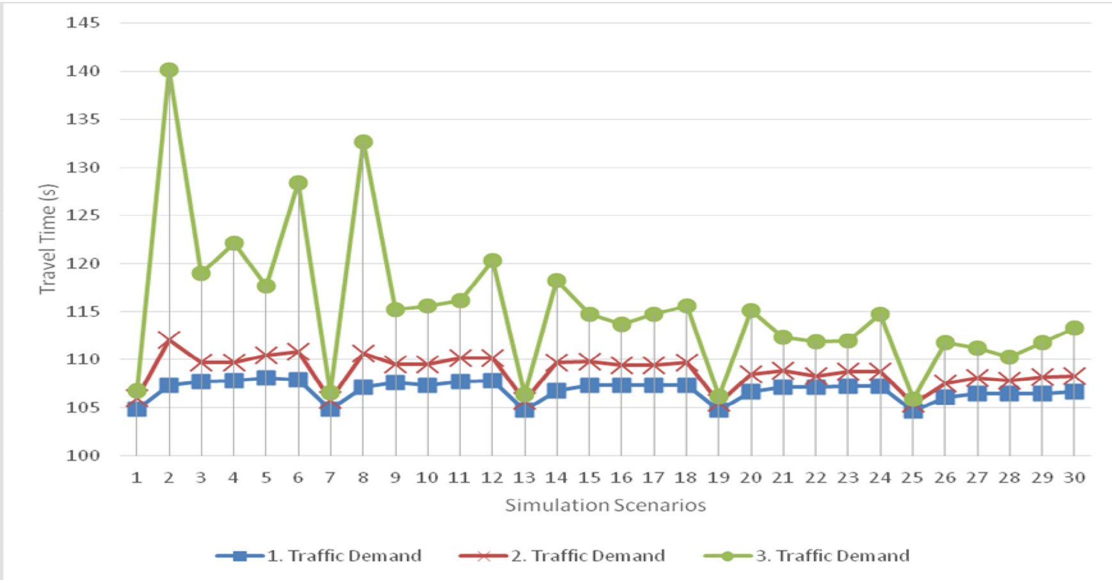

Figure 4.2. The average travel times of the simulation scenarios.

On the first traffic demand level, in the Figure 4.3, below, the average travel times of the vehicle ratios are compared for the scenarios where on the network there is LCSs implementation. 0% indicates that there are no autonomous vehicles, and as it is going to 100%, the ratio of autonomous vehicles is going to 100% in the network. In the scenarios, where there is only LCS control and no autonomous vehicles, there is no improvement in the average travel time, the lowest travel time is found out where the LCSs are at 341-115(1080 m) and the compliance rate is 100% at LCS2 and it is 0.47% higher than the travel time compared to the scenario, which there is no LCSs and autonomous vehicles. It is observed that there is no benefit of LCSs on the average travel time when there is low demand on road.

For the scenarios with LCS application, to have LCSs closer to the incident and for vehicles to obey LCS2 by 100% improve the most, compared to other scenarios. Also, autonomous presence in the network has an effect to reduce the average travel times. When the best scenario of autonomous vehicles, without the use of LCS, is compared with the scenario where there is no LCS and autonomous vehicles on the network, it is observed that the best scenario decreases the average travel time by 1.12%. Meanwhile, it is found that there is no effect of LCSs when there are 100% autonomous vehicles on the network for low demand.

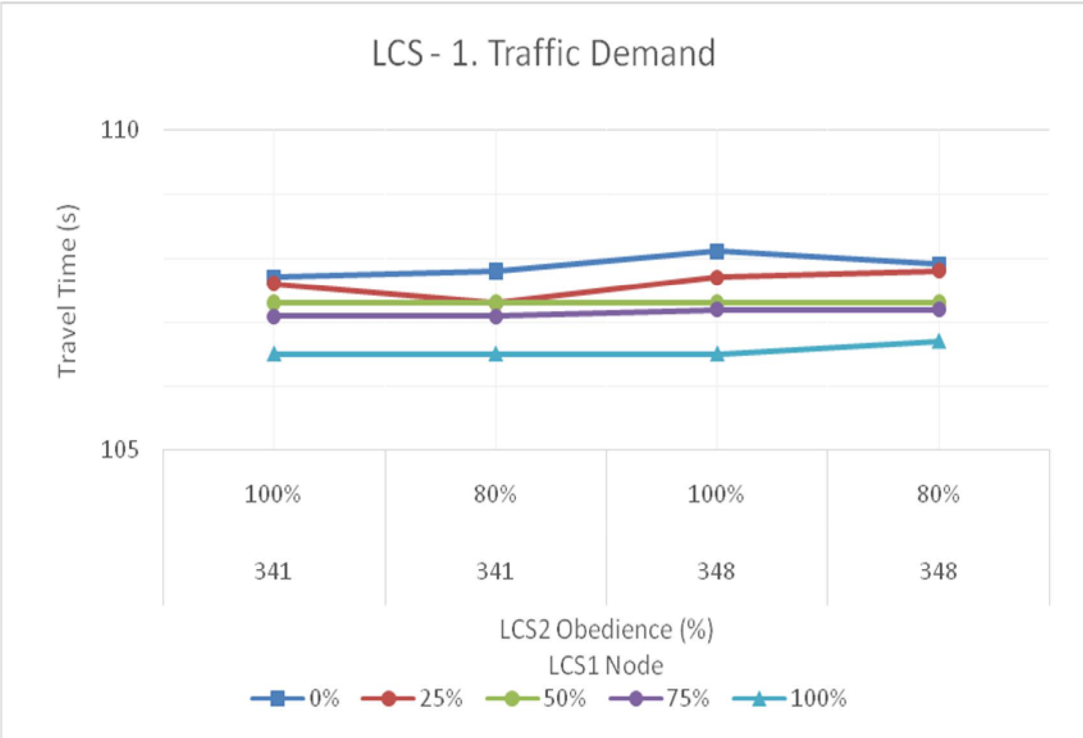

Figure 4.3. The average travel times of the simulation scenarios (1st traffic demand and LCSs).

For the second traffic demand level, (Figure 4.4), LCSs improve the average travel time compared to the scenarios where there are no LCSs and autonomous vehicles. The highest improvement is found out in the scenario where there are LCSs at 341-115 (1080 m) for both 80% and 100% obedience at LCS2 and the average travel time reduces by 2.14% compared to the scenario without LCS and autonomous vehicles. It is an indication that as the demand increases on the network; LCSs start to have impact on reducing the average travel times of vehicles.

For the first traffic demand level, it is observed that as autonomous vehicle ratio increases on the network, the average travel time decreases in all the scenarios. It is not the same for the second traffic demand level. It is observed that the best scenario of LCS implementation only has a lower average travel time by 0.09% compared to the scenario where there are 50% autonomous vehicles and the distance between LCSs is 588 m and the compliance to LCS2 is 100%. On the network, it is found out that depending on the locations of the LCSs and the compliance rate of the vehicles to LCS2, autonomous vehicle presence has a negative effect on the average travel time. The reason for this might be that since LCS1 are closer to the incident and the obedience is 100% at LCS2, and also autonomous vehicles' reaction time is lower, there might be created more stops of vehicles when they change lane. So it is important to evaluate the autonomous vehicles' presence considering the network conditions.

The best scenario of autonomous vehicles and LCS occurs when there are 100% autonomous vehicles, LCS1 is 588 m away from LCS2, and 80% of the vehicles obeys LCS2. The average travel time reduces by 1.73% compared to the scenario, where is only LCS and no autonomous vehicles. In this scenario, the average travel time reduces by 3.84% compared to the scenario where there is no LCSs and autonomous vehicles.

In the Figure 4.5, the third traffic demand level is found out as the demand level that has the highest differences of the average travel times between the scenarios compared to the other demands. The best scenario for LCSs implementation is produced where the locations of LCSs are 348-115 (1645 m to the incident) and the compliance rate of the vehicles is 100% at LCS2. The average travel time decreases by 16.05% in this scenario compared to the scenario that has no LCSs and autonomous vehicles, and it is the largest improvement for LCSs without any autonomous vehicle presence in the network. Therefore, for high demand levels to have a better improvement on the average travel times on the network, the distance between LCS1 and the incident should be decided as 1645 m instead of 1080 m. It is also significant to note that the result is found for the scenario where at LCS2 the vehicles comply the sign by 100%.

Meanwhile, for the scenario where there is 100% autonomous vehicles on the network, the location of LCS1, 348, and 80% obedience to LCS2 increase the average travel time by 1.34% compared to the travel time of the scenario where there is 100% autonomous vehicles and no LCSs. For this scenario, it is found out that the use of LCS and autonomous vehicles, simultaneously, improves the average travel time by 21.33% compared to the scenario where there is no LCS and autonomous vehicles, which is the highest improvement among all the scenarios in the simulation model.

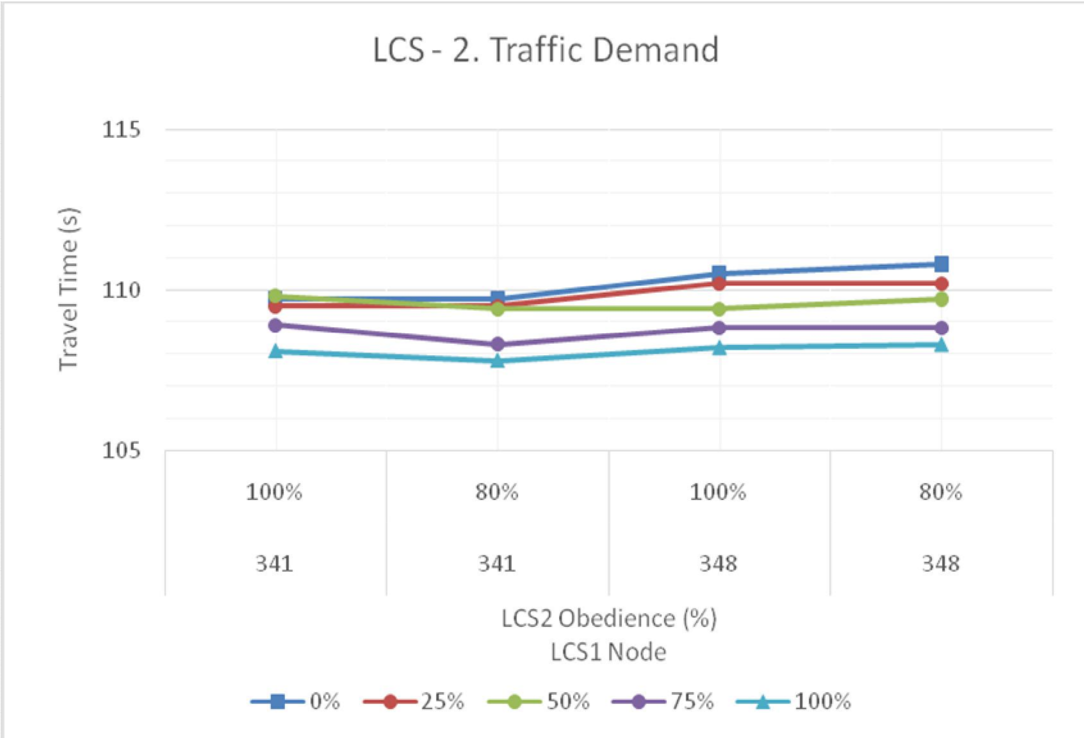

Figure 4.4. The average travel times of the simulation scenarios (2nd traffic demand and LCSs).

With respect to the average travel times along the network, the compliance rate of the vehicles at LCS2, LCS1 location and autonomous vehicles' ratio in the network are evaluated in the case of incident. 90 different scenarios are compared with the scenario where there is no LCS and autonomous vehicles for evaluation. It is found that for the lowest demand level, although LCS has no effect, as autonomous vehicles ratio increases, the average travel time decreases in the network. As the demand level increases, it is found that LCS and autonomous vehicles has more impact on the average times. It is also indicated that there is a scenario where there are both human-driven and autonomous vehicles on the road, and LCSs cause a rise in the average travel time.

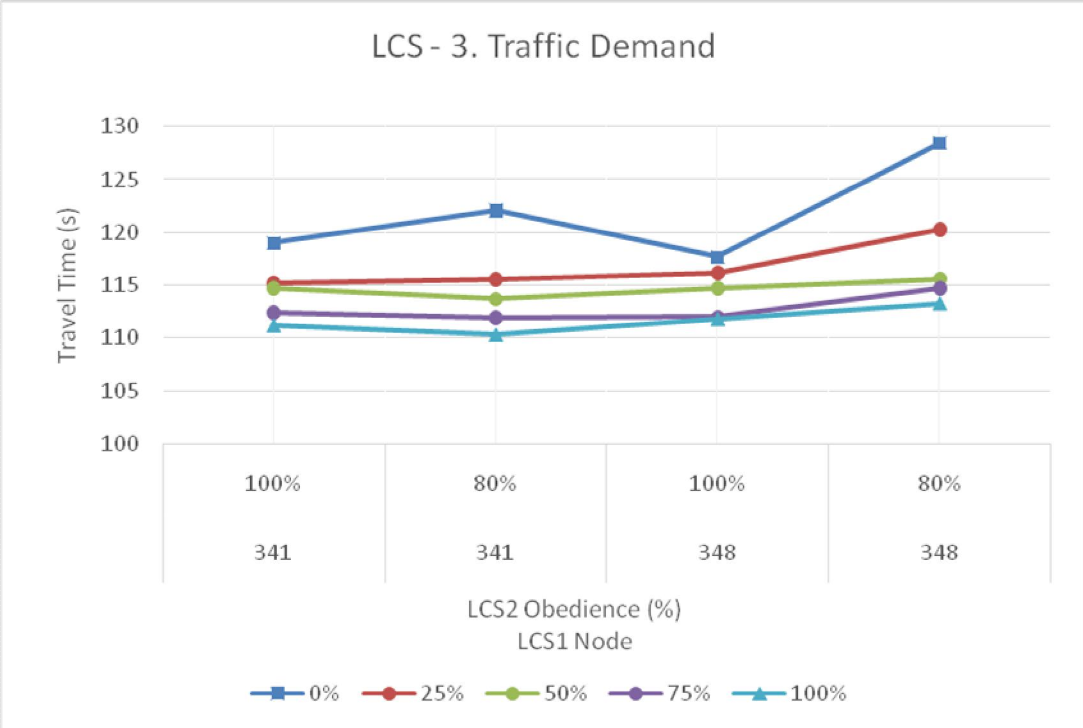

Figure 4.5. The average travel times of the simulation scenarios (3rd traffic demand and LCSs).

In Figure 4.6, Figure 4.7 and Figure 4.8, below, average link speeds of the vehicles for the three traffic demand levels are given. The link speeds are calculated by measuring the travel times of the vehicles between the detector points. The distances between the detectors are not regular. The incident occurs between 283 and 153, and the left lane where the incident occurs is closed between these detectors. The distance between them is 38 m. In the Figure 4.6, it is seen that at D8 the incident occurs, and since the incident lane is closed, the average link speed of the vehicles reduces. D7, between the detectors of 115-283, is the link just before the incident link. The distance between the detectors is 522 m. At D9, just after the incident link, between the detectors of 153-1, with a length of 282, the average link speeds represent the reached speeds of the vehicles after they just pass the closed lane. The average link speeds at D7, D8 and D9 are examined to evaluate the effects of autonomous vehicles and LCS on arriving and passing the closed lane in the network. In order to compare the results, the scenario without any autonomous vehicles and LCS application is compared with the best LCS, the best Autonomous and the best Autonomous + LCS scenarios, selected for each traffic demand levels among 90 scenarios.

For the first traffic demand level, in Figure 4.6, it is seen that the average link speeds at D7, the link just before the incident, and at D9, the link just after the incident, for the three best scenarios and the scenario without any application are around the same values and no improvements are observed. The improvements for the three best scenarios are observed at D8, the incident link. In the best scenario of LCS use only, the distance between LCSs is 558 m and the compliance rate of vehicles to LCS2 is 100%, and the best scenario of LCS use only improves the average link speed at D8 by 3.3%. The best improvement on the link, D8, is achieved in the scenario where there are 100% autonomous vehicles, LCS1 is 558 m away from LCS2 and the obedience of vehicles to LCS2 is 80%. The average link speed increases by 5.5% compared to the scenario where there is no autonomous vehicle and LCS application. It shows that on the bottleneck, LCS application has an impact on increasing the average link speed when it is both used with human-driven or autonomous vehicles.

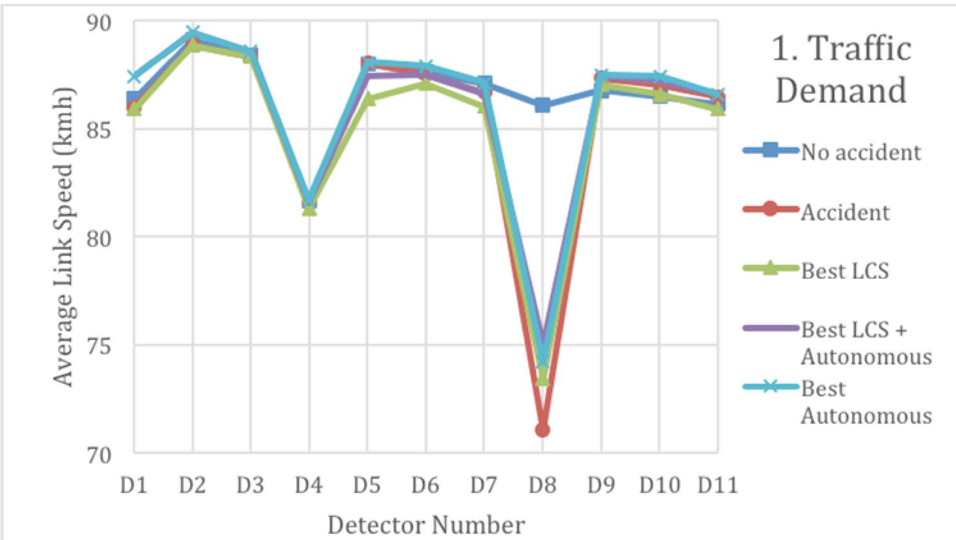

Figure 4.6. The average link speeds of best LCS, best LCS + autonomous and best autonomous scenarios (1st traffic demand).

In the second traffic demand level, (Figure 4.7.), the best Autonomous scenario without LCS control increases the average link speeds at D7 and D9 by 3.13% and 0.83%, respectively, compared to the scenario where there is no autonomous vehicle and LCS control. At D8, the place where the incident occurs, Best LCS + Autonomous scenario also has a higher effect on the average link speed than the other scenarios. In the scenario, there are 100% autonomous vehicles, the distance between LCSs is 558 m, and the obedience of vehicles is 80%. The average link speed is improved by 8.59%, compared to the scenario where there is no LCS and autonomous vehicles. Meanwhile, when the Best LCS + Autonomous and Best Autonomous scenarios are compared, LCS improves the average link speed by 3.14%.

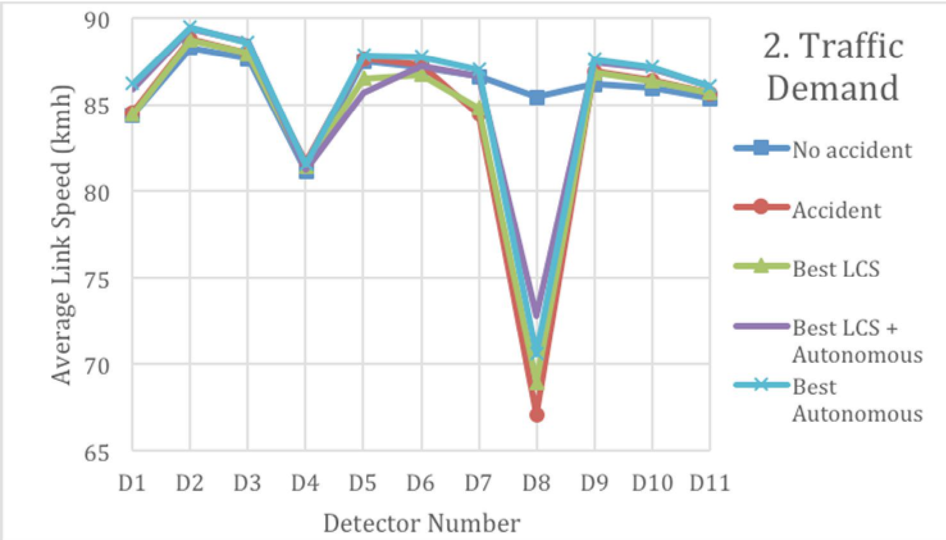

Figure 4.7. The average link speeds of best LCS, Best LCS + autonomous and nest autonomous scenarios (2nd traffic demand).

In the Figure 4.8, below, different from the first and second traffic demand levels, for the third traffic demand level, the changes of the average link speeds of the best LCS scenario throughout the network is not similar to the best Autonomous and the best LCS + Autonomous scenarios. In the best LCS scenario, for the third Traffic Demand level, the distance between LCSs is 1123 m and the obedience to LCS2 is 100%, and the scenario improves the average link speed by 14.61% compared to the scenario without any application. The largest improvement is found out as 19.17% at D7 in best LCS + Autonomous scenario, where LCS1 is 588 away from LCS2 and the obedience to LCS2 is 80%. For the best Autonomous scenario, the improvement is by 18.37% at D7, which is lower than the impact of Best LCS + Autonomous scenario. It indicates both LCSs and AVs, no matter they are used separately or simultaneously, have an impact on improving traffic flow in the case of an incident.

Although, in the link, D7, just before the incident, the average link speeds are higher for the three best scenario than the scenario without any application, in the link, D8, the incident link, the average link speeds are lower except the best LCS + Autonomous scenario. The average link speed at D8 for Best LCS + Autonomous scenario is higher than by 2.51%, and this indicates that by using both LCS and autonomous vehicles on the network simultaneously, the flow at D8 is improved.

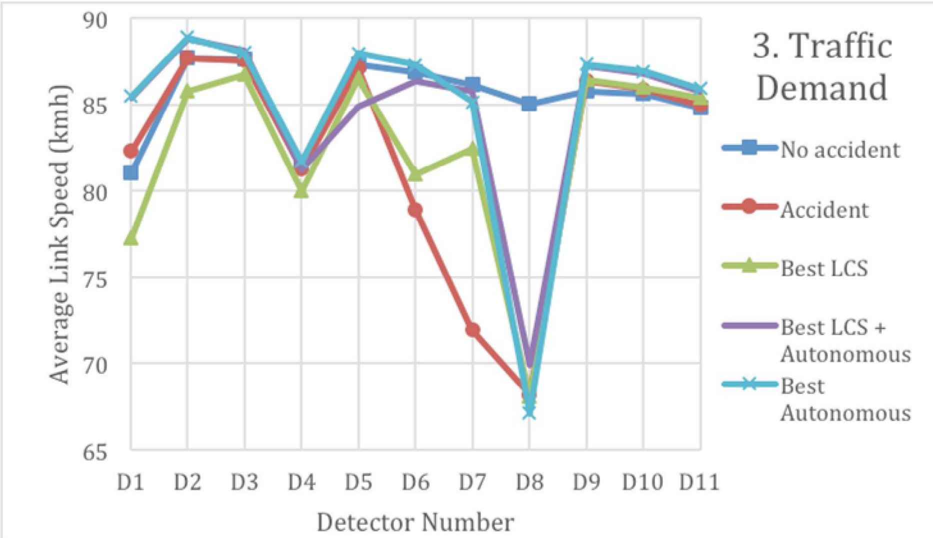

Figure 4.8. The average link speeds of best LCS, best LCS + autonomous and best autonomous scenarios (3rd traffic demand).

From the average link speed comparison for different demands, it is seen that the use of LCS and AV in the networks improves the traffic flow more as the traffic demand level on the network is getting higher. Even though, autonomous vehicles' participation has more influence on the link speeds than LCS, they are more beneficial when they are used together on the network.

The results are discussed by comparing the average travel times and the average link speeds between detectors. It is found out that as the traffic demand level increases in the network, the impacts of AVs and LCSs become both higher. The effect of autonomous vehicles in the network is higher than the effect of LCSs, when they are compared separately, on the scenarios where there are no autonomous vehicles and LCSs. It is also stated that for the third traffic demand level, the use of LCS and autonomous vehicles on the network together improves the traffic more than only autonomous vehicles application without LCS.

Below, in the tables, Table 4.2, Table 4.3, and Table 4.4., the best scenarios of LCS only, Autonomous only, and LCS + Autonomous, compared to the base scenario where there are no LCS and autonomous vehicle application, for the three traffic demand levels are given.

For the first traffic demand, the best LCS scenario is the scenario where the distance of the LCS1 is 1080 m and the compliance rate of the vehicles to LCS2 is 100%, although it does not improve the flow in the network. Best LCS + Autonomous scenario occurs when the locations of the LCSs are the same, but the obedience is 80%, and improves the average travel time by 0.75%, and the average speed by 0.82% compared to the scenario where there are no autonomous vehicles and LCS control. In the best Autonomous scenario, the average travel time decreases by 1.12%, while the mean speed increases by 1.06% compared to the case where there is no autonomous vehicles and LCSs. It shows that for low demands, LCS does not have an impact on the network, for both with or without autonomous vehicles. On the other hand, introducing autonomous vehicles into traffic improves the traffic flow.

Table 4.2. Average travel times and average speeds of the best LCS, LCS + autonomous, and autonomous scenarios (1st traffic demand).

1. Traffic Demand	Average Travel Time (s)	Change (%)	Average Speed (kmh)	Change (%)
No accident	104,9		86,8	
Accident	107,3		84,9	
Best LCS	107,7	0,37%	84,6	-0,35%
Best LCS + Autonomous	106,5	-0,75%	85,6	0,82%
Best Autonomous	106,1	-1,12%	85,8	1,06%

As the traffic demand rises, the effect of AVs and LCS increases, as it can be seen in the Table 4.3, below. For the second traffic demand level, LCS improves the traffic flow by decreasing the average travel time by 2.14% and increasing the average speed by 2.22%, when LCS1 is at 341, 1080 m away from the incident, and the obedience of the vehicles to LCS2 is 80%. It shows that to see the signals at around 1 km away from the incident affects the traffic flow more than the signs at around 1.5 km away from the incident on the network for the second traffic demand level. When autonomous vehicles are introduced to the network, it is seen that Best LCS + Autonomous scenario improves the average travel time by 3.84% and the average speed by 4.19% compared to the scenario without any LCS and autonomous vehicle application. The Best LCS + Autonomous scenario is the scenario where LCS1 is at 341 and the obedience of the vehicles to LCS2 is 80%. It is found that to have obedience as 80% rather than 100% may improve the traffic flow since it prevents overutilization of the lanes where the vehicles move. The best scenario for autonomous vehicles without LCS improves the travel time by 4.10%, while the average speed increases by %4.43% when there are 100% autonomous vehicles in the network. This result shows that LCS may not applicable in the network where there are 100% autonomous vehicles and traffic demands are at these levels.

Table 4.3. Average travel times and average speeds of the best LCS, LCS + autonomous, and autonomous scenarios (2nd traffic demand).

2. Traffic Demand	**Average Travel Time (s)**	**Change (%)**	**Average Speed (kmh)**	**Change (%)**
No accident	106,0		85,9	
Accident	112,1		81,2	
Best LCS	109,7	-2,14%	83	2,22%
Best LCS + Autonomous	107,8	-3,84%	84,6	4,19%
Best Autonomous	107,5	-4,10%	84,8	4,43%

In the third traffic demand, it is seen that using LCSs and introducing AVs into the network achieve high improvements. In the best LCS scenario, there are 16.95% and 19.08% improvements in the average travel time and the average speed, respectively. The scenario occurs when LCS1 is at 348, 1645 m away from the incident, and the obedience of the vehicles to LCS2 is 100%. It is a finding that for the high traffic demand levels in the network, as the distance of LCS1 to the incident increases, the vehicles decide to change their lanes earlier, and so the capacity is used more efficient in the network before they reach to the incident location. For the best scenario of LCS + Autonomous, the average travel time reduces by 21.33% and the average speed increases by 27.08%. It is the scenario where LCS1 is at 341, 1080 m away from the incident, and the obedience of the vehicles to LCS2 is 80%. It indicates that since reaction time and time headway of autonomous vehicles are less than human-drivers in the network, they use the capacity of the road more efficiently. So, for autonomous vehicles to have the LCSs closer to the incident gets the most success in the network for the third Traffic Demand level.

Table 4.4. Average travel times and average speeds of the best LCS, LCS + autonomous, and autonomous scenarios (3rd traffic demand).

3. Traffic Demand	**Average Travel Time (s)**	**Change (%)**	**Average Speed (kmh)**	**Change (%)**
No accident	106,8		85,3	
Accident	140,2		65	
Best LCS	117,7	-16,05%	77,4	19,08%
Best LCS + Autonomous	110,3	-21,33%	82,6	27,08%
Best Autonomous	111,8	-20,26%	81,5	25,38%

In the Table 4.2, Table 4.3, and Table 4.4, the best LCS, LCS + Autonomous and Autonomous scenarios are compared to the base scenario where there is no autonomous vehicles and LCS control. For each traffic demand levels, autonomous vehicles improve the average travel times and speeds of vehicles in the network. For the second and third traffic demand levels, the use of only LCS control improves the traffic on the network. On the third traffic demand level, it is indicated that the best scenario is presented when LCS and autonomous vehicles are used in the network together.

5. CONCLUSION

In the simulation model, autonomous vehicles' effect on a network in the case of an incident is evaluated for 90 different scenarios. The network is chosen from a certain section of D100 Highway, in Istanbul, a length of 2.5 km, starting from Çağlayan Interchange to the entrance of Mecidiyeköy. The road includes Lane Control Signals on several locations that enable to warn the vehicles about the lane change and several detectors to measure the travel times of link speeds of vehicle [29]. PARAMICS is used to model the road as the simulation program. PARAMICS has the necessary input options to design the network and change the characteristic features of vehicles. It also gives the sufficient result reports for the desired values the study aim to have [51].

The main aim of the study is to see the impact of autonomous vehicles on a network, and in order to that, 5 different autonomous vehicle ratios are introduced to the scenarios. (0%, 25%, 50%, 75% and 100%). Also, evaluation of LCS in respect to its location and the compliance rates of vehicles to LCS2 is objected in the thesis. To evaluate LCS, there are scenarios generated with and without LCS. To observe the importance of the location of LCS, two locations are selected for the first sign of LCS. The distances between the first and second tag are selected as 558 m and 1123 m, which are the most compared distances for LCS in the literature. In addition to this, as it is stated in the literature, obedience of vehicles to the signals has influence to the improvements of LCS. To evaluate the importance of compliance rates, the scenarios are generated for 80% and 100% compliance rates of the vehicles, to the second signal, which is before the incident. All these scenarios for AVs and LCSs generated in the model for 3 different traffic demand levels to observe their impacts in different realistic situations. The incident occurs between the nodes 283 and 153, and D8 is indicated as the link where the incident occurs. D7, the link, indicates the link between the nodes, 115 and 153, just before the incident link.

In all scenarios, it is found that autonomous vehicle presence in the traffic improves the average travel time and the mean speed of vehicles, and the improvements get higher as autonomous vehicles ratio in the network increases. In the best scenario of autonomous vehicles without the use of LCS in the network, for the lowest traffic demand level, it is found that there are 1.12% and 1.06% improvements in respect to the average travel time and the mean speed, respectively. The reason for these improvements is that although all the vehicles have enough space for lane change and they do not have to lower their speeds, the low reaction time of autonomous vehicles creates a faster reaction to change the incident lane, and the low time headway of autonomous vehicles has an impact on them to use the capacity better on the network. It is also observed that for the incident scenario where there are all human-driven vehicles and no LCS control, in the lowest traffic demand level, the average travel time increases by 2.29% and the mean speed decreases by 2.19% compared to the scenario where there is no incident. On the other hand, these values for the medium traffic demand level are 5.76% and 5.47%, respectively. It shows that as traffic demand increases, delays for human-driven vehicles on the network are larger. In the incident scenario where there are 100% autonomous vehicles and no LCS for the second traffic demand level indicates that the average travel time decreases by 4.10% and the mean speed increases by 4.43% compared to the scenario where there is no incident, which are higher values than the results of the first traffic demand level. It is seen that as traffic demand in the network increases, the impact of autonomous vehicles on the reduction of average travel time and the increase of the mean speed becomes more valuable. The best achievements of the best autonomous vehicle scenario are found in the highest traffic demand level when there are 100% autonomous vehicles. Autonomous vehicles presence in the the network reduces the average travel time by 20.26% and increases the average speed by 25.38% relatively to the incident scenario where there are no autonomous vehicle and LCS application. It is found that autonomous vehicles regulates the traffic conditions by their selves without the need of any traffic management strategies in the case of a lane closure in the network.

The average link speeds of D7, the link before the incident occurs, and D8, the link where the incident occurs, for the best autonomous vehicles scenario are compared with the scenario where there is no autonomous vehicles and LCS to see the impact of AVs on bottlenecks. For the lowest traffic demand level, the average link speeds are improved by 0.52% and 4.40% at D7 and D8, respectively. It shows that at the bottleneck, the reaction time advantage of autonomous vehicles improves the traffic flow. For the medium traffic demand level, the average link speeds are also improved by 3.13% and 5.29% at D7 and

D8, respectively. This also supports the finding on the results of the average travel time and the average speed, which is that as the highest demand level in a network increases, autonomous vehicles improve the average link speed more in the case of an incident. When the demand level reaches to the highest traffic demand level, it is observed that the average link speed, at D7, increases by 18.37%, while the average link speed, at D8, decreases by 1.59%. It shows that although the vehicles moves much faster until the incident place, relatively to the human-driven vehicles, they may not get into the incident link, where there is one lane less, even though their reaction time is lower than the human-driven vehicles. In the network, for the highest traffic demand level, high speed before the lane closure causes not to regulate the traffic flow well in the case of an incident.

In the model, it is also objected to evaluate the effect of LCSs in the means of their locations and the compliance rate of vehicles to LCS2. For the best scenarios of LCSs use only and no autonomous vehicles, the results are not in the same direction compared to the scenarios of autonomous vehicles. When the demand is at the lowest traffic demand level, LCSs do not improve the average travel time and the average speed of vehicles in any scenario compared to the scenario where there is no autonomous vehicles and LCS control. It is evidence that for low demands to use LCSs do not advance the traffic flow of the network. As the demand increases, it is observed that LCS use is more efficient. For the medium traffic demand level, in the best scenario of LCS use where there are no autonomous vehicles, the distance between LCSs is 558 m and the first signal has a distance of 1080 m to the incident. 80% of the vehicles comply with the second signal, closer to the incident. The improvements for the best LCS scenario are by 2.14% and 2.22% for the average travel time and the mean speed, respectively. For the medium demand level, it is observed that to have a closer LCSs and less compliance rate to the last tag before the incident is more beneficial to increase the traffic flow. The use of LCS, similar to the effect of autonomous vehicles, has a considerably higher impact on improvement of the traffic for the highest demand level. As the traffic demand reaches the highest traffic demand level in the network, the improvements reaches their highest values as 16.05% and 19.08% for the average travel time and the mean speed of vehicles, respectively, compared to the scenario where there is no autonomous vehicles and LCS application. The best LCS scenario is accomplished when the distance between LCSs is 1123 m and the first tag to the incident place is 1645 m, and also the compliance rate to the second tag is 100%. It indicates that for higher demands to have a longer distance between LCSs may improve the traffic flow on the network more. Here, it is important to note the scenario is best since all vehicles obey to the second tag by 100%. If 100% of the vehicles does not comply with the second tag, and instead the compliance rate becomes 80%, it is observed that the best scenario becomes the worst scenario, and the second best scenario of LCS use only is when the first LCS is at 341, which is closer to the incident.

The average link speeds of the best LCS scenarios for the traffic demands are examined, and for lowest first traffic demand level, at D7, just before the incident occurs, there is no improvement. Though, at D8, the incident link, the average link speed increases by 3.36% in the best LCS scenario, which is an indication that LCS might be helpful to regulate the bottleneck speed. For the medium demand level, as it is similar to the average travel time and the mean speed change along the whole network for the best only LCS use scenario, the average link speed increases by 0.51% and 2.78% at D7 and D8, respectively, compared to the scenario where there are no autonomous vehicles and LCS. The results of the best LCS scenario for the highest traffic demand level indicate the same finding with the finding, coming from the best autonomous vehicle scenario. It is found out that although there is an improvement in the average link speed by 14.61% at D7, there is a decrease at D8 by 0.14%. As for the best autonomous vehicle scenario it is stated that a decrease of the average link speed at D8 is observed since the high speed at D7 for the highest demand level causes for vehicles not to change their lanes efficiently in the network.

The final comparison in the study is made to evaluate the effect of autonomous vehicles and LCS when they are used simultaneously in the case of an incident. It is an important evaluation since in reality autonomous vehicles will be introduced to the traffic while there are still human-driven vehicles, which traffic management systems such as LCS are necessary for them to regulate traffic. It is also significant to see whether LCS has an impact on autonomous vehicles. For the lowest traffic demand, only LCS use does not help to any improvements to traffic flow in respect of the average travel time and the mean speed throughout the network. Similarly, best LCS + Autonomous scenario decreases the average travel time by 0.75% and increases the mean speed by 0.82% compared to the scenario where there are no autonomous vehicles and LCS application. For the medium traffic demand level, in the best LCS + Autonomous scenario, average travel times increases by 0.28% and average speed decreases by 0.24%, relatively to the best Autonomous scenario. So it should be stated that for the lowest demand level, LCS use with or without autonomous vehicles is not efficient in the network. It should also be stated that for the medium traffic demand level, LCSs use does not improve the average travel time and speed for autonomous vehicles. It is observed that for the medium demand level when there are 50% autonomous vehicles in the network, and LCS1 is at 341, 588 m away from 115, at the 100% compliance rate the average travel time decreases compared to the scenario where there are no autonomous vehicles and LCSs. This is the only scenario, which autonomous vehicles presence in the network traffic does not help to reduce the average travel times. Therefore, it is an important result that autonomous vehicles presence for some ratios may not have a positive impact to traffic environment for a scenario where LCSs are not correctly used in the network. When the traffic demand level reaches the third traffic demand level, it is seen that LCS use with autonomous vehicles develops the traffic flow. In the best LCS + Autonomous scenario, which LCS1 is at 341, 588 m away from the LCS2, and 100% compliance rate of vehicles to LCS2, the average travel time reduces by 21.33% and the average mean speed increases by 27.08%, compared to the incident scenario where there are no autonomous vehicles and LCS. The scenario has the highest improvements in all 90 scenarios run in the simulation. As the main objective of the evaluation of LCS with autonomous vehicles is whether LCS use has improvements on autonomous vehicles, it is found that for high demand LCS has an important impact on traffic where there is autonomous vehicles presence in the network.

The effect of the use of LCS with autonomous vehicles is seen more on the average link speeds, at D7 and D8. For all the traffic demand levels, it is observed that the highest average link speeds at D7 and D8 are achieved in the best LCS + Autonomous scenarios, except a scenario when the demand level is lowest. For the first traffic demand level, it shows that although the average link speed increases by 4.4% at D8, the incident link, the use of LCS and autonomous vehicles simultaneously do not improve the average link speed before the vehicles reach to the lane closure. The effect of LCS on autonomous vehicles for this scenario should be stated as though, at D7, the vehicles have a higher speed when there is no LCSs, at D8 if LCSs are used, the average link speed is higher than the best Autonomous scenario. It is a contribution of LCSs to autonomous vehicles on bottlenecks. At the incident link, the best LCS + Autonomous scenarios have always the higher average link speeds than the average link speeds of the best autonomous scenarios. The best LCS + Autonomous scenarios for all the traffic demand levels are the only scenario where at D8, the incident link, the average link speed is higher than the scenario, where there is no LCSs and AVs.

As a summary, the findings of the study are given below:

- In the evaluation of autonomous vehicles, the simulation model gives significant results.
- In all simulated scenarios, autonomous vehicle presence into the network improves the average travel times and speeds, relatively to the incident scenario.
- As the traffic demand level increases in the network, the impact of autonomous vehicles increases as well.
- In the best autonomous vehicles scenario, autonomous vehicles improve the average travel time by 20.26%, and the average speed by 25.38% relatively to the incident scenario for the highest traffic demand level in the network.
- Although autonomous vehicles improve the average link speeds for low demands, when the traffic demand level is highest, autonomous vehicles do not improve the average speed of the incident link in the network.
- In the evaluation of LCS with human-driven vehicles, for low demands, it does not have a positive impact on the average travel times and speeds in the network.
- As the traffic demand level increases in the network, the effect of LCS on the average travel times and speeds of human-driven vehicles become more important.
- In the highest demand level, 100% compliance rate of the human-driven vehicles to the LCS2, which is closer to the incident, improves the traffic more.
- The best scenario of only LCS implication is achieved in the third (highest) traffic demand level when the distance between LCSs is 1123 m, and the compliance rate

to the second tag is 100%. In the best scenario, LCSs improve the average travel time by 16.05% and the average speed by %19.08% compared to the scenario where there are no autonomous vehicles and LCS.

- LCS has a positive impact on the average speeds for low demand levels, but not for high demand levels. It has a higher impact than autonomous vehicles, however it does not improve the average bottleneck link speed.
- The best LCS + Autonomous scenario does not improve the average travel times and speeds compared to the best autonomous vehicle scenarios for low demand levels.
- In a scenario, which includes LCSs and 50% autonomous vehicles, it is found that the average travel time increases comparing the scenario which has 0% autonomous vehicles but the locations of LCSs and the compliance rate are the same.
- LCS improves the best autonomous scenario for the highest demand level.
- The best scenario in all the scenarios is achieved when there are 100% autonomous vehicles in the network and LCS is used.
- In the best scenario, LCS1 is at 341, 558 m away from LCS2, and the compliance rate to LCS2 is 80% and it improves the average travel time and speed by 21.33% and 27.08%, respectively, compared to the scenario where there are no autonomous vehicles and LCS.
- When all the vehicles are autonomous vehicles in the network, less compliance rate to LCS2 and closer distance LCS1 to the incident improve the average travel time and speed more.
- The best achievements on the average link speeds at D7 and D8 for the highest demand level are also found out in the best LCS + Autonomous scenario.

In the thesis, autonomous vehicles and LCS are evaluated separately and simultaneously to see their benefits in the case of accident. The results of the study are helpful to understand the effect of autonomous vehicles when they are introduced into traffic. As more characteristics features of autonomous vehicles are found, by implementing the new characteristic values into simulation models, the results may be improved in the future studies.

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