공학석사 학위논문

Integrated Control of Lane Change and Speed Advisory at Urban Network in a Connected and Autonomous Vehicle Environment

자율협력주행 환경의 도시부 네트워크 차로변경 및 속도추천 통합제어전략 개발

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한 희 동

Integrated Control of Lane Change and Speed Advisory at Urban Network in a Connected and Autonomous Vehicle Environment

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이 논문을 공학석사 학위논문으로 제출함

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한희동의 석사 학위논문을 인준함

2022년 8월

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Abstract

The purpose of this study is to develop the LC−GLESA strategy to overcome the limitations of the GLESA strategy which conducts longitudinal speed control in entry segments at urban intersections. The simulation analysis and case study were performed using traffic simulation sumo to develop the LC−GLESA strategy and to verify the effectiveness of the LC−GLESA strategy respectively. The LC−GLESA strategy was developed by establishing the vehicle dynamics model of connected and autonomous vehicles and the vehicle−to−infrastructure communication system in the simulation analysis. A simulation environment was constructed based on a road network, right−of−way, traffic light program, traffic demand, and travel speed around the Seoul National University Station in the case study. The performances of human−driven vehicles(HDVs), connected and autonomous vehicles(CAVs), GLESA strategy, and LC−GLESA strategy were measured in the constructed simulation environment. The performance of the GLESA strategy deteriorated in congested traffic states, and the LC−GLESA strategy improved the degraded performance. In addition, the performance of the LC−GLESA strategy depending on the level of services(LOS) and market penetration rate(MPR) of CAVs was evaluated. Considerable increments in throughput and number of conflicts were observed in the states between LOS B and C. The MPR of CAVs increased the throughput of the network and decreased fuel consumption and CO2 emission and travel time of HDVs. The results of this study could contribute to the establishment and operation of the LC−GLESA strategy.

Keywords : Urban signal intersection, Traffic management, Connected and autonomous vehicle, Lane change and speed advisory, Traffic simulation

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Chapter 1. Introduction

1.1 Problem Statement

Energy consumption of vehicles in the transportation sector is one of the major reasons for climate change and air pollution. Energy consumption in Domestic transportation counted for 32% of domestic petroleum consumption and 14% of the total greenhouse gas emissions in Korea in 2017(Government of the Republic of Korea., 2020). Nitrogen oxides, sulfur oxides, carbon oxides, and particulate matter emitted by the combustion of fossil fuels from internal endothermic engine vehicles in the transportation sector are recognized as one of the social problems. The transportation sector emitted 98 million tons of greenhouse gas in 2017, which is 2.8 times that of 35million tons in 1990, and the road transportation sector accounted for 96% of the whole sector(Government of the Republic of Korea., 2020).

The environmental problems in the road transportation sector could be solved through the introduction of autonomous vehicles and cooperative intelligent tranportation systems(C-ITS). The autonomous vehicles and C-ITS enable direct communication for vehicles, roadside equipment(RSE), and traffic management centers(TMS). V2X(Vehicle-to-Everything) includes V2V(Vehicle-to-Vehicle communication between vehicles) and V2I(Vehicle-to-Infrastructure communication between vehicles and infrastructure), which transmits information on traffic states to vehicles and the TMS. The TMS provides vehicles with a proactive operation strategy based on the collected the traffic information and improves the safety, efficiency, and environmental characteristics of the road operation system(Preuk et al., 2016; Edwards et al., 2018). The C-ITS provides road geometry, right of way, construction section, crash location, signal phase, and traffic state information with vehicles, and the vehicles proactively maneuver to evade the events in the urban network(Jandrisits et al., 2015; Katsaros et al., 2011).

The Green Light Entry Speed Advisory(GLESA) strategy is one of the ITS strategy that emphasizes the environmental characteristics of road operation in urban networks(Huang et al., 2018). The strategy requires the Dedicated Short-Range Communication(DSRC) data indicating the vehicle's position, speed, and acceleration, the Signal Phase and Timing(SpaT)data indicating signal cycle, current phase, and time to next phase(Stevanovic et al., 2013). The strategy reduces unnecessary acceleration/deceleration of vehicles approaching the intersection by recommending the entry speed information to the vehicles based on the DSRC and SPaT data(Mintsis et al., 2020). The SpaT data and DSRC data could be collected by RSEs or 5G wireless communication, and entry speed information is transmitted to vehicles within the wireless communication range(Sarker et al., 2019).

Studies of the GLESA strategy have evaluated the effectiveness of the strategy on the corridor network by focusing on the longitudinal vehicle dynamics. The lateral vehicle dynamics for the turning lane on the urban network were overlooked(Kloeppel et al., 2018). The vehicles that conducted the GLESA strategy occasionally could not change their lanes to the turning lane by surrounding vehicles, thus they did not carry out their planned trip. The GLESA strategy should be performed with lane changing strategy in order to solve the problem.

1.2 Research Objectives

The purpose of this study is to establish an environment of urban traffic states including turning lanes and to evaluate the effectiveness of the LC−GLESA strategy which is a combination of LC and GLESA strategy. The LC−GLESA strategy conducts LC and GLESA strategy in the upstream and downstream of entrance segments at the intersection respectively. The LC−GLESA strategy was developed in the simulation analysis chapter, and the effectiveness of the strategy was evaluated on a data−based network in the case study chapter.

The algorithm of the LC −GLESA strategy was developed and the effectiveness of the strategy was analyzed in the toy network. The vehicle dynamics model including human−driven vehicles(HDVs) and connected and autonomous vehicles(CAVs) was fitted based on the parameters of previous studies and V2I communication system for CAVs was constructed. The LC−GLESA strategy was developed based on the constructed V2I communication system, and the effectiveness of the strategy was evaluated in the toy network. The SNU network based on road, signal, traffic demand was established the and the effectiveness fo the LC−GLESA strategy developed in the previous chapter was analyzed. The effectiveness of GLESA and LC−GLESA strategies for free−flow and congestion states in the urban network was compared. In addition, the effectiveness of the LC−GLESA strategy for the level of service(LOS) and CAVs' market penetration rate(MPR) was identified. The result of this study could contribute to setting up the application location and operation scheme of the strategy.

Chapter 2. Literature Review

The GLESA algorithm has attention a lot of interest in computer science, industrial, and transportation engineering and extensive research has been conducted. Previous studies of the GLESA strategy have contributed to the strategy algorithm by reflecting strategy performance, traffic states and communication distance, queues, adapted traffic light, autonomous vehicles, and fuel consumption model.

The early study focused on the performance of the GLESA strategy excluding the traffic states. Mandava et al. (2009) performed a probabilistic simulation analysis by setting up the link length and communication distance to a uniform distribution. The objective function was defined as the minimization of the acceleration of the vehicle and the fuel consumption of the strategy was evaluated. The strategy indicated a 14% reduction in fuel consumption compared to what the strategy was not implemented.

Subsequently, studies analyzed the effectiveness of strategies reflecting traffic states and communication distance. Tielert et al. (2010) discussed the strategy for communication distance and demonstrated that 600m is the maximum distance to maximize the effectiveness of the strategy. Staubach et al. (2014) conducted an experiment with a driving simulation and the optimal distances of the strategy in the urban and rural regions were proposed as 300m and 400m respectively. Katsaros et al. (2011) suggested that the high market penetration rate of vehicles performing the strategy entailed an 80% reduction in waiting time and a 7% reduction in fuel consumption. Eckhoff et al. (2013) pointed out the 11.5% reduction of CO_2 emission in free-flow states, while CO_2 emission reduction of the vehicle with the strategy was undermined compared to the vehicle without the strategy.

Njobelo et al. (2018) proposed the strategy considering the dissipation time of queues. Information on the queue at the intersection was collected through V2I communication, and the dissipation time of the queue was estimated. Entry speed calculated by estimated dissipation time of the queue was recommended, the strategy overperformed the GLESA strategy in reduction of waiting time and dissipation time of queue. Zhang et al. (2020)divided the intersection entry link in half and implemented the GLESA strategy in the upstream segment and the recalculated GLESA strategy with the dissipation time of queues in the downstream segment. The strategy was superior to the GLESA strategy by 11.8% and 4.9% of fuel consumption in simulation and real-world experiments respectively.

Van Katwijk and Gabriel (2015) investigated the effectiveness of the GLESA strategy on the adapted traffic light rather than a fixed one. The strategy with the adapted traffic light caused heterogeneous time between the traffic phase in the received information and the one at the intersection and incurred increment of conflicts between vehicles. Subsequently, studies providing methods to predict SpaT information in historical data have been addressed to solve the problem with the adapted traffic light(Stevanovic et al. (2013); Stebbins et al. (2016).

Stebbins et al. (2017) developed the GLESA strategy conbinated with platoons decreasing waiting time and fuel consumption with 40% and 18% respectively. McConky and Rungta (2019) devised the GLESA strategy for autonomous vehicles investigated the effectiveness of the strategy on market penetration rate(MPR) of them. The strategy indicated 30% reduction of fuel consumption when the MPR of autonomous was over 50 %. Masera et al. (2019) formulated the GLESA for minization of stopping time at red light and identified the effectivenss of the strategy. Assuming that all vehilles on the road were autonomous vehicles, the decrement of stopping time up to 28 seconds per a vehicle was observed.

In previous studies, the fuel consumption was calculated with point-mass kinematic model requiring to conduct interpolation of data. Some studies relied on non-linear dynamics, four-gear transmission, electric vehicle model to estimate accurately endothermic and electric fuel consumption(Rakha and

Kamalanathsharma, 2011; De Nunzio et al., 2016; Guardiola et al., 2019; Simchon and Rabinovici, 2020).

Most of the GLESA studies conducted so far have neglected data-driven network and traffic states. The longitudinal vehicle dyanmics was attentioned without the lateral vehicle dynamics for turning lanes. The GLESA strategy disturbing the vehicle taking a lane chang at congestion states deteriorated traffic system(Eckhoff, D. et al. 2013). In this study, the LC-GLESA strategy was developed to improve the limit of the GLESA strategy and evaluated the performance of the strategy in data-driven network reflecting traffic infrastructure and demand data.

Chapter 3. Eco-Driving Strategy Operation

3.1 Framework

LC-GLESA strategy overcame the limitations of the GLESA strategy by performing LC and GLESA strategies respectively at the entry of the intersection. V2I communication system included the framework of collecting and processing data, finding the entry lane and speed, and sending eco-driving control information(Fig 1). The approaching lane and arrival time were estimated with the collected DSRC, Trip, SpaT, and MAP data through RSUs around the vehicle and infrastructure. The data collected and processed from RSUs was transmitted to the coordinates calculating entry lane and speed. The calculated entry lane and speed information was sent to the RSUs. The RSUs installed at the entry segment of the intersection provided LC-GLESA information with approaching vehicles, thus the vehicle conducted the strategy.

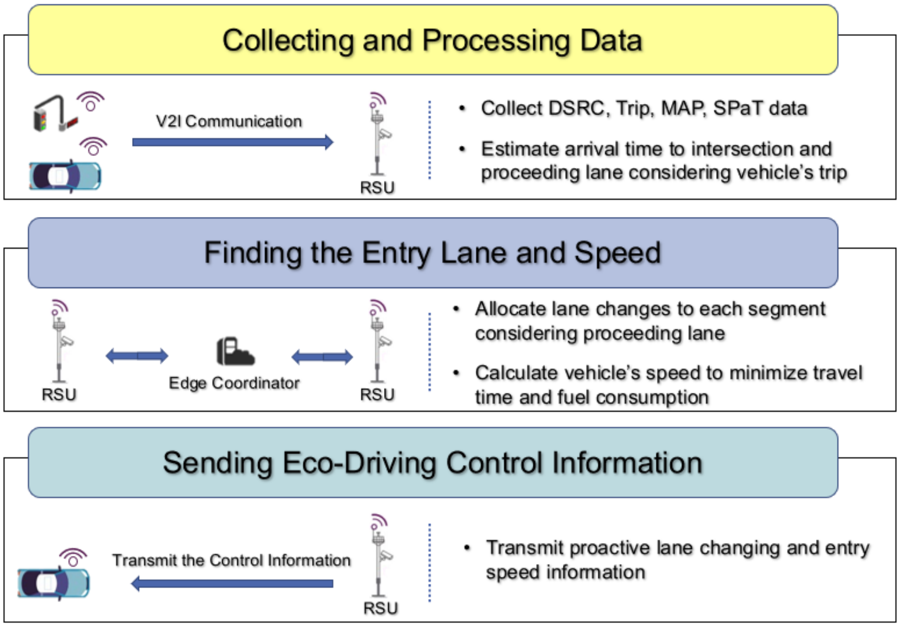


Figure 1 Framework of the Eco-Driving control on urban networks

3.2 Collecting and Processing Data

The RSUs collected the DSRC, Trip, SpaT, and MAP data to conduct the proposed strategy. The DSRC data included the position, speed, and acceleration of vehicles and the Trip data indicated the routes of vehicles. The MAP data included the geometry, right-of-way, and lane and the SpaT data indicated the traffic light program and signal phase(Fig 2).

The RSUs estimated the vehicle's entry lane at the intersection by comparing the vehicle's location collected in real-time with the turning lane included in the vehicle's route. The RSUs collected the vehicle's position, speed and acceleration information, traffic light system, and signal phase information at intersectoin. The arrival time was estimated and the remaining and the next green phases were calculated based on the collected data. CAVs were defined as vehicles equipped with OBUs or 5G wireless communication devices that receive and send the data. In this study, it was assumed that communication delay does not occur.

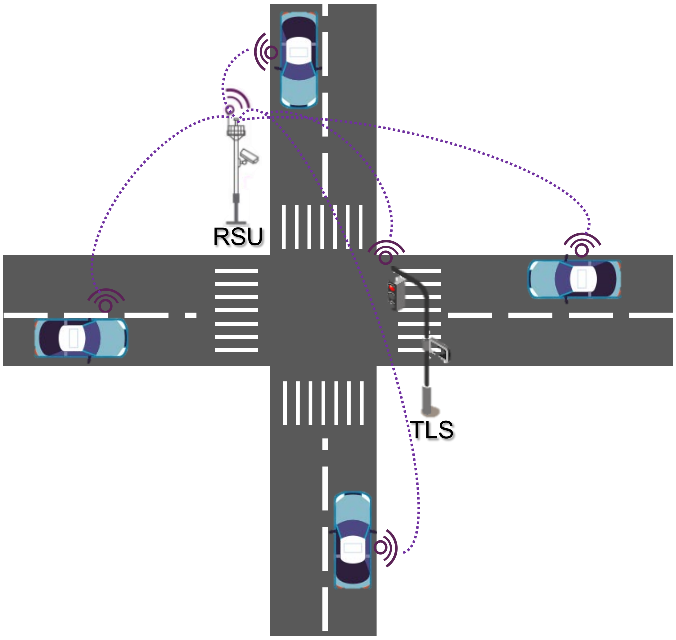


Figure 2 Collecting DSRC, Trip, MAP, SPaT Data

3.3 Finding the Entry Lane and Speed

The LC-GLESA strategty consisted of LC and GLESA strategy. The LC strategy estimated the vehicle's entry lane at the intersection by comparing the collected vehicle's location with the turning lane included in the vehicle's route. The target lane was selected based on the estimated entry lane of vehicles. The lane changing to the selected lane was performed in the order of a left-turning lane, a right-turning lane, and a straight-through lane. The lane changing was performed upstream of the entry and the lane change interval was set to 3.6 seconds(Kim et al., 2020).

The GLESA strategy indicated entry speed information for minimizing the fuel consumption and travel time of vehicles. The arrival time at the intersection was estimated by newton's motion equation with the position, speed, acceleration of vehicles within communication range. It was assumed that the vehicle maneuvers to the intersection maintaining a constant velocity or acceleration motion that approached communication range. The estimated arrival time at the intersection and signal phase at that time were compared, and the reference speed of vehicles was calculated constraining speed and acceleration to minimize travel time. The maximum speed of the reference speed was constrained to the speed limit on roads, and the acceleration of that was limited to $[-3.5 m/s^2, 2.5\ m/s^2]$ for safety and comfort driving behavior(Sharara et al., 2019).

3.3.1 Estimating target lane

$$h_t = \begin{cases} 0 & if\ (y_t = y_{\Delta t_{tls,0}}) \\ \dfrac{(y_t - y_{\Delta t_{tls,0}})}{n} & if\ (|y_t - y_{\Delta t_{tls,0}}| = n) \end{cases}$$

$y_t,\ y_{\Delta t_{tls,0}} \in \{1: left, 2: straight, 3: right\}$

$h_t \in \{-1: change\ to\ right\ lane, 0: keep\ the\ current\ lane, 1: change\ to\ left\ lane\}$

Where, y_t: the lane in which ego−vehicle is located at time t, $y_{\Delta t_{tls,0}}$: the lane where ego−vehicle is located at time $\Delta t_{tls,0}$ on upstream of intersection, h_t: the target lane at time t, n: the number of lanes

3.3.2 Performing the lane changing

$$g_t = \begin{cases} h_t & if\ (\ y_{\Delta t_{tls,0}} = left\ turn\ lane) \\ h_{t+3.6} & if\ (\ y_{\Delta t_{tls,0}} = right\ turn\ lane) \\ h_{t+7.2} & if\ (\ y_{\Delta t_{tls,0}} = straight\ lane) \end{cases}$$

Where, g_t: the action of lane change at time t

3.3.3 Estimating arrival time at intersection

$$d(t) = v(t) \cdot t + 0.5a(t) \cdot t^2$$

$$t_{tls,0} = \begin{cases} \dfrac{d_i(t)}{v(t)} & if\ a(t) = 0 \\ -\dfrac{v(t)}{a(t)} + \sqrt{\dfrac{v(t)^2}{a(t)} + \dfrac{2d_i(t)}{a(t)}} & if\ a(t) \neq 0 \end{cases}$$

Where, $d_i(t)[m]$: distance from the ith TLS at time t, $v(t)[m/s]$: speed of the Ego−vehicle at time t, $a(t)[m/s^2]$: acceleration of the Ego−vehicle at time t

3.3.4 Determining reference speed

$$minimize\ f(v)$$

$$subject\ to \begin{cases} v_{min} \leq v_r \leq v_{max} \\ a_{min} \leq a_r \leq a_{max} \\ phase_i(t + \Delta t_{tls}(v_r)) = Green \end{cases}$$

Where, $f(v) = d_i(t)/v_r$: travel time to reach the upstream TLS i, $a_r(t)[m/s]$: acceleration to reach the reference speed v_r

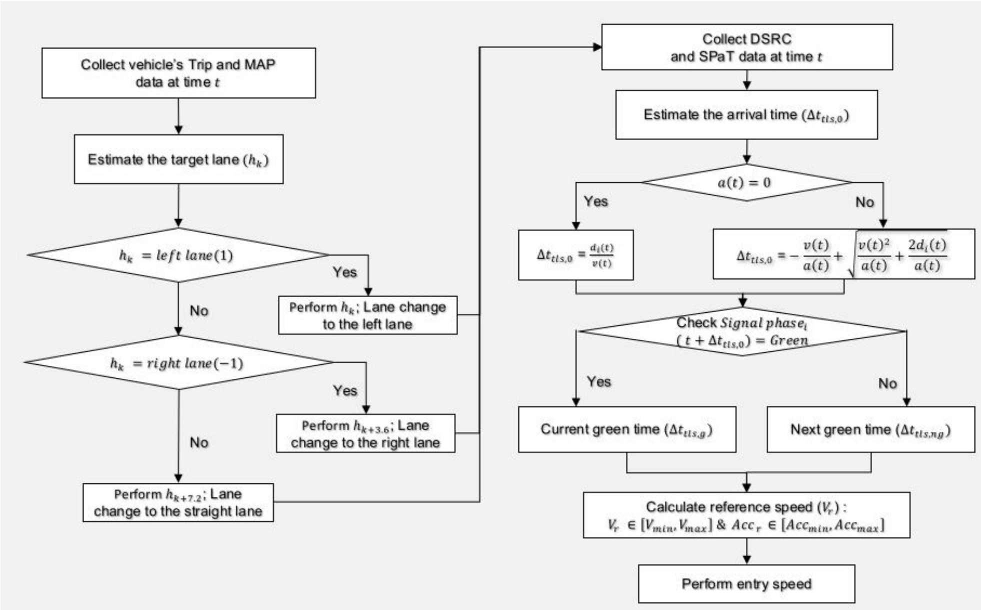


Figure 3 LC-GLESA algorithm system

3.4 Sending Eco−Driving Control Information

The LC−GLESA strategy conducts LC and GLESA strategy in the upstream and downstream of entrance segments at the intersection respectively(Fig 4). The lane changing zone was set to 150*m*, and the LC interval was limited to 3.6 seconds(kim et al. 2020). The lane changing interval was set to 50*m* based on the urban speed limit of 50 *km/hr* in Article 19, Paragraph 1, Item 1 of the Enforcement Rule of the 『Road Traffic Act』 in Korea. The lane changing strategy was performed in the order of a left−turning lane, a right−turning lane, and a straight−through lane each 50*m*. The GLOSA zone was set to the section which was 150m excluding the lane changing zone from the intersection entrance segment. The GLESA strategy sent entry speed information based on the arrival time of vehicles and signal phase at the intersection.

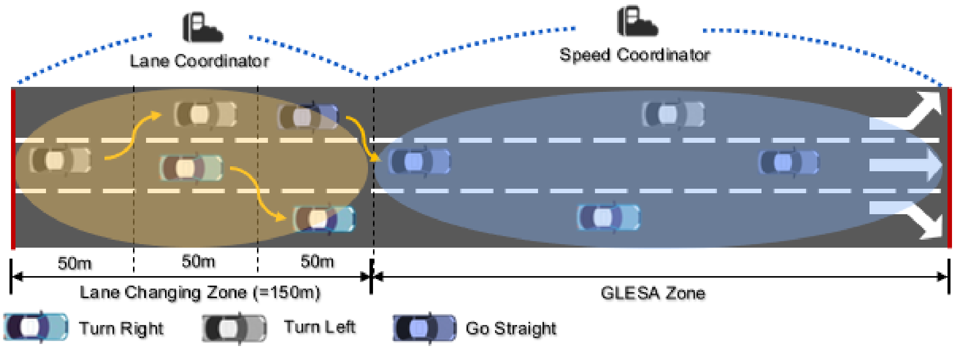


Figure 4 Operation of LC−GLESA strategy

Chapter 4. Simulation Analysis

4.1 Simulation Design

LC-GLESA strategy was implemented in the Simulation of Urban MObility (SUMO) environment by using Python API. The Simulation Analysis was conducted to inspect the vehicle behavior of HDVs and CAVs in virtual urban intersections. The vehicle dynamics, GLESA, and LC-GLESA strategy tests were conducted in the order. The parameters of the vehicle dynamics model to reflect the driving behavior of HDVs and CAVs were refered to the previous study (M Guériau and I Dusparic, 2020, Table 1). HDVs were defined as the vehicles maneuvered by drivers without the communication devices, presenting aggressive and individual driving behavior. CAVs were defined as the vehicles maneuvered by the sensors and OBUs, representing conservative and cooperative driving behaviors. CAVs performed the GLESA and LC-GLESA strategy through V2I communication.

Table 1 Vehicle dynamics model parameter for HDVs and CAVs

Parameters	HDV (Passenger Car)	CAV level 4 (Passenger Car)
Car-following model	**Krauss**	**IDM**
Speed deviation (%)	**0.1**	**0.05**
Time headway (s)	**1.2**	**1**
Min gap (m)	**2.5**	**1**
Max accel. (m/s^2)	**2.5**	**1**
Deceleration (m/s^2)	**7.5**	**7.5**
Max decel. (m/s^2)	**9**	**9**
Imperfection	**0.5**	**0.05**
Lane-changing model	**LC2013**	
Cooperation	**0.5**	**1**
Anticipation	**0.5**	**1**

4.2 Vehicle Dynamic Test

The performances of vehicle dynamics of HDVs and CAVs were evaluated at an intersection in a virtual urban network. The network length was 200m, and the traffic light was located at 100m. 48 vehicles were generated with a uniform distribution and the performances between the vehicle models were inspected. The number of conflicts among the measure of effectiveness(MOE) was set when the time-to-collision(TTC) values was less than 2 seconds(Song et al., 2009).

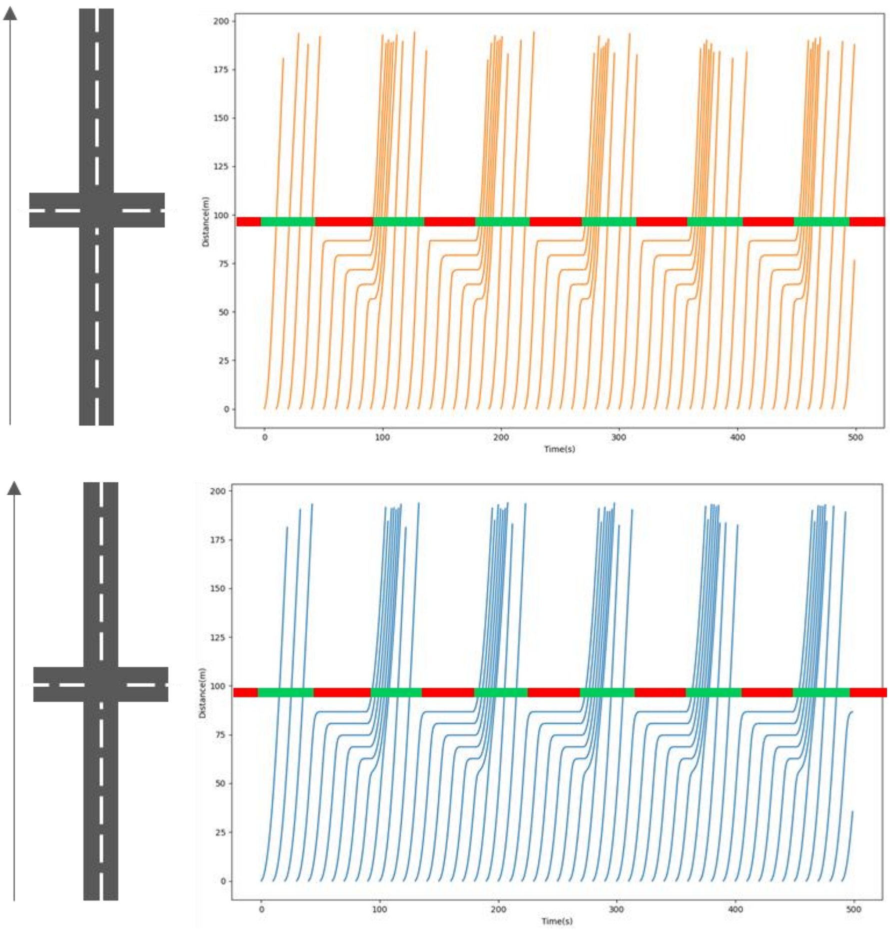


Figure 5 Time-Space diagram (HDVs (above) and CAVs (below))

The result of performance on HDVs and CAVs was presented in table 2. CAVs indicated the vehicle maneuvering depending on vision sensory such as a camera, radar, and lidar. The fuel consumption and CO2 emission, waiting time, and travel time of HDVs decreased by 8%, 13%, and 18% respectively compared to CAVs. However, the number of conflicts on HDVs increased by 56% compared to CAVs. The result extrapolated from characteristics of driving behavior on HDVs and CAVs.

Table 2 The result of vehicle dynamics test

Outputs	**HDV (Passenger Car)**	**CAV level 4 (Passenger Car)**
Throughput	**48**	**48**
Fuel consumption (ml)	**2,056**	**2,235**
CO2 (g)	**4,783**	**5,200**
Total waiting time (s)	**484**	**560**
Total travel time (s)	**1,566**	**2,201**
Average vehicular travel speed (km/hr)	**26**	**18**
Number of conflicts	**78**	**50**

4.3 Control Logic Test

The performances of the control logic of GLESA and LC−GLESA were evaluated at an intersection in a virtual urban network. The driving behaviors of CAVs performing GLESA strategy and HDVs in a single intersection were evaluated. The network length was 400m, and the traffic light was located at 300m. An HDV and CAV were generated to compare the driving behavior depending on strategy (Fig 6). A CAV passed the intersection at constant speed in considering the time of the next green phase in the entrance segment.

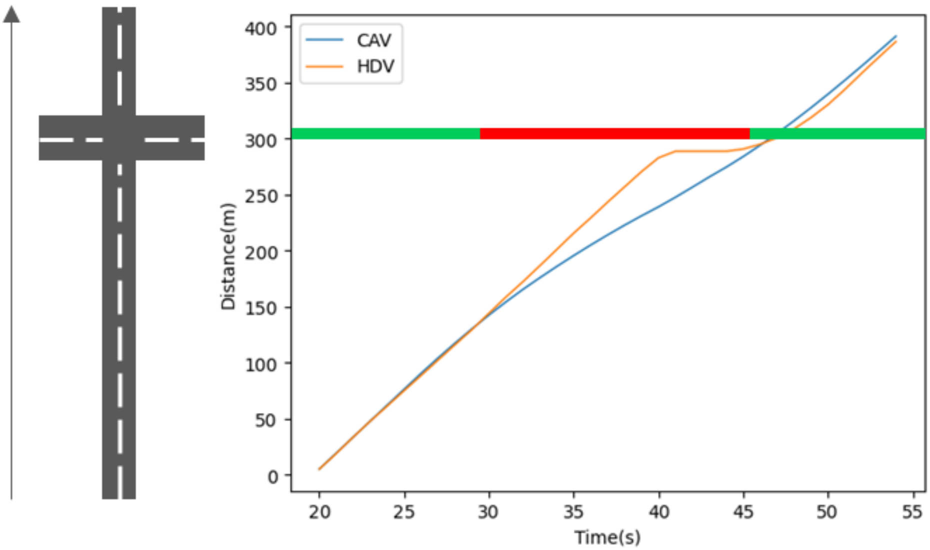


Figure 6 Time−Space diagram (GLESA strategy in single intersection)

The result of performance on CAVs performing GLESA strategy and HDVs at a single intersection was presented in table 3. CAVs reduced fuel consumption and CO_2 emission, and waiting time by 40% and 3 seconds respectively compared to HDVs.

Table 3 The result of GLESA in a single intersection

Outputs	HDV (Passenger Car)	CAV level 4 (Passenger Car)
Throughput	**1**	**1**
Fuel consumption (ml)	**30**	**17**
CO2 (g)	**69**	**41**
Total waiting time (s)	**3**	**0**
Total travel time (s)	**35**	**35**
Average vehicular travel speed (km/hr)	**11.28**	**11.28**

The driving behaviors of CAVs performing GLESA strategy and HDVs in successive intersections were evaluated. The network length was 600m, and the traffic light was located at 200m and 400 m respectively. The successive intersections adopted a coordinated traffic light program and a CAV performing GLESA strategy and HDV were generated to compare the driving behavior depending on strategy(Fig 7). A CAV accelerated its speed to pass the first intersection considering the time of the remaining green phase in the entrance segment and passed the second intersection at a constant speed to minimize its fuel consumption.

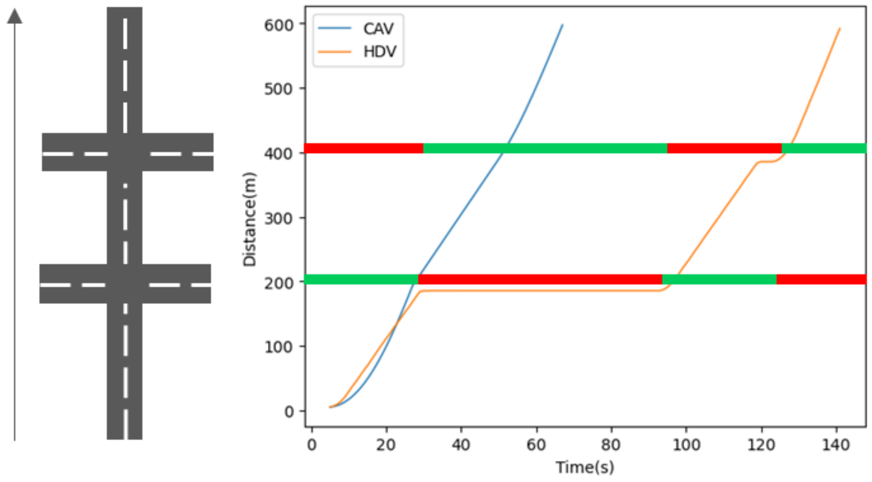


Figure 7 Time-Space diagram (GLESA strategy in successive intersections)

The result of performance on CAVs performing GLESA strategy and HDVs at a successive intersection was presented in table 4. CAVs reduced fuel consumption and CO2 emission, and travel time by 42% and 54% respectively compared to HDVs. The performance of the GLESA strategy in a successive intersection with a coordinated signal effect was greater than one in a single intersection.

Table 4 The result of GLESA in successive intersections

Outputs	**HDV (Passenger Car)**	**CAV level 4 (Passenger Car)**
Throughput	**1**	**1**
Fuel consumption (ml)	**124**	**72**
CO2 (g)	**290**	**168**
Total waiting time (s)	**65**	**0**
Total travel time (s)	**137**	**63**
Average vehicular travel speed (km/hr)	**4**	**9**

The driving behaviors of CAVs, CAVs which performed GLESA and LC−GLESA strategy and HDVs in a 4−diresctional intersection were evaluated. The network length was 400m, and the traffic light was located at 200m. The lane changing and GLESA zone were divided in the 150m upstream and 50m downstream of entrance segments at the intersection respectively. 900 vehicles per 15minutes were generated with a uniform distribution to compare the performances between the HDVs and CAVs at intersection in urban network(Fig 8). The traffic light cycle was 90 seconds, and the phase for each direction was set to green phase(33s)−yellow phase(3s)−left turn phase(11s)−yellow phase(3s).

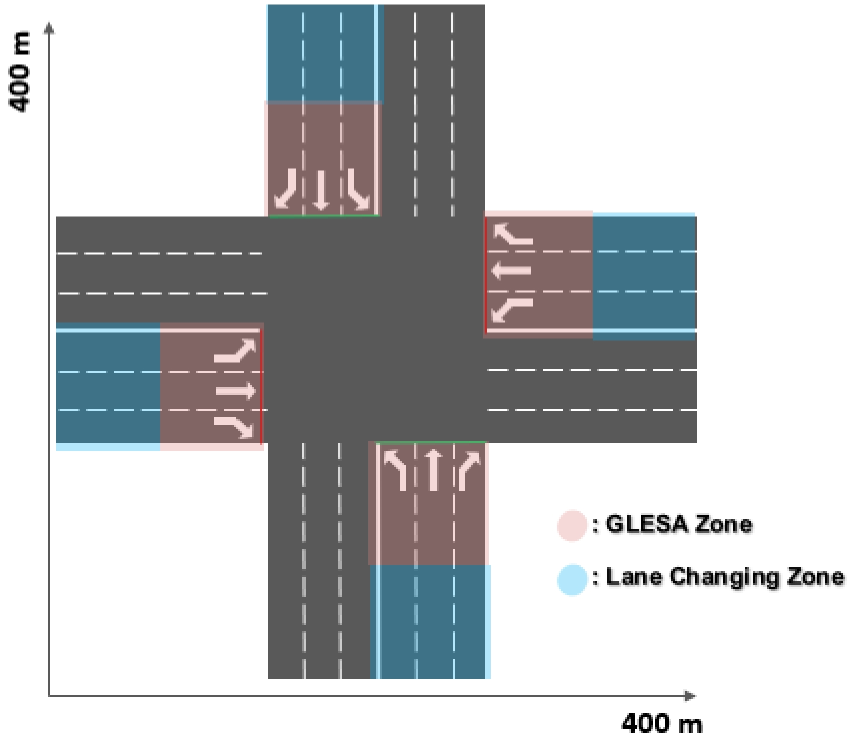


Figure 8 Toy network configuration (LC−GLESA strategy in a 4−directional intersection)

The result of performance on CAVs, CAVs performing GLESA and LC−GLESA strategy and HDVs at a 4−diresctional intersection was presented in table 5. CAVs performing LC−GLESA strategy reduced fuel consumption and CO2 emission, travel time, and number of conflicts by 47.81 ml, 111.21 g, 2.73 seconds, 1.36 respectively compared to HDVs. CAVs performing LC−GLESA strategy reduced fuel consumption and CO2 emission, travel time, and number of conflicts by 2.28 ml, 5.31 g, 5.74 seconds, 0.19 respectively compared to CAVs performing GLESA strategy. The performance of the LC−GLESA strategy in a intersection including 6 lanes round trip was the best based on throughput, fuel consumption and CO2 emission, travel time and number of conflicts, on the other hand, that of CAVs was the worst.

Table 5 The result of the strategies in the 4−directional intersection

Outputs	**HDV**	**CAV level4**	**CAV level 4 GLESA**	**CAV level 4 LC-GLESA**
Throughput	**600**	**576**	**877**	**891**
Average vehicular fuel consumption (ml)	**171**	**190**	**123**	**121**
Average vehicular CO2 (g)	**399**	**442**	**287**	**282**
Average vehicular travel time (s)	**186**	**143**	**183**	**177**
Average vehicular conflicts	**4.34**	**3.53**	**2.98**	**2.79**

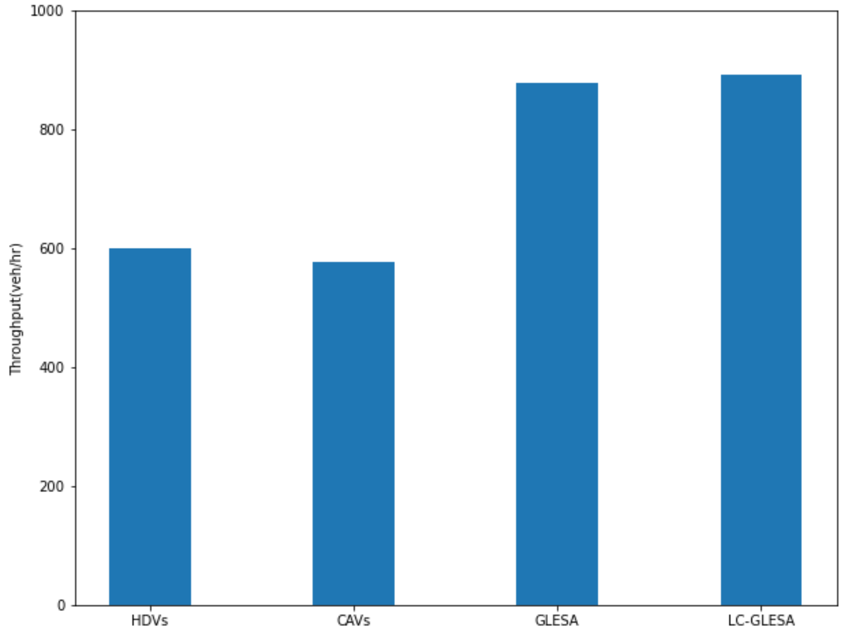


Figure 9 The result of the strategies for networks in the 4-directional intersection

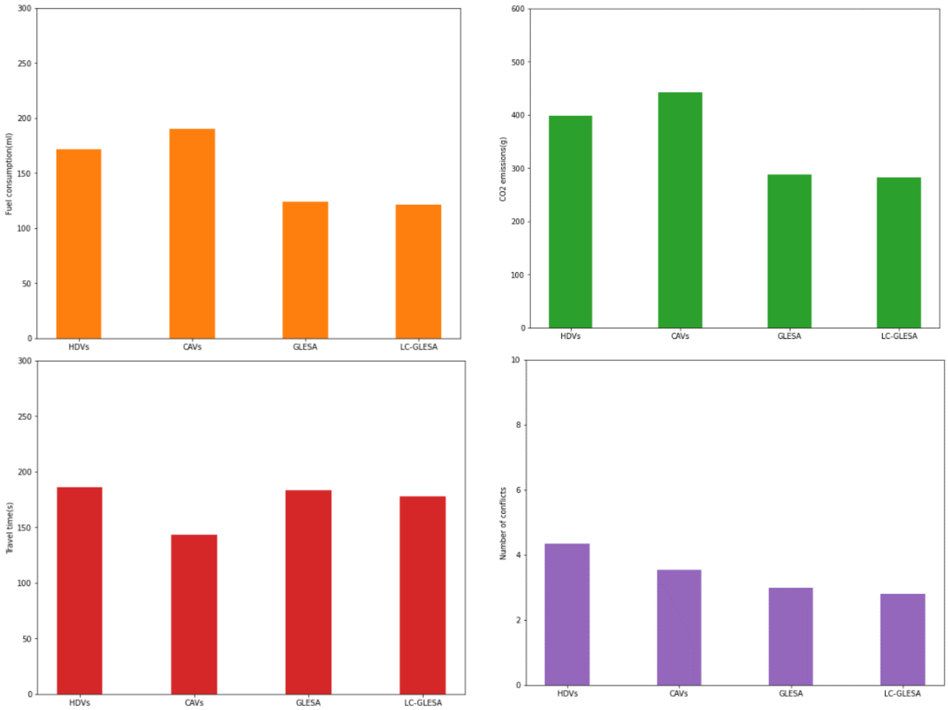


Figure 10 The result of the strategies for vehicles in the 4-directional intersection

Chapter 5. Case Study

5.1 System Architecture

The system architecture of the case study constituted input data, model API, SUMO simulation, and output data (Fig 11). The input data included traffic signal phase, traffic demand, road network, and right-of-way, and a simulation environment based on the data was constructed. The driving behavior of the vehicles in the simulation was presented by the vehicles dynamics model. The longitudinal and lateral motion control of vehicles with the V2I communication system was implemented through TCP/IP protocol based on the Traffic Control Interface (TRACI) module. Fuel consumption and CO2 emission of vehicles were calculated to proportion the speed and acceleration of vehicles by the HBEFA3/PC_G_EU4 model. Simulation analysis was performed by reflecting input data, vehicle dynamics model, V2I driving control, and fuel consumption model API. The output of the simulation analysis included the throughput of the network, travel time, fuel consumption and CO2 emission, and conflicts of the vehicle.

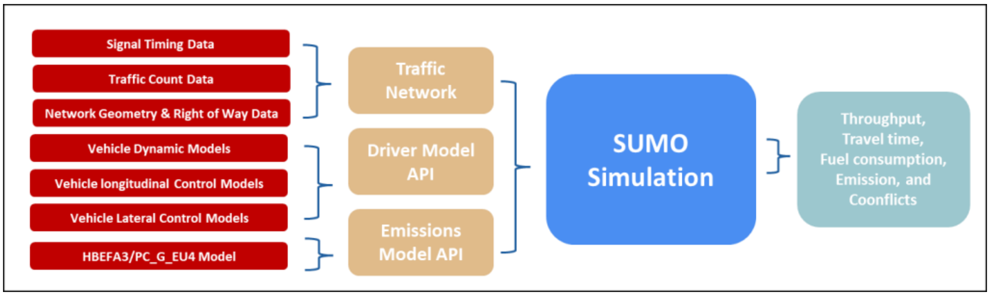


Figure 11 System architecture of the simulation study

5.2 Simulation Design

The network configuration of the case study included three urban arterial roads (37.4842° N, 126.9453° E) and (37.4775° N, 126.9592° E) around the Seoul National University Station. The three urban arterial roads represented Nambusunhwan−ro(1.51km), Gwanak−ro(1.16 km), and Bongcheon−ro(1.63 km) with 19 intersections(Fig 12). The time−of−day(TOD) data indicating the program of the traffic light on weekdays in November 2021 were applied to the simulation configuration.

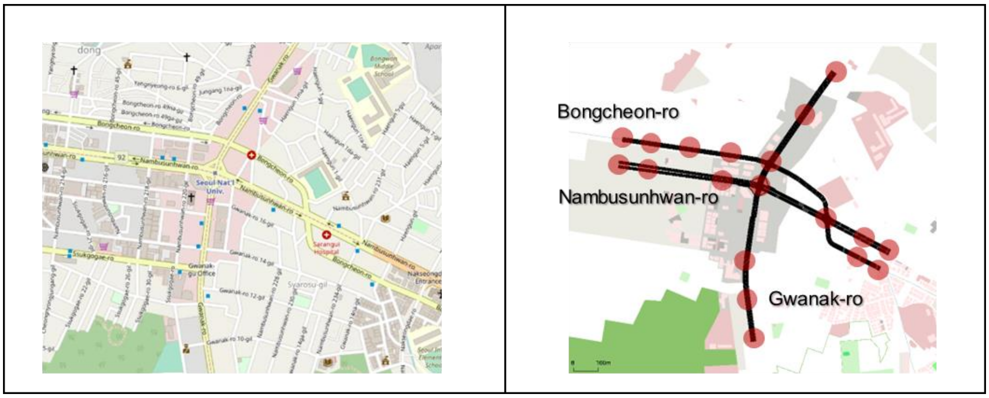
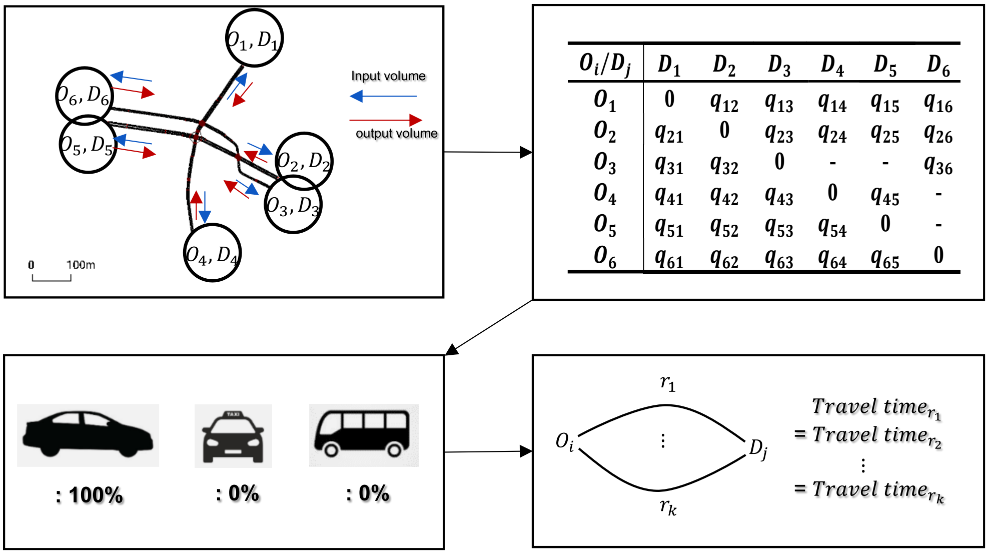


Figure 12 The SNU station network; OSM map (Left), SUMO network configuration (Right)

The traffic demand in the simulation was generated using the traditional 4−step model(Fig 13). In the trip generation step, 800 $vehs/hr/4lanes$ and 2400 $vehs/hr/4lanes$ traffic volumes were generated as the free−flow and congestion states in a fringe of the network based on nakseongdae station at 3 AM and 9 AM on Novermber 18, 2021. In the trip distribution step, the origins and destinations matrix was written based on the right−of−way and traffic volume in the network. The traffic volumes between origins and destinations were defined as the decision variables, and the objective function was to maximize the summation of decision variables. A flow conservative constraint that kept the traffic volumes between inflow and outflow equaled to the ones between origins and destinations was applied, and the ones between origins and destinations were distributed using integer programming(IP). In the mode choice step, all vehicles in the network were assumed to be passenger cars with 100% of the vehicle selection probability. In the trip assignment step, the vehicle's routes were assigned for balancing the travel times of each route using a dynamic user equilibrium algorithm. The probability of route selection was adjusted by updating the weight of route selection based on the average travel time for each route for 15 minutes.



O_i/D_j	D_1	D_2	D_3	D_4	D_5	D_6
O_1	0	q_{12}	q_{13}	q_{14}	q_{15}	q_{16}
O_2	q_{21}	0	q_{23}	q_{24}	q_{25}	q_{26}
O_3	q_{31}	q_{32}	0	-	-	q_{36}
O_4	q_{41}	q_{42}	q_{43}	0	q_{45}	-
O_5	q_{51}	q_{52}	q_{53}	q_{54}	0	-
O_6	q_{61}	q_{62}	q_{63}	q_{64}	q_{65}	0

Figure 13 The framework of SNU station traffic demand

The results of the traditional 4-step model on the free-flow and congestion states were represented by a macroscopic fundamental diagram(Fig 14). The macroscopic fundamental diagram indicated the traffic states with the flow, density, and speed depending on 73 links for 1 minute. The free-flow states with low density and volume and the congestion states with high density and volume were identified.

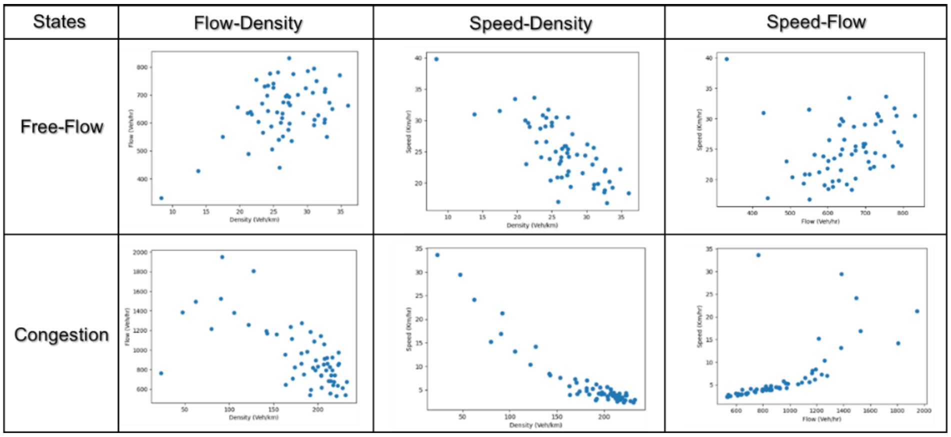


Figure 14 The result of MFD in the SNU station network; Free-Flow states (above), Congestion states (below)

error (MAE) of the average travel speed in links on free−flow and congestion states presented 2.47 km/hr, 8.6 km/hr respectively. The travel speeds of the entrance segments were observed to be relatively greater than the one simulated. The greater MAEs of entrance segments in congestion states resulted from the observed one including channelized traffic.

Table 6 The result of Calibration in SNU network; Free-Flow states (above), Congestion states (below)

Gwanak-ro	Euncheon Intersection	Bongcheon Intersection	Seoul Nat'l Univ Station	Gwanak-gu Office	Seoul Nat'l Univ
Southbound lane (→)	28.1 (30.6)	25.2 (24.6)	32.0 (28.7)	27.2 (31.7)	
Northbound lane (←)	31.2 (31.5)	29.0 (30.5)	32.5 (31.5)	27.0 (27.8)	

Nambusunhwan-ro	KT Gwanak Branch	Seoul Nat'l Univ Station	Wondang Elementary School	Nakseongdae
Eastbound lane (→)	25.0 (22.6)	22.6 (26.7)	39.4 (38.5)	
Westbound lane (←)	34.7 (37.7)	26.4 (23.8)	31.6 (28.3)	

Bongcheon-ro	Hyundai Market	Bongcheon Intersection	Wondang Elementary School
Eastbound lane (→)	30.2 (27.1)	24.2 (28.8)	
Westbound lane (←)	35.4 (39)	26.6 (24.1)	

Gwanak-ro	Euncheon Intersection	Bongcheon Intersection	Seoul Nat'l Univ Station	Gwanak-gu Office	Seoul Nat'l Univ
Southbound lane (→)	4.0 (12.9)	13.1 (14.7)	26.8 (18.5)	20.9 (20)	
Northbound lane (←)	33.6 (30.7)	7 (24.9)	1.6 (17)	2 (26.4)	

Nambusunhwan-ro	KT Gwanak Branch	Seoul Nat'l Univ Station	Wondang Elementary School	Nakseongdae
Eastbound lane (→)	2.2 (10.3)	21.8 (23)	25.6 (15.9)	
Westbound lane (←)	28.8 (34.7)	10.8 (19)	3.2 (25.8)	

Bongcheon-ro	Hyundai Market	Bongcheon Intersection	Wondang Elementary School
Eastbound lane (→)	2.4 (18.8)	18.9 (17.1)	
Westbound lane (←)	30.7 (31.1)	16.5 (17.1)	

**note: simulation value (observed value)*

5.3 Eco−Driving Control

The effectiveness of the strategy was evaluated by setting the communication segment of the LC−GLESA and GLESA strategy at the intersections in the Seoul National University Station network. The LC−GLESA and GLESA strategy were implemented in the entrance segment at 4−directional, single, successive intersections. The lane changing zone was set to a 150m segment upstream at the 4−directional intersection, and the LC interval was limited to 50m based on the urban speed limit of 50km/hr(Kim et al. 2020). The GLESA zone was set to the segment downstream excluding LC zone at the 4−directional intersection and the single and successive intersection. The ranges of GLESA strategy on reference speed and acceleration were limit to [10km/hr, 50km/hr], [−3.5m/s^2, 2.5m/s^2] respectively(Sharara et al., 2019).

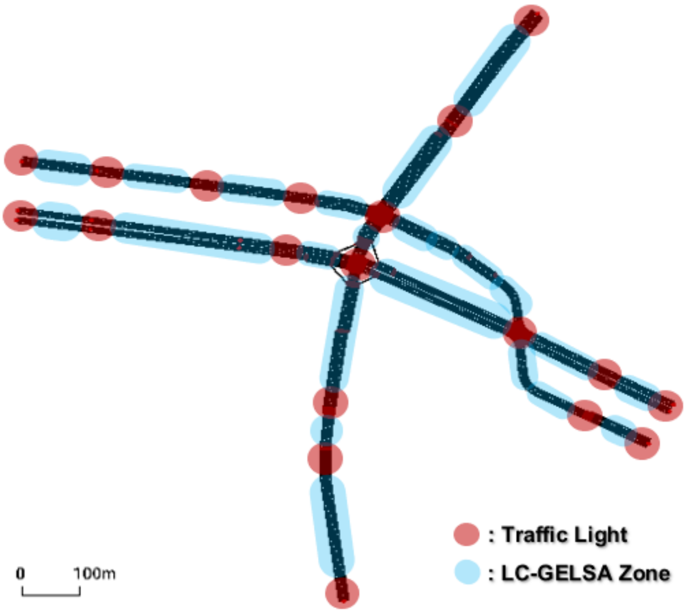


Figure 15 The Control zone in SNU Station Network

The effectiveness of the proposed strategy was evaluated by deriving indicators of throughput from the network, fuel consumption and CO2 emission, travel time, and number of conflicts from vehicles(Table 7, 8). When the traffic state was a free-flow condition, the LC-GLESA and GLESA strategy indicated a slight improvement in that the throughput increased by less than 1% compared to the HDVs. As the CAVs, GLESA and, LC-GLESA strategy were introduced, the fuel consumption and CO2 emission, travel time, and the number of conflicts tended to be improved. The LC-GLESA strategy reduced fuel consumption and CO2 emission, travel time, and the number of conflicts by 14.7%, 4%, and 36.3%, respectively, compared to HDVs. The LC-GLESA strategy reduced fuel consumption and CO2 emission, travel time, and the number of conflicts by 2%, 1.4%, and 3.8%, respectively, compared to CAVs. The LC-GLESA strategy reduced fuel consumption and CO2 emission, travel time, and the number of conflicts by 1.5%, 1.4%, and 2.4%, respectively, compared to the GLESA strategy. The performance of the LC-GLESA strategy on free-flow states was judged to be insufficient.

Table 7 The result of the control strategies for the networks in the free-flow states

Traffic Condition	Outputs	HDV	CAV level 4	CAV level 4 GLESA	CAV level 4 LC-GLESA
Free_Flow	Throughput	4,251	4,257	4,258	4,256
	Average vehicular fuel consumption (ml)	224	195	194	191
	Average vehicular CO2 (g)	523	455	453	446
	Average vehicular travel time (s)	220	214	214	211
	Average vehicular conflicts	6.3	4.17	4.11	4.01

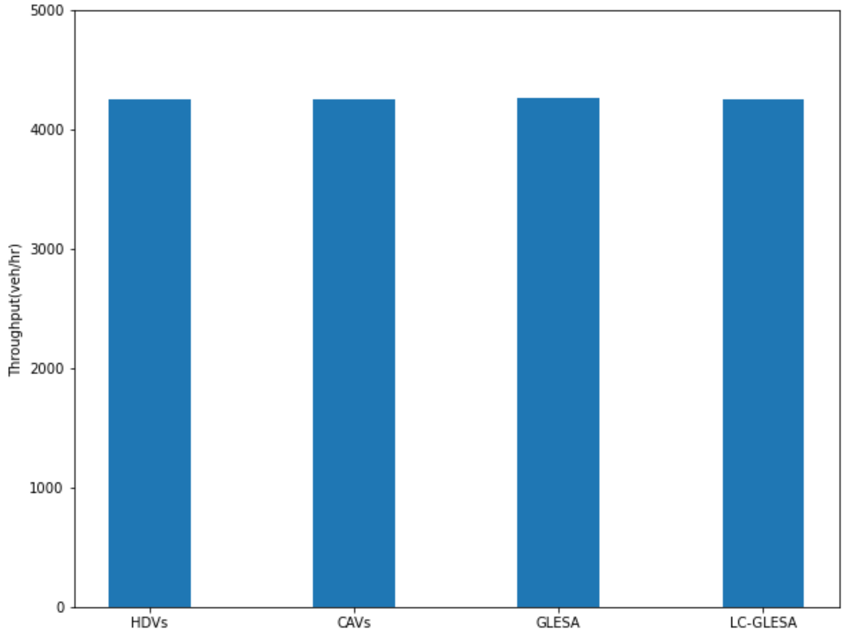


Figure 16 The result of the control strategies for the networks in the free-flow states

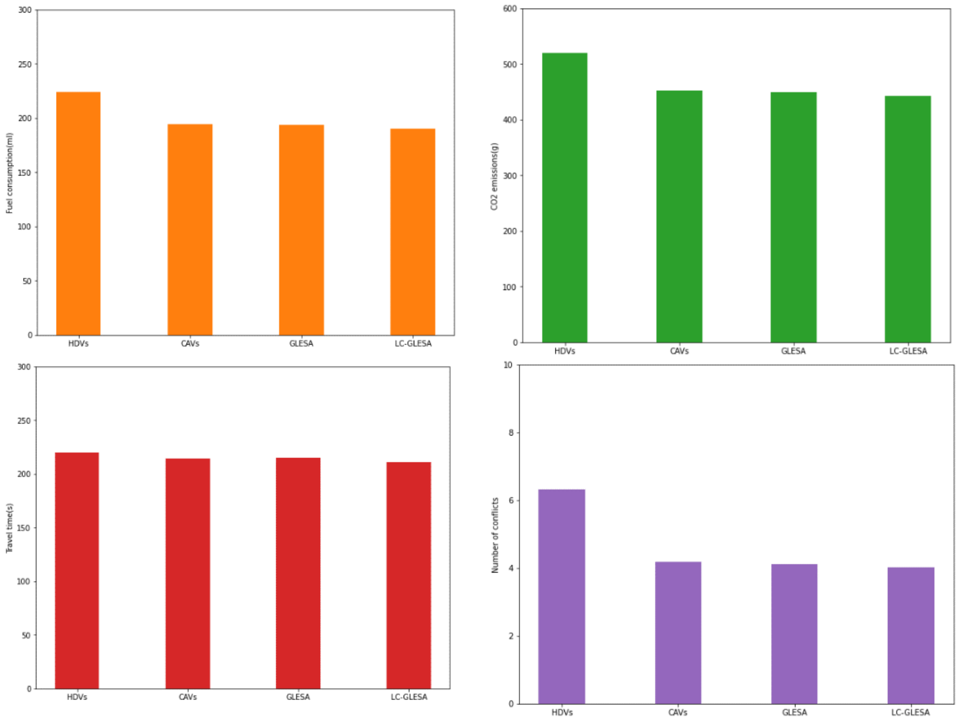


Figure 17 The result of the control strategies for the vehicles in the free-flow states

When the traffic state was a congestion condition, the LC-GLESA strategy indicated considerable improvement in that the throughput increased compared to the HDVs. In contrast, the GLESA strategy presented deterioration in that throughput decreased compared to the HDVs. The throughput of CAVs and LC-GLESA strategy increased by 15% and 41% respectively, and the GLESA strategy decreased by 9% compared to HDVs. As the CAVs and LC-GLESA strategy were introduced, the fuel consumption and CO2 emission, travel time, and the number of conflicts tended to be improved. The LC-GLESA strategy reduced fuel consumption and CO2 emission, travel time, and the number of conflicts by 45%, 47%, and 35.4%, respectively, compared to HDVs. The LC-GLESA strategy reduced fuel consumption and CO2 emission, travel time, and the number of conflicts by 15.1%, 17%, and 27.6%, respectively, compared to CAVs. In contrast, the GLESA strategy increased fuel consumption and CO2 emission, travel time, and the number of conflicts by 6.4%, 2.2%, and 13.8%, respectively, compared to CAVs.

A limitation of the GLESA strategy is that vehicles equipped with the OBUs or 5G wireless communication devices are prevented from performing a lane change at congested intersections (Eckhoff, D. et al. 2013). The vehicle that failed to change lanes either got stuck at the intersections or performed aggressive lane changes. These movements of the vehicles obstructed the traffic flow in some segments. The LC-GLESA strategy overcomes the limitation of the GLESA strategy to improve the traffic flow and enhance the safety, mobility, and environment of each vehicle.

Table 8 The result of the control strategies for the networks in the congestion states

Traffic Condition	Outputs	HDV	CAV level 4	CAV level 4 GLESA	CAV level 4 LC-GLESA
Congestion	Throughput	4,845	5,559	4,405	6,827
	Average vehicular fuel consumption (ml)	591	384	408	326
	Average vehicular CO2 (g)	1,376	893	950	758
	Average vehicular travel time (s)	678	432	422	358
	Average vehicular conflicts	10.3	9.18	7.91	6.65

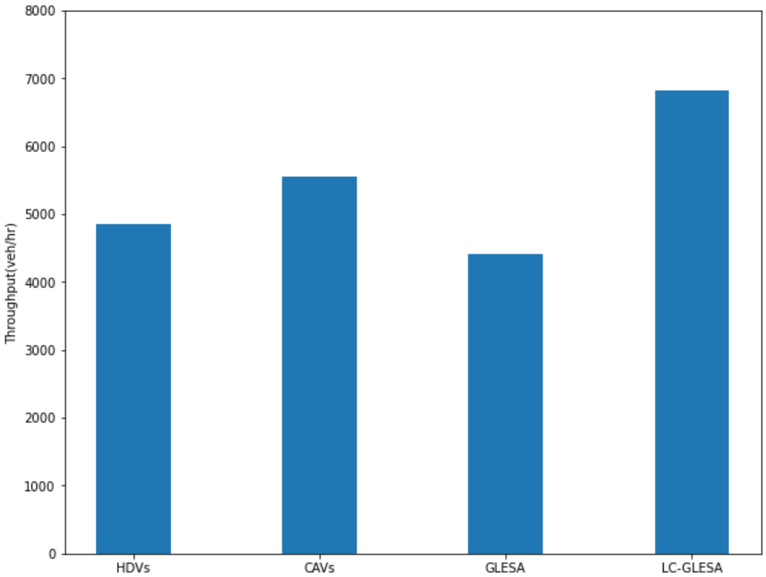


Figure 18 The result of the control strategies for the networks in congestion states

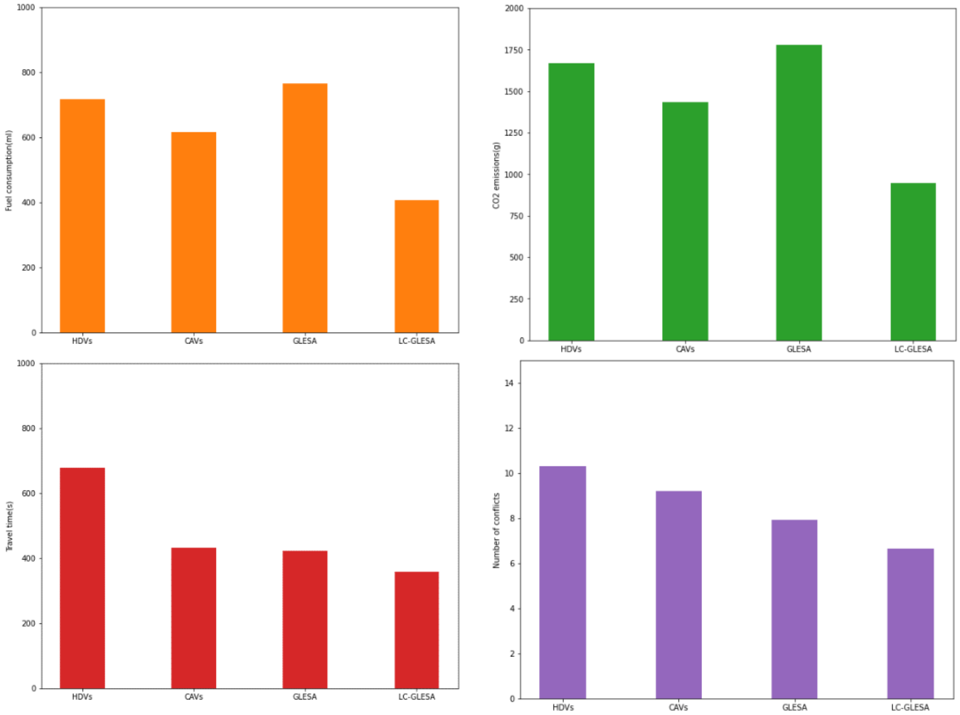


Figure 19 The result of the control strategies for the vehicles in congestion states

The performance of the LC−GLESA strategy was heterogeneous depending on the traffic states. The performance of the LC−GLESA strategy was measured with the level of service (LOS) for intersections in urban areas based on the Korea Highway Capacity Manual(Table 9). As the LOS rosed, throughput, fuel consumption and CO2 emission, travel time, the number of conflicts of the LC−GLESA strategy increased. The throughput and number of conflicts had climbed to a record 224%와 107% between LOS B and LOS C. The fuel consumption and CO2 emission and travel time had climbed to a record 29% between LOS E and LOS F.

Table 9 The effectiveness of the LC-GLESA based on the LOS

LOS	Waiting time (s)	Throughput	Average vehicular fuel consumption (ml)	Average vehicular CO2 (g)	Average vehicular travel time (s)	Average vehicular conflicts
≤B	30	1,163	151	352	162	1.72
≤C	50	3,767	169	394	186	3.56
≤D	70	4,699	202	470	222	4.26
≤E	100	5,186	227	530	250	4.89
≤F	220	6,128	293	683	322	5.99
≤FF	340	7,325	349	813	385	7.15

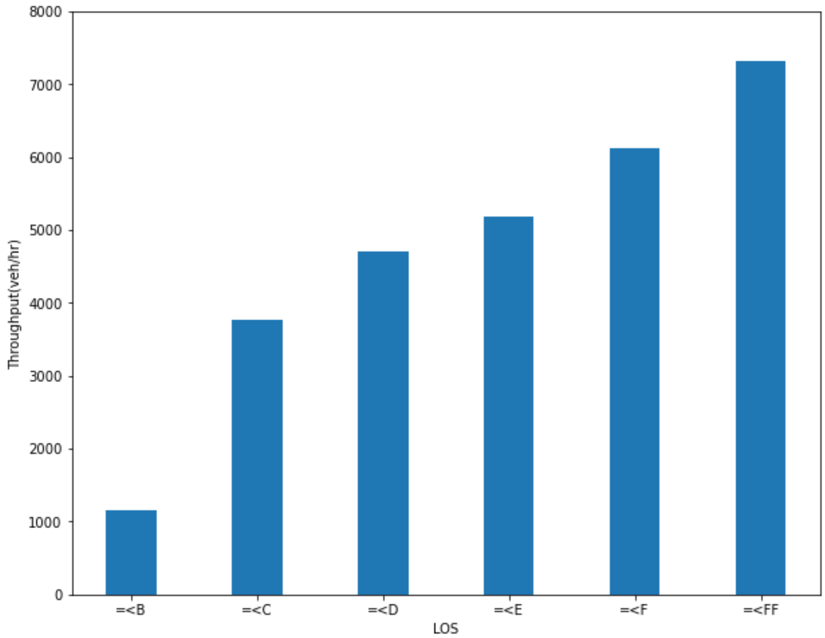


Figure 20 The effectiveness of the LC-GLESA for the networks based on the LOS

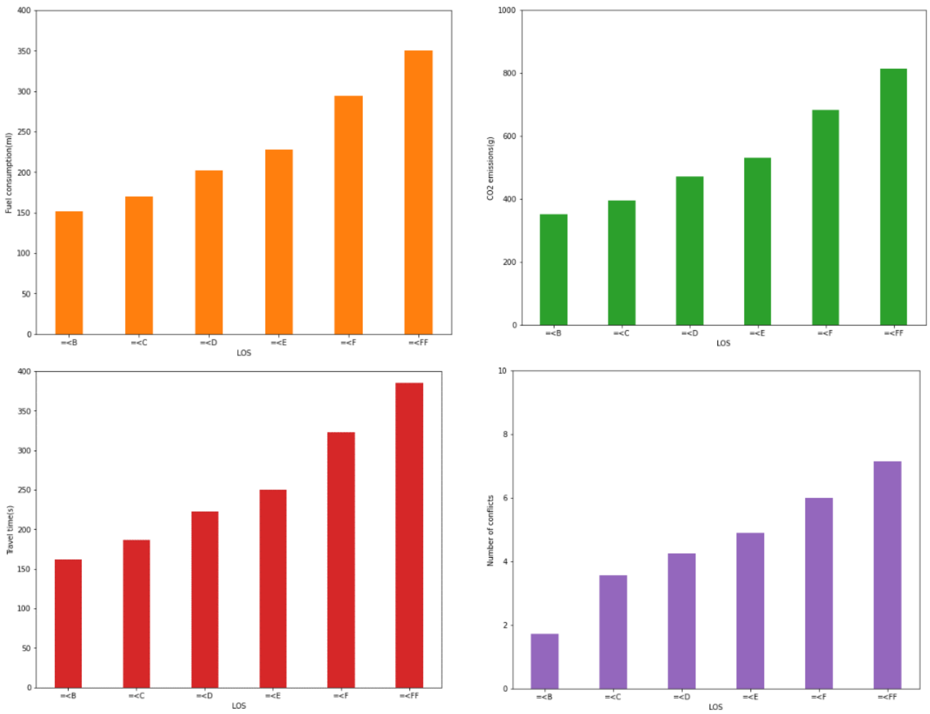


Figure 21 The effectiveness of the LC-GLESA for the vehicles based on the LOS

CAVs were expected to be introduced into the market gradually, and the performance of the LC-GLESA strategy was heterogeneous depending on the market penetration rate (MPR) of CAVs. The effectiveness of thenetwork and vehicle was measured depending on the CAV's MPR conducting the LC-GLESA strategy(Table 10).

The traffic demand assigned to the network was set to the congestion states in the table 8, and the MPR of the CAVs conducting LC-GELSA strategy was adjusted. As the MPR of CAVs rosed, the throughput of the network increased gradually excluding the 40%, 50%, and 80% the CAV's MPR. As the MPR of CAVs rosed from 0% to 100%, the throughput of the network increased by 41%. Among the 41% increment in the throughput, the MPR of CAVs between 0% to 70% accounted for 40% of the throughput, and the one remained did 1%. In 40% and 50% MPR of CAVs, the disparity of HDVs and CAVs was 120 vehicles, and the throughput of the network plummeted.

The fuel consumption and CO_2 emission of CAVs and HDVs were diminished excluding 40% MPR. The 10%, 50%, 90%, and 100% MPR of CAVs revealed over 10% deductions of the fuel consumption and CO_2 emission. CAVs consumed fuel and emitted CO_2 greater than HDVs regardless of the market penetration of CAVs. The travel time of CAVs and HDVs decreased excluding 40% MPR of CAVs. The 10%, 50%, 90%, and 100% MPR of CAVs revealed over 10% deductions of travel time. CAVs took travel time greater than HDVs regardless of the market penetration of CAVs. The number of conflicts of CAVs and HDVs decreased in over 50% MPR of CAVs. The CAVs and HDVs in 10% MPR of CAVs had climbed to a record in the number of conflicts. CAVs provoked conflicts less than HDVs excluding 10% MPR of CAVs.

Table 10 The effectiveness of the LC-GLESA based on the MPR of CAVs

	MPR (%)	0	10	20	30	40	50	60	70	80	90	100
HDVs	Throughput	4,845	4,861	4,536	4,165	3,733	2,396	2,834	2,434	1,884	1,434	-
	Average vehicular fuel consumption (ml)	591	483	467	432	441	419	401	386	369	353	-
	Average vehicular CO2 (g)	1,376	1,125	1,086	1,006	1,026	974	933	898	858	818	-
	Average vehicular travel ttme (s)	678	562	537	501	517	474	458	442	414	385	-
	Average vehicular conflicts	10.3	10.51	10.57	9.99	10.16	10.71	9.86	9.75	9.13	8.52	-
CAVs	Throughput	-	797	1,377	1,916	2,452	2,276	3,732	4,334	4,873	5,850	6,827
	Average vehicular fuel consumption (ml)	-	566	520	489	496	463	439	437	417	371	326
	Average vehicular CO2 (g)	-	1,318	1,211	1,139	1,154	1,078	1,023	1,016	971	864	758
	Average vehicular travel time (s)	-	707	644	604	618	555	527	515	488	423	358
	Average vehicular conflicts	-	10.85	10.17	9.62	9.26	9.57	8.67	8.70	8.44	7.40	6.65
Total	Throughput	4,845	5,658	5,913	6,081	6,185	4,672	6,557	6,768	6,757	6,792	6,827
	Average vehicular fuel consumption (ml)	591	495	479	450	462	440	423	418	404	365	326
	Average vehicular CO2 (g)	1,376	1,152	1,115	1,048	1,076	1,025	984	974	940	849	758
	Average vehicular travel time (s)	678	582	562	533	577	513	496	489	467	413	358
	Average vehicular conflicts	10.30	10.56	10.48	9.88	9.8	10.15	9.20	9.07	8.64	7.64	6.66

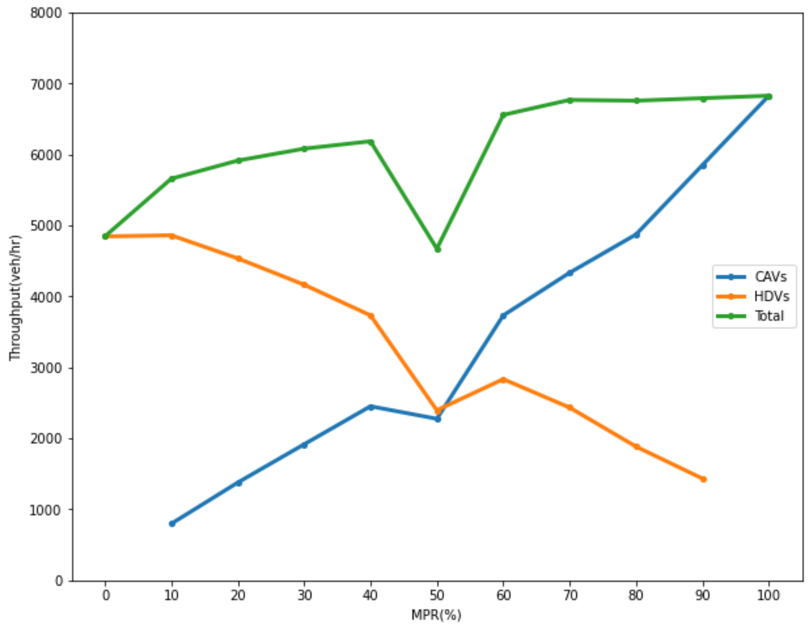


Figure 22 The effectiveness of the LC-GLESA for the networks based on the MPR

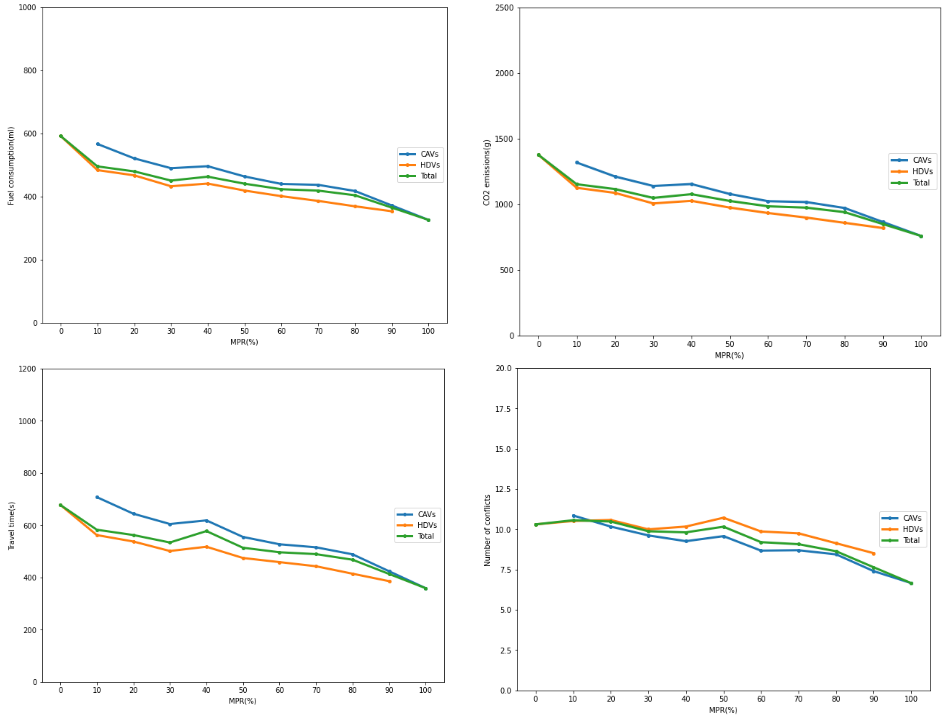


Figure 23 The effectiveness of the LC-GLESA for the vehicles based on the MPR

Chapter 6. Conclusion

In this study, The LC-GLESA strategy was proposed to overcome the limitation of the GLESA strategy and to improve the effectiveness of the GLESA strategy in congestion states. The LC-GLESA conducted proactively a lane change with the Trip and MAP data, and controlled entry speed with the DSRC and SPaT data. The effectiveness of the HDVs, CAVs, GLESA, and LC-GLESA in the data-driven network was measured to demonstrate the improvement of the LC-GLESA strategy. The performance of CAVs, GLESA, and LC-GLESA strategies was slightly improved compared to HDVs in free-flow states. The performance of the GLESA strategy deteriorated in the congestion states representing the limitations of the GLESA strategy commented in previous studies. However, the LC-GLESA strategy overcame the limitation of the GLESA strategy and improved considerablely the performance of network and vehicles.

The performance of the LC-GLESA strategy was measured on the LOS and the MPR of CAVs to establish the operation policy of the LC-GLESA strategy. Great enhancement of throughput and the number of conflicts were discovered in the traffic states between LOS B and LOS C. The LC-GLESA strategy could improve greatly traffic flow of the network in the traffic states between LOS B and LOS C. Considerable increments of fuel consumption and CO2 emission and travel time were observed in the traffic states between LOS E and LOS F. The LC-GLESA strategy could economize considerably fuel consumption and CO2 emission and travel time of the CAVs in the traffic states below LOS E.

Among the MPR of CAVs, MPR of CAVs between 0% and 70% accounted for the considerable increment in the throughput. The 50% MPR of CAVs was revealed to great decrement in the throughput. The fuel consumption and CO2 emission decreased excluding the 40% MPR of CAVs. The travel time was reduced excluding the 40% MPR of CAVs. The fuel consumption and CO2 emission and travel time of the CAVs were revealed greater than those of HDVs. The CAVs and HDVs in 50% MPR of CAVs had climbed to a record in the number of conflicts. CAVs provoked conflicts less than HDVs excluding 10% MPR of CAVs. The market penetration of the CAVs implementing the LC−GLESA strategy improved the throughput of the network, fuel consumption and CO2 emission and travel time of HDVs.

The results of this study discussed that the LC−GLESA strategy overcame the limitation of the GLESA strategy and improved the performance of fuel consumption and CO2 emission, throughput, travel time, number of conflicts. The performance of the LC−GLESA strategy has a significantly positive effect in an environment with dense traffic volume and traffic lights such as Seoul and was expected to derive considerable economic value. The results of this study could contribute to the establishment and operation of the LC−GLESA strategy depending on the LOS and MPR of CAVs.

In this study, the LC−GLESA strategy was designed with fixed logic parameters of the lane change interval and lane change order. The LC−GLESA could be advanced by applying the V2V communication controlling dynamically the lane change interval and lane change order in further study.

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요　　약(국문 초록)

자율협력주행 환경의 도시부 네트워크 차로변경 및 속도추천 통합제어전략 개발

본 연구는 자율협력주행 환경에서 도시부 교차로 진입구간을 대상으로 교차로 진입속도 추천전략의 한계를 극복하는 LC-GLESA 전략을 개발하는 것을 목표로 한다. 제안된 전략을 개발하고 전략의 효과를 검증하기 위하여 미시 교통시뮬레이션 SUMO를 사용하여 시뮬레이션 실험과 사례연구를 수행하였다. 시뮬레이션 실험을 통해 자율주행차량의 차량모형과 V2I 통신시스템을 구축하여 LC-GLESA 전략을 개발하였다. 사례연구를 통해 서울대입구역 인근의 도시부 도로네트워크, 통행권, 신호현시, 교통량, 통행속도 데이터를 기반의 실제 도시부 교통상황을 모사하는 시뮬레이션 환경을 구축하였다. 구축된 시뮬레이션 환경에서 일반차량, 자율주행차량, GLESA, LC-GLESA 전략의 효과를 평가하였다. 혼잡교통 상황에서 GLESA 전략의 성능이 저하되었으며, LC-GLESA 전략이 저하된 성능을 개선하는 것이 확인되었다. 추가로, 서비스수준 및 자율주행차의 시장침투율에 따른 LC-GLESA 전략의 성능을 평가하였다. 서비스수준이 B와 C 사이의 교통상황에서 처리교통량과 차량당 상충건수의 상당한 증가량이 관찰되었다. 자율주행차량의 시장침투는 네트워크의 처리교통량을 향상시키고, 일반차량의 연료소비량과 CO2 방출량, 통행시간을 감소시켰다. 본 연구의 결과는 LC-GLESA의 전략 수립 및 운영에 기여할 수 있을 것으로 판단된다.

주요어 : 도시부 신호교차로, 교통 제어관리, 자율협력주행, 차로변경 및 교차로 진입속도 추천 전략, 교통 시뮬레이션

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