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Autonomous driving parking robot systems for urban environmental benefit evaluation

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ABSTRACT

Many countries are now taking environmental issues seriously and working towards neutral. Therefore, this study aims to reduce carbon emissions by suggesting ways to reduce the use of passenger cars and induce the use of public transportation and walking modes. To this end, a valet parking robot system was designed in a transfer car park outside Seoul. The effect of the system was quantified. By implementing the valet parking robot system in the transfer parking lots, the time to find a parking space and the time to park after finding a parking space are reduced when using existing parking lots. In other words, the valet parking robot system can reduce out-of-vehicle time, and the reduction in travel time can induce a modal shift from existing car users to public transport. Furthermore, by reducing the number of cars in the city center, vehicle kilometer traveled(VKT) will be reduced, and the emission of pollutants that cause air pollution will also be reduced due to less traffic on public roads in the city center. This study analyzes this quantitatively and concludes that the implementation of a valet parking robot system can have a positive environmental impact.

1. Introduction

Traffic congestion is a problem in urban centers in many countries around the world, slowing the speed of vehicles on the road and resulting in longer travel times for passengers (Anupriya et al., 2023). Traffic congestion is considered one of the biggest causes of air pollution, which is caused by emissions from vehicles (Abed et al., 2020). In Seoul, the capital city of South Korea, business and commercial facilities are increasingly concentrated in the city center, and extreme traffic congestion is caused by the large number of people traveling to the area, especially during rush hour (You, 2022). During rush hour, traffic within Seoul becomes more congested due to traffic flowing in and out of the city's major business districts from outside the city as well as within the city itself. As a result, even if there is little congestion in the suburbs, it becomes more severe as you enter the city center. The long-term policy of sustainable transport development promotes cycling and contributes to an increase in the number of users of the road transport network for short-distance transport (Macioszek and Granà, 2022), and electric scooter systems are also widely used in micro-mobility systems in many cities around the world (Macioszek et al., 2023; Choi et al., 2023b). Such personal transport is mainly used to connect the first and last mile to public transport, such as subways and buses. In other words, to induce the transition of car users to sustainable transport, it is necessary to induce the use of public transport. Park and Ride (P&R) has been widely adopted and implemented as a way to reduce parking demand and alleviate traffic congestion in urban centers (Wang et al., 2020). This study aims to reduce car use by encouraging people to drive outside the city center, park on roads where congestion starts, and transfer to public transport. As parking and transfer times becomes longer, passengers will choose to drive directly to their destination by car, so parking and transfer time should be minimized to prevent this (Pang and Khani, 2018). Therefore, this study investigates how to reduce parking and transfer time to induce travelers to use transit parking.

Recently, parking robots have been developed for parking cars and are considered a promising technology to provide reliable parking efficiency. In this study, these valet parking robots were considered to save parking time in order to encourage transfer to public transportation. If a robot replaces the process of manually searching for a parking space, parking, walking to public transportation, and then transferring to public transport, where passengers can park their car at the entrance and immediately transfer to public transport, it can reduce the time spent parking and transferring, which can reduce the time spent out of the

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vehicle and lead to a modal split effect towards public transport(Altieri et al., 2020). Reducing the number of passenger cars on city streets can also have a positive impact on the environment by reducing air pollution emissions from passenger cars (Migliore et al., 2020). In this study, a valet parking robot system that takes care of parking saves the time spent on parking and reduces out-of-vehicle time to encourage transfers to public transport. This study calculates the change in the number of passenger cars in the entire city center due to the transfer and quantitatively analyzes the expected environmental benefits. The world is facing problems such as air pollution caused by traffic congestion, and traffic congestion, especially during rush hours, is increasing from the outskirts of the city to the city center. This study aims to consider positive environmental benefits such as reducing air pollution by introducing a valet parking robot system and reducing parking search, execution time and transfer time for public transport. Fig. 1 illustrates the effectiveness of the valet parking robot system from an environmental perspective. The introduction of the valet parking robot system explains that the reduction in VKT due to the sharing of public transport by existing car users can reduce various air pollutants caused by car use.

2. Literature review

2.1. Valet parking robot system status and technology trends

A valet parking robot system is a system that allows a vehicle to be parked in a parking space without a user, and it can move to a specific location when the user wants, such a valet parking robot system is being developed by dividing it into an exploratory driving process, an autonomous parking process, and a return driving process (Jo et al., 2023). In line with the different types of parking robots and their emergence, optimization techniques have been proposed. Li and Miao (2020) performed the path planning and scheduling of the robotic parking system in a mathematical expression to live the parking problem of the stereo garage and showed that it was effective in reducing waiting time. Chen et al. (2021) proposed a genetic algorithm for high-density parking lots and a time-enhanced A* path planning algorithm. It proved to be excellent in terms of execution time and distance. The TEA* algorithm was also chosen because it is easy to implement. Chai et al. (2023) proposed a deep learning-based projection planning and control strategy to improve the parking manoeuvre problem of the autonomous ground vehicle (AGV). Through the RDNN-based motion planning approach, the optimal parking plan and real-time application of the control system were described. Zhou et al. (2021) drew a roadmap according to the technological development direction of the AGV parking robot. At that time, it was explained that the integration of the AGV parking robot and the stereo garage and the improvement of the internal mechanism of the parking robot are the current technological trends. It was also mentioned that the mechanism used together with the safety device and the parking robot will need to be strengthened in the future. Thus, the technological level of the parking robot system is advancing and its effects are also being positively implemented. Williams (2019) introduced Stanley Robotics from France, who explained the role of the parking robots. Using airport parking demand as an example, he said that parking capacity could be increased by up to 50% by using a parking robot system in the same area of space. In addition, drivers are said to be very satisfied with the parking robot service as it can save time and reduce the burden of accidents. However, there is a lack of research on the modal split effects of parking robots. Therefore, this study will analyze the effect of reducing transfer time and the environmental benefits of using parking robots to transfer passenger cars.

2.2. Effects of walking and public transportation on reduced transit distance/time

Garcia-Martinez et al. (2018) investigated the inefficiency of transfer factors in multimodal public transport using an SP survey. Walking distance and walking time for transfers were perceived as significant barriers. The waiting time for the next mode of transport was also perceived as a significant penalty. The act of transferring itself was perceived as taking about 15 min of travel time in the vehicle. Walking time was perceived as an even greater negative if more than one transfer was required. However, the study was limited to urban public transport users. Islam et al. (2015) analyzed the factors influencing the mode choice of P&R users. They found that in-vehicle time in public transport and transfer time in P&R were the most important factors affecting transportation mode choices. In particular, the shorter the in-vehicle time in public transportation and the shorter the transfer time, the more people preferred P&R to single-occupancy vehicle use. Huang et al. (2019) quantitatively analyzed the factors influencing the use of P&R. The study focused on areas with active P&R at the time of the study. The results showed that parking fees, public transport transit time, and P&R transit time influenced P&R preference. The sensitivity to transfer time was greatest, and it was concluded that parking charges and the design of parking facilities are important for public transport and P&R use. Ying and Xiang (2009) investigated the conditions for car users to use P&R. About 88% of the respondents were willing to use P&R if the waiting time was 5 min or less. Regarding the number of transfers, about 89% of the respondents would accept one transfer after P&R. About 98% of respondents said they would choose P&R if the walking distance was within 500 m. Thus, short waiting times, including transfers and short walking distances were found to improve the use of public transport. Iseki and Taylor (2009) found that reducing walking distance, walking

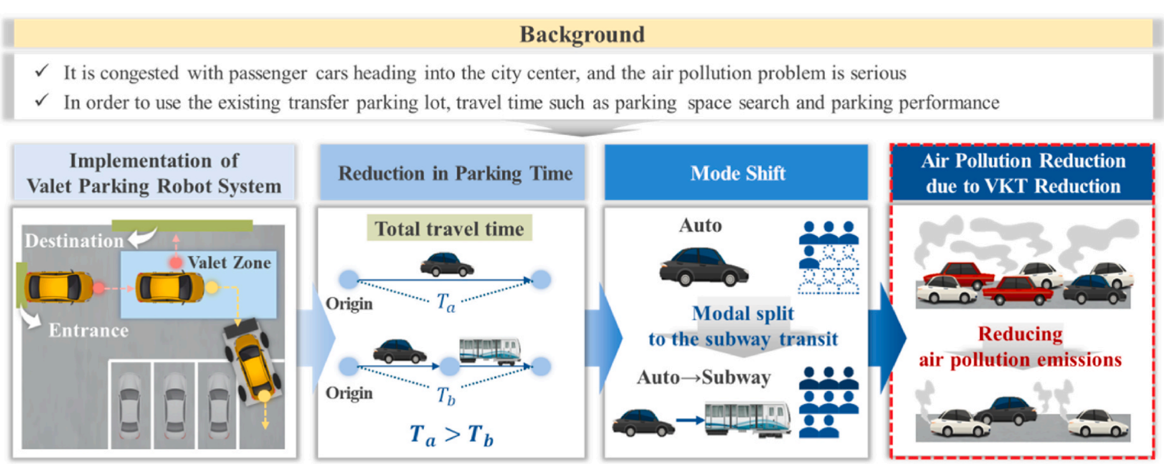

Fig. 1. Effectiveness of valet parking robot system in environmental aspect.

time and waiting time can significantly increase the efficiency and utilization of public transport systems. The impact of reducing transfer times was calculated in economic terms. The scenarios were compared using travel costs including transfer times. The travel cost in the scenario that minimized transfer time was $19 less than the cost in the scenario that maximized it. The study analyzed a $2.42 reduction in travel costs as equivalent to a 63% increase in average travel speed. In conclusion, reducing transfer times has a very positive impact on the experience of using public transport. This study analyzes how much transfer time is reduced by implementing the valet parking robot system to induce the use of public transport mode, how much transfer time is reduced by implementing the valet parking robot, and how much existing car users can be shifted to public transport as transfer time is reduced.

2.3. Environmental benefits of increased walking and public transportation

Li (2016) explains that public transport is an environmentally effective modes, noting that the activation of public transport in passenger cars helps to reduce traffic congestion, reduce energy consumption, and improve air quality. In particular, Ochiai et al. (2021) analyzed the effect of mode choice by combining total travel time and CO_2 emissions, arguing that choosing environmentally friendly transport mode helps to reduce air pollution. The results showed that CO_2 emissions can be reduced by 9.23%. Fan et al. (2018) highlighted the importance of considering air pollutants in the transportation sector and evaluated the extent of air emissions related to transportation. Fan et al. states that in addition to the method of evaluating only greenhouse gas emissions, a transportation system should be established that considers air pollutant emissions. In this study, only freight movement was analyzed, but it is important to promote environmentally friendly transportation such as public transportation and walking in both freight and passenger transportation. Bencekri et al. (2023) evaluated the effects of carbon reduction policies implemented in the transport sector. Different policies were evaluated based on the amount of change in carbon emissions according to living patterns, and it was analyzed that the construction of a mobility hub, one of the policies to activate public transport, has the most distinct carbon reduction effect. It was concluded that the implementation of a mobility hub, which is part of the use of public transport, contributes more to environmental friendliness than policies such as the promotion of electric vehicles or the introduction of congestion charges. This study also quantitatively analyzes the positive effects in the environmental effects that occur when existing car users switch to public transport due to the parking robot.

2.4. Agenda in the age of self-driving

As the era of autonomous driving comes, various changes in cities are predicted, and various studies are underway to cope with them. Vitale Brovarone et al. (2021) proposed a 2050 urban plan according to the era of autonomous driving with superblock cities, explaining positive opportunities. Sequentially, in 2020–2030, it aims to set the urban infrastructure for autonomous driving and to test technologies such as V2I. In 2030–2040, the previously tested parts are established and the use of AV services is promoted. 2040–2050, roads inside the super block are reconstructed to improve the quality of life of the city. As a result, it was proved that private vehicles can be suppressed, shared mobility can be promoted, and free spaces can be secured. Likewise, Curbed(2016) explained that the need for parking spaces will decrease and the space allocated to public areas of cities will further increase as AV is commercialized. For example, taking San Francisco as an example, it has been explained that road diets are possible as road traffic decreases through AV, and accordingly, large public spaces in cities can be utilized. Wellik and Kockelman (2020) explained the impact of fully adopting autonomous driving on residential land use in the area. As a result of analyzing it in the background of Oston City, it was predicted that the number of households would partially decrease and the number of developable land would increase. At this time, as a result of analyzing it with a shared autonomous vehicle (SAV) scenario, it was analyzed that the urban sprawl phenomenon due to the reduction of travel time would increase. Nogués et al. (2020) were concerned about the urban sprawl in the era of autonomous driving and proposed future urban plans to alleviate it. Nogués et al. argued that it would be effective to increase the means-sharing rate of walking, public transportation, and bicycles, promote shared transportation, limit access to engine-based modes in the center of the city, and use urban free space. And it has been proved by experts that this policy will be effective. Manivasakan et al. (2021) conducted a study in a case in Melbourne, Australia, arguing the need for a new urban infrastructure plan for the implementation of autonomous driving. In particular, the infrastructure evaluation framework was presented based on three criteria: safety, efficiency (reduction of commuting time), and accessibility (access to essential services of AV), and based on this, the conceptual design of road networks was designed as follows. In addition, the emergence of autonomous vehicles can raise environmental awareness and have a positive impact on the transition to a sustainable city (Cugurullo et al., 2021).

According to the literature review, the technology of the Barrett parking robot system is developing rapidly, and the advent of the self-driving era is expected to have a positive impact on the transition to a sustainable city, such as solving the urban sprawl phenomenon. In addition, the efficient park and ride operation with the introduction of the valet parking robot system suggests that existing car users can expect a change in public transportation mode due to shorter parking time, and the decrease in car use can have positive environmental effects due to reduced air pollutant emissions.

3. Methodology

This study concludes that the implementation of a valet parking robot system in transit parking facilities can induce transfers from traditional car users to public transportation. To this end, it analyzes how much passenger's out-of-vehicle time is shortened when the valet parking robot system is implemented after assuming parking search time and parking execution time according to the size of the parking lot. Second, it analyzes how much modal splits occur due to transit to public transportation due to a decrease in non-vehicle time. Finally, the reduction of road mileage (VKT) due to the mode shift to public transportation and the resulting positive environmental impact are calculated. Fig. 2 shows the framework of this study. The variables used in the methodology are described in Table 1. In addition, Ku et al. (2022) and Choi et al. (2023a) analyzed a similar effect due to the implementation of mobility hubs, and we reformulated the equation after reviewing their paper.

3.1. Estimation of transfer parking time

For passengers using a traditional transit parking lot, it is a common procedure to enter the parking lot, search for a parking spot, park the vehicle in the found spot, get out of the vehicle, and transfer. The valet parking robot system is a system in which a passenger car user parks in a designated area (Valet Zone) and the valet parking robot immediately finds a suitable spot and parks the car. This greatly reduces the time for parking lot users to navigate and perform parking. In this study, it is assumed that the time saved by allowing the robot to park the car varies depending on the size of the parking lot. The time saved by the implementation of a valet parking robot system is illustrated in Fig. 3. In Fig. 3, before the implementation of the valet parking robot, the Seek Time (T1) represents the time to search for a parking spot, the Parking Time (T_2) represents the time to park after finding a parking spot, and the Transit Time (T_3) represents the time to get out of the car after parking and move to transfer. Valet zone Parking Time (T_0), after the implementation of the Valet parking robot, represents the time it takes

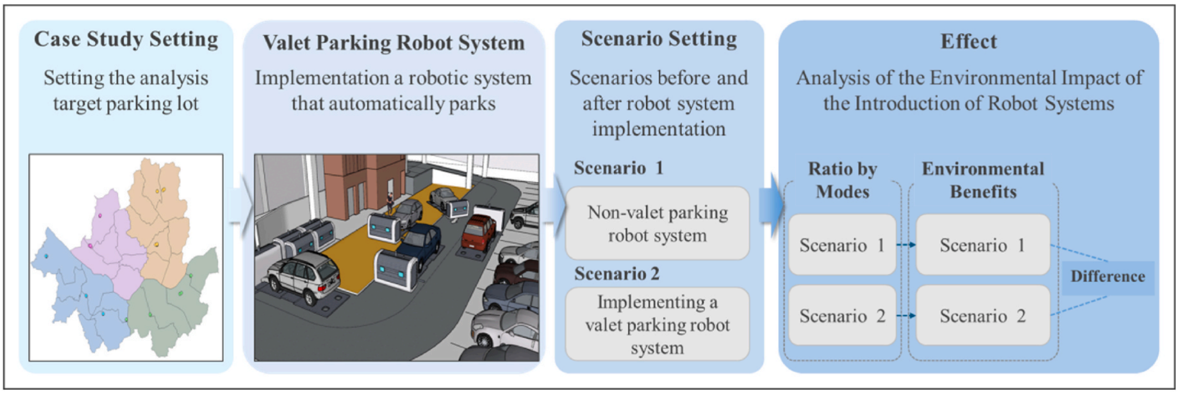

Fig. 2. Framework of this study.

Table 1
Description of variables used in this study.

Notation	Description
T_0	Time to park the vehicle in Valet Zone
T_1	Time spent navigating an empty parking space
T_2	Time required to park after searching for an empty parking space
T_3	Time taken to get off the vehicle and move to the transfer passageway
P_{ri}	Selection probability of choosing modified mode i
$P_{i(or\ j)}$	The probability of selection of mode i (or j) (i (or j)
$V_{i(or\ j)}$	Utility function of each mode i (or j) of the choice set I (or J)
$V_{a(or\ b)}$	Utility function of each mode a (or b) (a: 1)auto, 2)taxi/b: 1)bus, 2) subway)
$C_{ta(or\ b)}$	Travel time coefficient for mode a (or b)
$TT_{a(or\ b)}$	Travel time by mode a (or b)
C_{ob}	Out-of-vehicle time coefficient for mode b
OT_b	Out-of-vehicle time by mode b
EC	Difference of environmental benefits
$EC_{without(or\ with)}$	Environmental cost(with or without a robotic system)
V	Speed of vehicle
L	Finite set of links in Seoul
K	Type of vehicle(k: 1)auto, 2)bus, 3)truck)
D_{lk}	The vehicle's travel distance (km) to link l by vehicle type (Before implementing valet parking robot)
D^{*}_{lk}	The vehicle's travel distance (km) to link l by vehicle type (After implementing valet parking robot)
C^{v}_{lk}	The air pollution cost/km for link l and vehicle type k and speed v.

to park a vehicle in the valet zone. T_1 and T_2, which are travel times before the robot is implemented, are not incurred by the user after the robot is implemented because the robot performs them instead. In the case of T_3, it is the time that occurs both before and after the robot is implemented, but the robot system has the effect of reducing T_3 by reducing $T_1$and T_2. In this study, we analyze how much T_1 and T_2 are reduced by the implementation of a valet parking robot system and what effects it has.

T_1 can vary depending on factors such as the shape and size of the parking lot. If the parking lot is nearly full, it may take more time to find a parking space. The seek time is also affected by whether the driver is familiar with the parking space, i.e., the seek time can be reduced if the driver is parking in a familiar environment. Finally, seek time can vary depending on whether the flow of vehicles in the parking lot is smooth or congested with vehicles looking for or exiting a parking space this study measures parking lots to estimate the average parking time of parking lots under typical conditions. In this case, the typical situation is a parking lot that is not congested and has around 1000 parking spaces. It is assumed that the average search time is 3–5 min, and the parking time is generally 1–2 min. These times can vary depending on the driver's parking skills and the location of the parking space. These hours were set based on research on general parking conditions in Korea and the results of research. Therefore, it is not applicable to all parking lots and is the assumed time. Therefore, in this study, several stops were set as case studies to estimate the average search time and average parking time based on the assumed time assuming the number of parking spaces (size).

3.2. Effect of public transportation shift due to reduced transfer time

In this study, the deployment of the valet parking robot system determines the degree to which users who currently use cars can induce public transportation modal splits through transfer parking lots. This quantifies the environmental benefits by determining how much VKT can be reduced by implementing a valet parking robot system. The transportation demand forecasting model is a model that is continuously used for rational transportation planning and transportation system evaluation. In this study, transportation demand is estimated using the

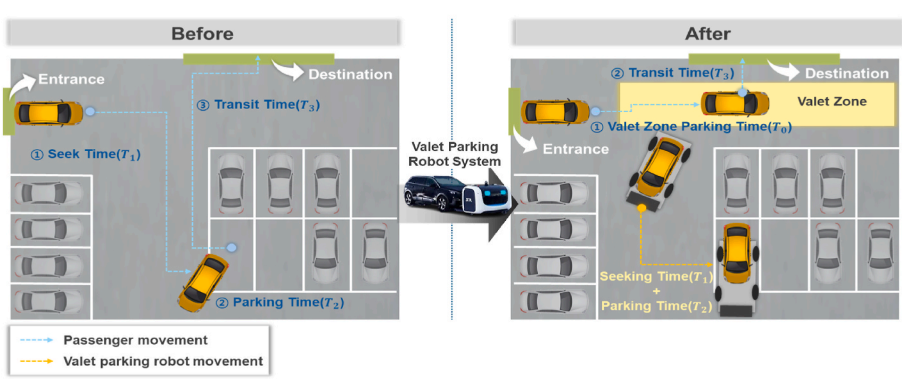

Fig. 3. Travel time before and after the implementation of the valet parking robot system.

most commonly used traditional four-step model. Transportation demand forecasting mainly consists of four steps: trip generation, trip distribution, modal split(mode shift), and trip assignment (Ahmed, 2012). Trip generation is a step that estimates the number of people or vehicles traveling out of or into a given area or zone within a city. Trip distribution is a step that predicts the amount of traffic traveling between each origin-destination pair. Modal split is a step that predicts the share of traffic between the origin and destination for each mode of transportation. Finally, trip assignment is a step that predicts the traffic volume by route between the origin and destination for each mode. To carry out this transportation demand forecasting process, this study calculated the modal split effect by changing the in-vehicle time and out-of-vehicle time parameters through the introduction of the valet parking robot system using the EMME/4 simulation program. To do this, the situation such as EMME/4 was set through the road and rail traffic settlement process and entered the in-vehicle time and out-of-vehicle time data to simulate it.

In the mode segmentation stage, a valet parking robot system can be established to analyze how the mode is switched. Factors that influence mode choice include travel cost, travel time, waiting time, and comfort (Devika and Harikrishna, 2020). In this study, analyze the modal split caused by the implementation of a valet parking robot system that reduces passenger's extra-vehicle time. Probabilistic choice models have been most commonly used to predict the probability of transportation mode choice. Also, the logit model is a typical model used in probabilistic choice models (Rigaut, 2022). Multinomial logit models are often used for modal split models due to their improved simplicity and flexibility in handling multiple explanatory variables (Das et al., 2021). Among them, the incremental logit model can understand the change in utility between the old mode and the new mode, which can be used to predict the probability of choosing the new mode (Pukhova et al., 2021). The incremental logit model expression for the choice probability is Eq. (3.1). In this study, the utility change for the extra-vehicle time before and after the valet parking robot system is implemented is identified, and the probability of public transportation transfer selection is predicted using this.

$$P_{ri} = \frac{P_i \bullet exp\ (\Delta V_i)}{\sum_{j=1}^{J} P_j \bullet exp\ (\Delta V_j)} \tag{3.1}$$

where P_{ri} is the probability of selection of the modified mode i, P_i is the probability of selecting the existing mode i, and each has a utility function ΔV_i mode $i(i = 1, 2, 3, \ldots, I)$ consists of 1) cars, 2) buses, 3) subways, and 4) taxis. ΔV_j is changes of utility of mode $j(j = 1,2,3,\ldots,J)$.

In this study, the values provided by the Korea Development Institute (KDI) guidelines were used, and the utility function consists of travel time and travel cost (Ku et al., 2022). Since out-of-vehicle is reduced by the implementation of the valet parking robot system, the modal split can be calculated by adjusting the travel time in the utility function. In Eq. (3.2), V_a is the utility function of a passenger car/taxi, and in Eq. (3.3), V_b yields the utility function for a bus/subway, and so on.

$$V_a = C_{ta} \times TT_a \ - C_{ca} \times TC_a \tag{3.2}$$

$$V_b = C_{tb} \times TT_b \ - C_{cb} \times TC_b + C_{ob} \times OT_b \tag{3.3}$$

Where, C_{ti} is the coefficient for mode i (i = 1,2)travel time, TT_i is the travel time by mode i, C_{ci} is the coefficient for mode i (i = 1,2) travel cost, TC_i represents the travel cost by mode i, the mode i consists of 1) car, 2) taxi. C_{tj} is the coefficient for mode j (j = 1,2)travel time, TT_j is the travel time by mode j, C_{cj} is the coefficient for mode j (j = 1,2) travel cost, TC_j represents the travel cost by mode j, C_{oj} is the out-of-vehicle time coefficient for mode j, OT_j is the out-of-vehicle time by mode j, the mode j consists of 1) bus 2) subway.

3.3. Environmental benefits

This study aims to analyze the environmental impact of the implementation of a valet parking robot system by reducing VKT by encouraging passengers who previously traveled to the city center by car to park outside the city center and travel to the city center by public transportation. In the literature review, it was mentioned that increased use of public transportation helps to improve air quality. Based on this, this study aims to quantitatively analyze the effect of implementation a valet parking robot system on reducing air pollution. To do so, first, the air pollution unit price is calculated by converting the emission factors for various pollutants generated by passenger cars into costs by pollutant, mode, and speed. The difference in cost (EC) of reducing air pollution due to the implementation of the valet parking robot system is equal to the difference between the cost ($EC_{with/without}$) of air pollution before and after the implementation of the valet parking robot system and this can be seen from Eq. (3.4), the air pollution cost before the implementation of the valet parking robot system is given by Eq. (3.5), and the air pollution cost after its implementation is Eq. (3.6).

$$EB = EC_{without} - EC_{with} \tag{3.4}$$

$$EC_{without} = \sum_{v=1}^{V} \sum_{l=1}^{L} \sum_{k=1}^{K} D_{lk} C_{lk}^{v} \tag{3.5}$$

$$EC_{with} = \sum_{v=1}^{V} \sum_{l=1}^{L} \sum_{k=1}^{K} D_{lk}^{*} C_{lk}^{v} \tag{3.5}$$

where, D_{lk} and D_{lk}^{*} are the vehicle's travel distance (km) to link l by vehicle type k when the valet parking robot system was not implemented in the transit parking lot and when it was implemented, k consists of 1) auto, 2) bus, and 3) truck, L is a finite set of links in Seoul, C_{lk}^{v} represents the air pollution cost/km for link l and vehicle type k and speed v.

4. Analysis of outcomes

4.1. Design of P&R with valet parking robot system

Before we begin to analyze the effectiveness of the implementation of the valet parking robot system, it is necessary to design how the valet parking robot system will be implemented. In this study, it is assumed that passengers enter and park at the entrance of the parking lot in the valet zone designed in the space closest to the transfer entrance as shown in Fig. 3 in Chapter 3.1. When a passenger park in the valet zone, the valet parking robot waiting in the waiting zone loads the vehicle and parks it in a space. Conversely, if the passenger wants to come back and use the vehicle again, the valet parking robot will find the passenger's vehicle again and park it in the valet parking zone so that the passenger can perform both the getting on and off process in the valet parking zone. Fig. 4 shows the exterior and interior of a transit parking lot. When entering the first floor and parking in the valet zone located right in front of the transit entrance, the valet parking robot loads the vehicle and parks it on the floor with a parking space. The movement of the valet parking robot can be understood through Fig. 5. In this study, the valet parking robot finds a parking space and manually parks. The amount of time saving in the out-of-vehicle time caused by this is calculated, and the modal split and environmental benefit according to the decrease in out-of-vehicle time are also calculated.

4.2. Case study

4.2.1. Characteristics of Seoul city and satellite city

In the case of Seoul, the capital of South Korea, the modal split rate in Seoul as of 2019 was 34.82% for passenger cars, 19.69% for buses, 25.34% for subways, 10.27% for subways + buses, and 9.87% for taxis, according to KTDB's origin-destination data, an authoritative source used for transportation demand forecasting in South Korea. In other

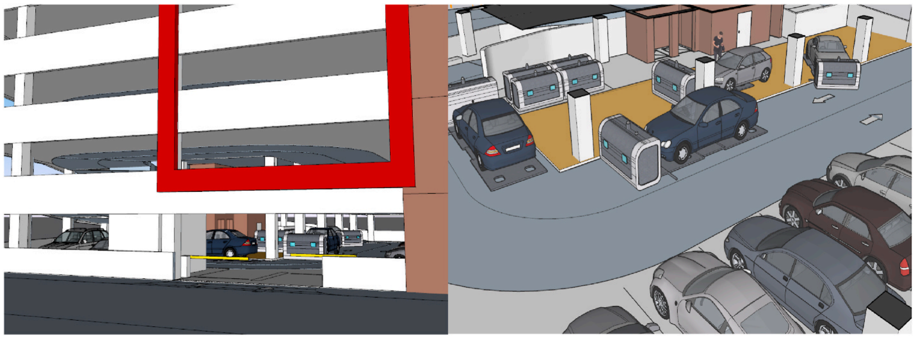

Fig. 4. External and internal views of transit parking lot with valet parking robot system.

Fig. 5. Movement of the valet parking robot system in the transfer parking lot.

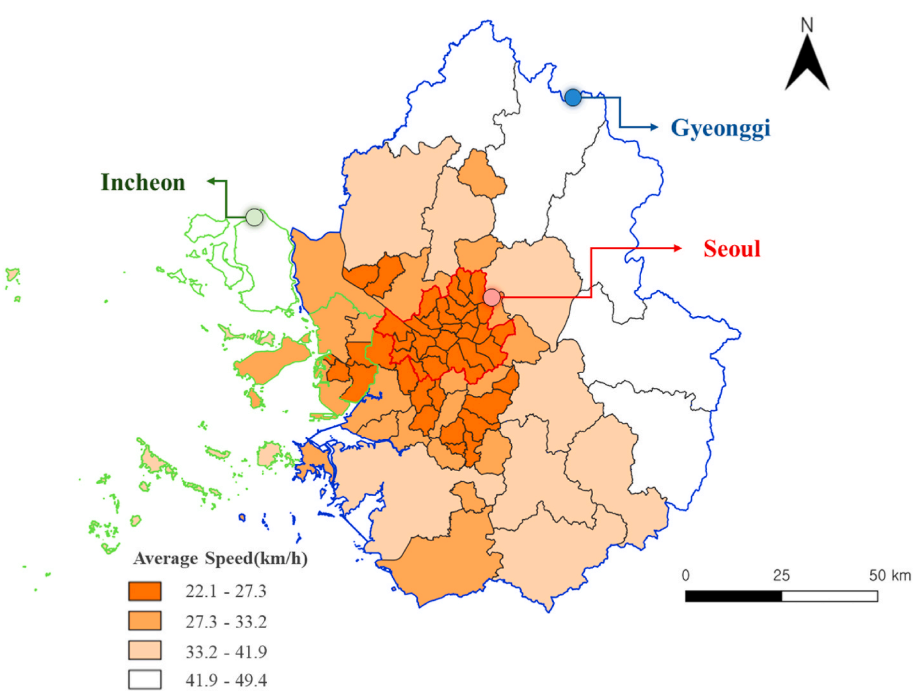

Fig. 6. Average traffic speed in Seoul, Gyeonggi, and Incheon (unit: km/hour).

words, the mode share of public transportation is about 65%. In particular, there are a lot of trips from many neighboring cities, as well as from within Seoul, that are intended to commute to Seoul. As a result, most of the traffic is concentrated during rush hours, causing severe delays inside Seoul during peak hours. Most roads in Seoul, with the exception of child protection zones listed in Seoul Open Data, are regulated at 50 km/h, except where the average speed limit is 30 km/h, the average passenger vehicle speed in 2022 for the entire roadway is 23.1 km/h from 6 a.m. to 10 p.m., 24. In addition, the traffic speed data distributed to Data Open Market in 2017 tends to decrease as you move towards Seoul, as shown in Fig. 6, even when compared to traffic speeds in the neighboring satellite cities of Incheon and Gyeonggi.

Seoul can be roughly divided into four regions based on the Han River: Northwest, Southwest, Northeast, and Southeast. Table 2 shows information on the municipalities included in each of the four regions, and Fig. 7 shows the four regions of Seoul and the satellite cities surrounding each region. Seoul is surrounded by satellite cities such as Incheon and Gyeonggi, and there is a lot of traffic from these satellite cities to Seoul. As a result, Seoul is experiencing severe congestion problems due to traffic generated within Seoul as well as traffic from satellite cities. In particular, the satellite cities located closest to the four major regions are known to have a high volume of commuting traffic to Seoul.

Seoul still has very well-designed public transportation networks, such as subway lines 1 through 9, and bus routes. For this reason, public transportation, such as subways and buses, can go anywhere in the city. In terms of time, it is possible to reach the destination much faster than driving a car with an average speed of around 20 km/h. For this reason, reducing the resistance of passengers to transferring their cars near the outskirts of the city could significantly increase the use of public transportation. Therefore, this study aims to reduce this resistance by using a valet parking robot system to encourage the use of public transportation.

4.2.2. Setting up P&R locations for analysis

In this study, to curb passenger car traffic in central Seoul, the valet parking robot system is introduced inside the transfer parking lot of a subway station located outside central Seoul so that many modal shifts can occur. To this end, in this study, transit parking lots at some transit stations in the inner city of Seoul were set as the target parking lots for analysis to reduce the use of passenger cars in the city center. The criteria for the stations to be analyzed are large in population, located outside the city center so that parking is possible in the outer area, and well connected to the subway mode. Fig. 8 shows the connected stations of the analyzed parking lots by region, and Table 3 is information on the number of parking lots and related routes, which I checked with the "Public Data Portal and the number of subway lines connected to it. In this study, the environmental impact is calculated by analyzing the extra-vehicle time saved when the valet parking robot system is introduced in the parking lot. The stations connected to each parking lot are all stations with more than one line, and if the robot system is deployed in these parking lots, more transfers can be expected. In particular, Gimpo International Airport Station and Cheongnyangni Station are designed with more than four routes, and the effect is expected to be greater due to the large size and usage of the station.

Table 2
Details of the 4 major areas of Seoul.

Division	Number of district	Including district
Southwest	7	Gangseo-gu, Yangcheon-gu, Guro-gu, Yeongdeungpo-gu, Dongjak-gu, Geumcheon-gu, Gwanak-gu
Northwest	6	Eunpyeong-gu, Seodaemun-gu, Mapo-gu, Jongno-gu, Jung-gu, Yongsan-gu
Southeast	4	Gangdong-gu, Songpa-gu, Gangnam-gu, Seocho-gu
Northeast	8	Dobong-gu, Nowon-gu, Gangbuk-gu, Seongbuk-gu, Dongdaemun-gu, Jungnang-gu, Seongdong-gu, Gwangjin-gu

4.3. Effect of modal shift and VKT reduction due to out-of-vehicle time reduction

The out-of-vehicle time saved by the implementation of the valet parking robot system in the transit parking lot of each area was assumed as shown in Table 4, considering the size of the parking lot at each station. In other words, the difference in parking time at the Gimpo international airport station transit parking lot is 14 min before and after the implementation of the robot system, which means that 14 min of time per car is saved by the implementation of the robot system. The implementation of the valet parking robot system has reduced the out-of-vehicle time and increased the utility, resulting in a decrease in traffic moving inside the city center of Seoul. At the same time, the implementation of the valet parking robot system increased the number of trips taken by public transportation by 13,872 trips per year in the southwest region, 16,239 trips per year in the southeast region, 10,773 trips per year in the northeast region, and 11,951 trips per year in the northwest region. In total, the implementation of the valet parking robot system in 12 subway station transit parking lots has increased general rail/subway traffic by 52,835 trips per year. In other words, the implementation of the valet parking robot system has converted 52,835 trips per year of traffic on existing public roads to subway mode. Table 5 shows the changes in mode shift in each of the southwest, southeast, northeast, and northwest regions before and after the introduction of the valet parking robot system.

4.4. Calculation of environmental benefits

The cost of air pollution emissions per kilometer varies by pollution source, and Table 6 shows the unit of air pollution cost by pollution source, i.e., for every kilometer of meritorious travel, the cost of air pollution is 13.88 KRW. By implementing the valet parking robot system in the analyzed parking lots, the total VKT decreased from 342,151,325 km/year to 328,983,020 km/year, a total of 13,168,305 km/year. The result of calculating the cost of air pollution reduction through the corresponding source unit and VKT savings is shown in Table 7, and it shows that a total benefit of KRW 182.78 billion/year is generated. In addition, based on the assumption that 4500 kg of CO_2 is emitted per 300,000 VKT, the emission reduction by implementing the system is 197,525 kg/year, which is summarized in Table 8. In other words, the implementation of the valet parking robot system in the 12 main analyzed parking lots in the outskirts of the city center can save KRW 182.78 billion/year in air pollution costs due to air pollution emissions and reduce CO_2 emissions by 197,525 kg/year, indicating a positive environmental impact.

5. Conclusion

As the climate worsens around the world, many sectors are working on solutions to address the issue. In particular, in the transportation sector, various policies are being put in place to reduce the use of passenger cars and shift the modal split to eco-friendly modes such as public transportation and walking. Currently, many cities, including Korea, are experiencing a concentration of traffic due to commuting to the city center from surrounding satellite cities. In particular, as many passengers use passenger cars to travel to the city center, the congestion on the roads is getting worse and worse, and environmental problems are also arising. To this end, this study proposes a valet parking robot system as a way to reduce the traffic of passenger cars heading to the city center. In Seoul, Korea, the amount of passenger cars heading to the city center is high, but the railroad network is well-developed, and it is easy to travel to various cities in Seoul by subway. Therefore, some service

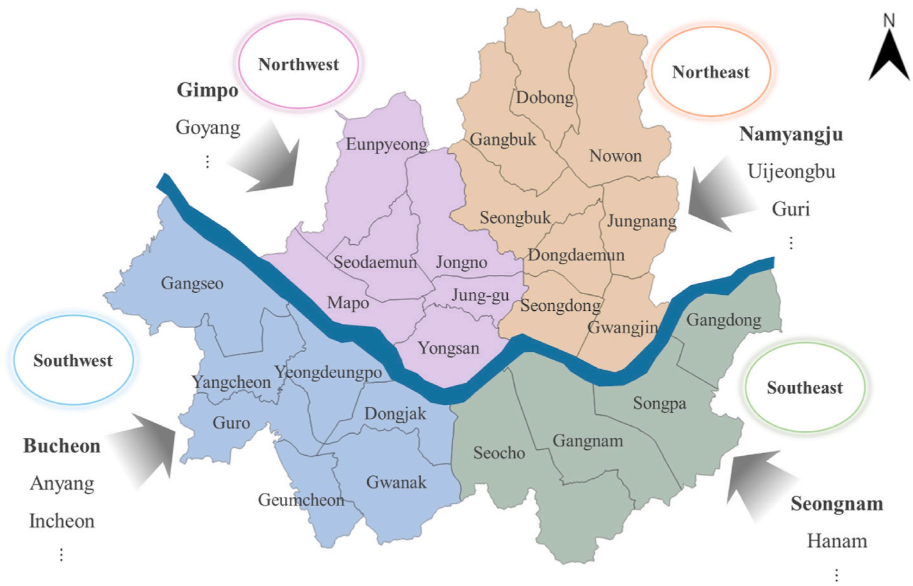

Fig. 7. Four major areas of Seoul and surrounding satellite cities.

Fig. 8. Selecting the implementation of the valet parking robot system.

improvements in the subway can be made to encourage people to use the subway. Valet parking robot systems can induce a mode shift by reducing the time it takes to park in transit parking lots near existing subway stations, thus reducing out-of-vehicle time for passengers. People using traditional transit parking lots have to spend time navigating from the moment they enter the parking lot to find a parking space, and parking time after passengers find a parking space. However, if a valet parking robot system is implemented, passengers will not incur such search time and parking time. In this study, the search time and parking time are assumed by considering the size of the parking lot. The assumed out-of-vehicle time was used to analyze the mode shift in each region, and the results showed that 9758 trips/year were shifted to public transportation in the southwest region, 13,227 trips/year in the southeast region, 7332 trips/year in the northeast region, and 8353 trips/year in the northwest region. This shows that as parking time decreases, people who used to drive to destinations in the city center by car have switched to parking in transit parking lots and transferring to the subway. This mode shift will reduce the use of passenger cars to travel within the city center, which can reduce emissions of various air pollutants on the road. For this purpose, the modal split value was used to calculate the change in total VKT on the road, and it can be seen that VKT decreased from 342,151,325 km/year to 328,983,020 km/year, a total of 13,168,305 km/year. In addition, the reduction in VKTs resulted in a total air pollution reduction benefit of KRW 182.78 billion/year and a total CO_2 emission reduction of 197,525 kg/year. Through this study, it was derived that the parking robot system has a modal split effect on public transport that can occur when parking time is reduced for car users. In addition, creating a modal split can reduce the VKT of existing

Table 3
Analysis target location details.

Regions	Station name	Number of parking space	Number of line
Seonam	Gimpo International Airport	3378	5
	Sindorim	2698	2
	Sillim	898	2
Seobuk	Yeonsinnae	1248	2
	Digital Media City	1698	3
Dongnam	Sadang	1063	2
	Yangjae	1424	2
	Jamsil	2361	2
	Cheonho	1431	2
Dongbuk	Changdong	1009	2
	Nowon	984	2
	Cheongnyangni	1325	4

Table 4
Changes in VKT before and after the implementation of the valet parking robot (unit: minute).

Division	Total time before robot system implemention		Total time After robot system implemention	Difference
	Seeking tme	Parking time	Valet zone parking time	
Gimpo International Airport	13.5	1.5	1	−14.0
Sindorim	10.8			−11.3
Sillim	3.6			−4.1
Yeonsinnae	5.0			−5.5
Digital Media City	6.8			−7.3
Sadang	4.3			−4.8
Yangjae	5.7			−6.2
Jamsil	9.4			−9.9
Cheonho	5.7			−6.2
Changdong	4.0			−4.5
Nowon	3.9			−4.4
Cheongnyangni	5.3			−5.8

Table 5
Before and after the implementation of the valet robot parking system, public transport mode shift (unit: trip/year).

Division	Before valet parking robot system		After valet parking robot system		Mode shift
	Car + Taxi	Bus + Subway	Car + Taxi	Bus + Subway	
Southwest	2,020,936	2,621,164	2,007,064	2,635,035	13,872
Northwest	1,605,696	2,623,931	1,593,745	2,635,883	11,951
Southeast	2,296,329	2,418,581	2,280,091	2,434,820	16,239
Northeast	1,671,536	2,333,841	1,660,764	2,344,614	10,773
Total	7,594,497	9,997,517	7,541,663	10,050,352	52,835

Table 6
Unit of air pollution cost by air pollution source (unit: KRW).

Division	*CO*	NO_x	*VOC*	$PM_{2.5}$	CO_2	Total
Unit	0.06	3.65	0.06	3.44	6.67	13.88

passenger cars, and if the VKT of passenger cars is reduced, air pollutant emissions from moving passenger cars in the city can be reduced. This will reduce the amount of air pollution generated in the city centre by reducing parking time with valet parking robot system and contribute to sustainable urban construction.

Table 7
Differences in air pollution cost before and after implementation of robot system.

Division	*VKT*	Car air pollution cost facter (KRW)	Cost (billion KRW/year)	Difference (billion KRW/year)
Non-robot system	342,151,325	13.88	4749.06	−182.78
Robot system	328,983,020		4566.28	

Table 8
Differences in CO_2 emissions before and after robot system implementation.

Division	VKT(km)	CO_2 emissions per 300,000 VKT (kg)	CO_2 emissions (kg/year)	Difference (kg/year)
Non-robot system	342,151,325	4500	5,132,270	197,525
Robot system	328,983,020		4,934,745	

6. Discussion

The expected effect of this study is an early example of implementing a new technology called the valet parking robot system to conduct a quantitative evaluation of traffic and environmental impact, which can be an important reference for actual implementation and can be useful for establishing environmental policies. By establishing a valet parking robot system, it is possible to propose policies in an effective way to reduce the number of cars in the city center by controlling urban sprawl and building a sustainable city. By establishing a valet parking robot system, policies can be proposed as an effective way to curb the sprawl phenomenon in the city centre and build a sustainable city by reducing the number of cars moving to the city centre.

However, the limitation of this study is that it is based on the size of the transfer car park and assumes the time required for car park navigation and parking, which is difficult to apply to all car parks and may be different from the average parking time of the whole car park. It also assumes general conditions and does not consider congestion in the car park.

As a future research direction, more realistic analysis results can be obtained by setting up and analyzing different scenarios that include variables such as parking lot size, parking demand, traffic patterns, and autonomous vehicle performance. Second, the simple structural models currently in use can be supplemented with state-of-the-art repair modeling techniques (queue matrix theory, simulation modeling, optimization techniques, etc.) to build models that can account for more realistic and complex situations. Third, real-time traffic and parking data can be secured and analyzed to increase the reliability of the model and prove the validity of the results. Fourth, sensitivity analysis can be performed to evaluate the effect of changes in key variables on the results and to verify the reliability of the model. In addition, incorporating an environmental perspective into our research provides valuable insights. By examining the environmental impacts of different traffic and parking scenarios, we can provide foundational views that inspire future research. This approach not only addresses operational and logistical aspects, but also contributes to sustainable urban planning. In summary, these proposed directions for future research will enable the analysis of more complex situations and foster collaboration with experts in relevant fields. By doing so, we aim to develop more reliable and comprehensive models that can inform policy-making and practical applications in urban planning and autonomous vehicle integration. The integration of environmental considerations will further enrich the scope of this research, providing a holistic view of the impacts and benefits of optimized traffic and parking management.

CRediT authorship contribution statement

Minje Choi: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Gayoung Kang:** Writing – original draft, Visualization, Methodology. **Seungjae Lee:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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