Potential of Urban Land Use by Autonomous Vehicles: analyzing land use potential in Seoul Capital Area of Korea

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\section*{ABSTRACT} This study simulates land use changes at a point in time when autonomous vehicles are widespread. If autonomous vehicles become the main means of transportation in the future, people can pass their time on the road by reading, eating, and interacting with friends. People will no longer have the burden of having to drive, and this will change people’s perception of travel time. In addition, this will have an impact on people’s choice of residence. Previous studies have already argued that if autonomous vehicles become commonplace, the city will become suburbanized. However, previous studies have not presented specific models or figures about such future cities. Therefore, this study seeks to suggest specific models of land use change when autonomous vehicles are dominant through the cellular automata method. For land use, residential, commercial, industrial, agricultural, social, public, and green areas are considered, and accessibility, land price, accessibility to green spaces, and neighborhood effects are selected as land use change factors. Simulations based on the scenarios presented in the study by Heinrichs (2016) show two representative results. First, most agricultural areas will decrease, and residential and commercial areas in Gyeonggi province will expand. Second, most land usage will change to residential land use, and only the central commercial area in Seoul will remain. This result can serve as a guideline for urban planning when autonomous vehicles become the main means of transportation. Furthermore, this work could be helpful for the development of regulations and policy enforcement around autonomous vehicles.

\section*{INDEX TERMS} autonomous vehicles, cellular automata, land use change, simulation

\section*{I. INTRODUCTION}

AUTONOMOUS driving is becoming an important issue in the field of transportation. Technologies related to autonomous vehicles are evolving rapidly, and it is feasible to envisage people traveling in autonomous vehicles in the near future. Autonomous vehicles drive themselves, judge roads, and cope with traffic and road situations, without human input. Autonomous vehicles are categorized into six levels, from level 0 to level 5, depending on the degree of control and ability to cope with situations \cite{1}. In addition, autonomous vehicles are grouped into two types, depending on who owns the autonomous vehicle, that is, whether they are shared or private autonomous vehicles \cite{2}. A shared autonomous vehicle implies that autonomous vehicles are shared and available to everyone \cite{3}, while a private autonomous vehicle implies that a person uses autonomous vehicle \cite{4}.

The introduction of autonomous vehicles will change people’s perception about the use of cars and travel costs \cite{5}. Heinrichs \cite{4} stated that if people were not constrained by driving time, they would choose to live in a residential area with better living conditions including greener area and cheaper land price, regardless of distance to their workplace.
and other significant locations. Accordingly, Heinrichs [4] argued that these patterns and behaviors would lead to the development of suburbs in a city. However, although the studies by Heinrichs [4] and Milakis et al. [6] demonstrated that suburbanization would occur due to the introduction of autonomous vehicles, their findings hardly demonstrated specific models or figures of the future city of autonomous vehicles. Guerra’s [7] study on the policy application of autonomous vehicles maintained that it was difficult to consider the operation of autonomous vehicles in relation to policies, due to the lack of prediction about the future cities that would be changed by autonomous vehicles. Furthermore, in the Republic of Korea, the Ministry of Land, Infrastructure and Transport is seeking to commercialize autonomous vehicles by 2020 [8]. It is necessary to study specific changes in future cities when autonomous vehicles become widespread.

Therefore, the research objectives of this study are (1) we seek to propose a model for land use changes by the introduction of autonomous vehicles, and (2) we seek to suggest policy implications as a result of simulation of land use changes when the use of autonomous vehicles becomes widespread. Section 2 explains relevant previous studies and section 3 explain the methods, variables and data used in this study. Section 4 demonstrates the results by two scenarios and section 5 discuss the results in the urban context. Section 6 concludes this study to identify its contributions and suggest further studies regarding autonomous vehicles in urban areas.

II. BACKGROUND

Studies on the introduction of autonomous vehicles and urban areas explore the social change [7], [9], [10], traffic change [11], and urban structure change [2], [5], [6], [12]–[14] in cities due to autonomous vehicles. Guerra [7] explained the difficulty of policy-making around autonomous vehicles. Meyer et al. [11] explained the difficulty of policy-making around autonomous vehicles, due to the uncertainty of autonomous vehicles. Greenblatt et al. [9] and Crayton et al. [10] described the environmental and public health effects following the introduction of autonomous vehicles. In terms of traffic change, Meyer et al. [11] simulated how the accessibility of urban traffic would change when autonomous vehicles would mainly dominate. Various studies have been conducted on the change of urban structure and land use when autonomous vehicles are used. Thankur et al. [5] designed four scenarios of circumstances from the introduction of autonomous vehicles, and the land use change by scenario was expressed as the change of population according to the distance from the Central Business District (CBD). Noyman et al. [2] illustrated change in urban structure, such as parking, roads, pedestrian routes, and subways when autonomous vehicles are introduced, depending on the ownership of autonomous vehicles. Zakharenko [12] argued that parking land use would change other land uses, eventually leading to a reduced density of economic activity. Milakis et al. [6] explained that enhanced accessibility affects the development of new centers, such as former suburban employment centers. Smith [13] predicted that with the introduction of autonomous vehicles, travel costs would be zero, and people would choose their residence regardless of the distance to work. Smith [13] also argued that laws or steps against urban sprawl are necessary. Kim et al. [14] simulated the change of land use when introducing autonomous vehicles to the Seoul Capital Area in the Republic of Korea. Using the agent based model, Kim et al. [14] predicted the location of urban development in 2050 with the introduction of autonomous driving, and the current urban growth pattern without autonomous driving. By comparing urban growth without autonomous vehicles and urban growth with autonomous vehicles, Kim et al. [14] derived clear differences between before and after the introduction of autonomous vehicles, and explained that the use of autonomous vehicles would result in decentralized urban growth. However, Kim et al. [14]’s study barely illustrated the specific distribution and changes of land use since the study simply predicted dispersed urban growth in the Seoul Capital Area.

Heinrichs [4] suggested three scenarios based on the level and role of autonomous vehicles, and demonstrated land use change depending on the scenario. The first scenario is the hypermobile city. The scenario explained that semi-autonomous vehicles would drive on highways, and serve as flexible, multimodal, and networked public transport systems. Using these autonomous vehicles, the city forms a mobility hub, and grows into a polycentric city. In addition, Heinrichs [4] suggested that the demand for parking lots would decrease in cities. The second scenario is the regenerative city. The scenario demonstrated that autonomous vehicles would serve as taxis, which drive on highways as commuters. With the use of these autonomous vehicles, the city would be suburbanized, and the center of the city would have high density. In addition, Heinrichs [4] illustrated that if autonomous vehicles mainly dominate, people would choose residential areas with low prices and green areas, and this would result in urban suburbanization and decentralized urban growth. The third scenario is the endless city. This scenario demonstrated that technological innovations, like the use of autonomous vehicles, would not occur, because of the high cost of constructing infrastructure. The city is as car-oriented as it is now, and the potential for using autonomous vehicles is not mentioned. Heinrichs [4] presented scenarios based on the degree of development and the role of autonomous vehicles, and illustrated the according change in land use. However, the study hardly provided specific modeling or results for the change of land use in future cities. Thus, the previous studies have the limitation that they could not provide specific prediction results or model for land use change when autonomous vehicles are mainly used. Therefore, we seek to present a specific model that can show the change of land use when introducing autonomous vehicles using a cellular automata model.
III. METHODS

This study adopts a cell-based simulation method to illustrate change in urban land use by autonomous vehicles. Although the existing cellular automata illustrated land use change over time, the cellular automata of the study shows land use change according to the scenarios. The Seoul Capital Area, an area in the Republic of Korea, is selected as the study area, and is divided into a grid of cells of (200 m by 200 m) size. Each cell is classified by cell state, that is, land use, and they have four attributes: Accessibility to major routes and major nodes, land price, accessibility to green space, and neighborhood effect. We consider eight land uses, which are residential, commercial, industrial, social, vacant, green area, public, and agricultural. Among these land uses, changeable land uses are residential, commercial, agricultural, and industrial; while non-changeable land uses are social, public, and green area. Transition potential for change is calculated depending on the weight of the attributes, and if this potential becomes larger than the potential to remain with the existing cell use, this cell will have a different land use.

A. CELLULAR AUTOMATA AND LAND USE CHANGES

The cellular automata used in this study is a method to simulate based on cell change. Cellular automata is one of the methodologies to predict land use change. Methods to predict change in land use can be divided into two categories: one is to predict land use change through individual actions, while the other is to predict land use change through analysis of the spatial interactions. Methods to simulate changes in land use patterns through the behavior of individuals are micro-economic and multi-agent models. Duranton and Turner [15] developed an urban growth model including population and land characteristics. López et al. [16] characterized land elements with their functions to demonstrate land-cover and land-cover change. The method for predicting land use change through analysis of spatial interaction is a cellular automata model. The cellular automata method has five factors: cell space, cell states, neighborhood, transition rule, and time step [17]. Each cell has its own characteristics, such as land use and population density, and the cell could have the potential to change to another characteristic, according to the transition rule. White et al. [18] first simulated urban land use change using cellular automata. The change in land use was predicted based on the formula that the land use of surrounding cells affected the change in land use of central cells. Barredo et al. [19] explained why cellular automata are used for urban scenario generation, and applied cellular automata to Dublin, Ireland. Barredo et al.’s study [19] took into account the suitability, neighborhood effect, and zoning status for the attributes of cells, which were used for the transition rule. Lau et al. [20] presented a simulation model for urban land use change using cellular automata. Lau et al. [20] considered three effects for land use change, that are attribute, heterogeneity, and gravity, and classified land use as ‘functions’ (changeable) and ‘permanent’ (non-changeable). Liping et al. [21] developed a combined model with cellular automata and Markov chain analysis to predict land use and land cover changes and predicted changes in the city by using satellite images. The elements of cellular automata are cell space, cell state, neighborhood, transition rule, and time step. Each element is different for each study using cellular automata. According to previous studies that adopted the cellular automata method, cell space usually uses a two-dimensional rectangular grid [18], [19]. More recently, there have been studies that have used irregular cell spaces for block size. In this study, we use a two-dimensional grid for cell space, and set the size of cell space to (200 m by 200 m).

The cell state is a variable representing the cell for modeling. For example, cell state represents land cover, land use, population density level, and so on. In this study, the cell state represents land use. Residential, commercial, industrial, agricultural, public, social, green area, and vacant land uses are used for the cell state. Neighborhood cells refer to cells linked with a cell. The range of neighborhood cells varies for every study. Square-range neighborhood and circular range neighborhood are used. Whereas typical studies used the 3 by 3 Moore neighborhood as the range of neighborhood [20], [22] or the Neumann Neighborhood, which is four cells adjoining a cell, in this study the range of neighborhood is within a radius of 400 meters. It was set to 400 meters, considering the extent of the main roads in Korea, and the distance of the neighborhood cells affecting the central cells. The transition rule defines the changes in the cell, and determines the result. For the transition rule, each cell has attribute values, which are set differently accordingly. The value calculated by the transition rule is called the transition potential. The transition potential implies the probability that a cell’s state would change to a different state. In this study, we create the transition rule by designating accessibility to major roads and nodes, land price, accessibility to green areas, and neighborhood effects as attribute values. Changes in land use could be illustrated through the transition rule. Time step indicates a set of discrete times that repeat the transition rule. In traditional studies using cellular automata, urban growth or land use change with time was observed. Since this study simulates the change of land use with the introduction of autonomous vehicles, it was considered more reasonable to simulate the change of land use according to the scenario, rather than the change of land use over time. Based on the two scenarios of the hypermobile city and the regenerative city in Heinrichs’s paper [4], we simulated the change of urban land use when autonomous vehicles mainly dominate. In particular, we used QGIS and developed Python codes in the QGIS to handle the collected data and compute the proposed algorithm.

B. LAND USES

Representative cell states are land uses in the study. Eight types of land use are chosen: Residential, commercial, social, agricultural, industrial, vacant, public, and green area. Land use in a cell is determined by the total floor area of buildings. Because most buildings in Korea are dense and high, the
total floor areas of buildings are used for calculation, rather than the building area. The land use of the largest total floor area is chosen as a representative land use per cell. The land use is divided into two types: “functions” (changeable), and “features” (permanent) [20]. Changeable land use includes “commercial”, “residential”, “industrial”, “agricultural”, and “vacant”. Permanent land use includes “social”, “public”, and “green area”. “Social” land use implies cultural and social facilities, such as school, hospital, sports facility, or religious facility. “Social” and “Public” land use are classified as permanent land use because of the location of schools and hospitals included in “social”, and public buildings and government included in “public” would not be affected by the use of autonomous vehicles. “Green area” refers to ecological nature, and only grade 3 in ecological nature is the area to be developed or used [23]. Accordingly, Permanent “green area” refers to areas other than grade 3 according to their ecological nature. In the study, we assume that vacant land use would change to another land use.

C. ATTRIBUTES
The transition rule consists of four attributes: Accessibility, land price, green accessibility, and neighborhood effect. Accessibility implies accessibility to major routes and major nodes. Green accessibility indicates accessibility to green spaces, which is selected for explaining residential choice. Depending on the land use, the weight of the attribute is different, and the transition potential is determined by the weight of each attribute. Since Heinrichs [4] emphasized the location of mobility hubs, low price of land and quality of green environment, the study adopt the four attributes to accessibility, land price, green accessibility and neighborhood effect to examine Heinrichs’ prediction.

1) Accessibility
Accessibility implies accessibility to major routes and major nodes. Accessibility is measured by integral accessibility. According to Stanilov’s definition [24], integral accessibility is defined as the ease of reaching one location from another, and is based on two factors: Distance to the adjacent free-way interchange, and distance to the adjacent major arterial. Accordingly, this study chooses two factors: Distance to the closest main road where autonomous vehicles would travel, and distance to the closest node where a transit system of autonomous vehicles would be built. The criteria for the main road were motorway, trunk, primary, and secondary roads of the OpenStreetMap [25]. The location of nodes is based on the intersection of the roads and both ends of the roads. In this way, the distance to the nearest main road and the distance to the nearest node are calculated for each cell, and the accessibility is calculated as the sum of two values.

2) Land Price
Land price data were collected from the National Geographic Information Institute (NGII) in Korea [26]. The study used land price data from 2017, which is the latest data. The land price of each cell is obtained by averaging the data of the land price overlapping the cell. There are some places where land price data do not exist, such as in mountain areas.

3) Green Accessibility
Accessibility to green space is measured according to the distance from the cell to green spaces. By creating buffers of 200 meters, 400 meters, 800 meters, and 1,600 meters from the cell, the weight of accessibility to green space depends on the range of buffers to which the green space belongs. For example, if a green space is located in a 200-meter buffer from a cell, the cell might have the highest grade in accessibility to green space. Green space is based on ecological nature that is classified according to ecological value, naturalness, landscape value, and so forth, for natural environments, such as mountains, rivers, inland wetlands, lakes, and farmland [23].

4) Neighborhood Effect
Neighborhood effect implies that the land use of neighborhood cells affects the central cell. In particular, if commercial cells are located around a central cell, this means the commercial cells will affect the land use changes of the central cell. As Efthymiou et al. [27] demonstrated the effect of neighboring areas in finding the locations of electric vehicle charge, it is necessary to consider neighboring conditions in the city to identify locational effects. The weight of neighborhood effects is set by the distribution of current land uses of the Seoul Capital Area in Korea. The neighborhood effect is calculated by the following formula [19]:

\[ N_K = \sum_c \sum_l w_{K,L,c} \cdot I_{c,l} \]  

\[ N_K \] is the neighborhood effect with \( K \) land use, \( w_{K,L,c} \) is the weighting parameter of the land use \( L \) within \( c \) distance. As mentioned above, the weighting parameter is set with distribution of the current land uses of the Seoul Capital Area in Korea, and Figure 1 shows the weighting parameter by land use. The range of \( c \) is set to 400 m as the extent to which neighboring cells affect the central cell. The neighborhood effect is calculated using each cell’s land use in (200, 400, 600, 800, and 1,000) m created in each cell, and the ratio of land use of cells overlapping with the buffers is used to calculate the neighborhood effect. In this study, the neighborhood effect is considered within the range of 400 m, which can be defined as the range of neighboring effect in Korea. In Figure 1 four graphs show a notable change up to 400 m, and a similar pattern after 400 m. Therefore, \( c \) is set to 400 m. \( I_{c,l} \) is the inertia effect; \( I_{c,l} = 1 \) if a cell has a land use \( L \) in the range \( c \), if not, \( I_{c,l} = 0 \).

D. TRANSITION RULE
The transition rule is a formula for finding the probability that the land use of a cell will change to another land use in cellular automata. The probability is referred to as a transition
potential, and the transition potential is calculated with the weight of the attributes. In this study, we set four attributes to calculate the transition potential of land use change by autonomous vehicles, which is accessibility to major routes and major nodes, land price, accessibility to green space, and neighborhood effect.

$$P_K = \prod_{V} (V_K + 1)$$  \hspace{1cm} (2)

where, $V$ includes $A$ (accessibility), $L$ (land price), $G$ (green space accessibility) and $N$ (neighborhood effect) and $K$ is the land use of a cell, and $P_K$ is the transition potential of the cell for land use $K$. $A_K$ is the weight of the accessibility to major routes and major nodes of the cell for land use $K$, $0 \leq A_K \leq 1$, and $L_K$ is the weight of the land price of the cell for land use $K$, $0 \leq L_K \leq 1$. $G_K$ is the weight of accessibility to green space of the cell for land use $K$, $0 \leq G_K \leq 1$, which reflects residential choice, and $N_K$ is the weight of the neighborhood effect of the cell for land use $K$, $0 \leq N_K \leq 1$. The transition potential for each cell depends on the value of the attributes of the cell, and has the probability of changing to each land use. The algorithm for the transition rule is illustrated in Figure 2.
The potential that a land use of a cell will change to another land use is signified by $P_i$. In the expression, $i$ implies land use. For example, $P_c$ signifies the potential that it will turn into commercial land use. After finding the potential of changing to a different land use, the maximum value of the potential is chosen. If the maximum value is greater than the potential of retaining a cell will turn into a land use with the potential. On the other hand, if the maximum value is less than the potential of keeping a cell’s land use, this cell does not change to another land use. Based on this transition rule, the study simulates the land use change when and if autonomous vehicles are introduced.

IV. THE CASE STUDY AREA

The Seoul Capital Area in the Republic of Korea is selected as the study area. The area consists of the capital Seoul, Incheon, and Gyeonggi province. This area is concentrated in economic and administrative functions, with an area of about 11,700 km2, and a population of 26 million. Around half of Korea’s population resides there. Figure 3 shows Seoul Capital Area. For cellular automata simulation, the Seoul Capital Area is divided into cells. The size of the cells is 200 m by 200 m, and 279,742 cells cover the Seoul Capital Area.

A. DATA COLLECTION

The study uses various data to designate the land use for each cell, and obtain the values of land use factors for each cell. As mentioned earlier, the land use of a cell is defined by the total floor area of buildings in the cell. In order to obtain the land use of cells, we use GIS building integrated information data [28]. As shown in Figure 4, the floor area of buildings within a cell is calculated, and classified according to land use. The land use with the highest floor area is the representative land use of the cell.

In this study, four factors for land use change are considered: Accessibility, land price, accessibility to green space, and neighborhood effect. To calculate the accessibility for each cell, major route data and major node data are necessary. The major route data use motorways, trunk, primary, and secondary roads in OpenStreetMap, and the distance to the major route is calculated from the roads data [25]. Figure 5 illustrates the major route data used in this study.

Major node data use Intelligent Transport Systems Standard Node data [29]. Nodes on both ends of roads and at the intersections where the transfer systems of autonomous vehicles would be installed are used, and the distance to major nodes is calculated through the node data. Figure 6 shows the node data used in this study.

Land price data are based on the National Geographic Information Institute in Korea (NGII) statistical map [26]. Since (200 m × 200 m) data do not exist, which is the cell size of this study, (100 m × 100 m) data are used. The land price data are calculated by averaging the overlapping land price data for each cell.

To calculate the accessibility to green space, green space data are required. The green space data are based on an ecological nature map, and level 1 and level 2 in an ecological nature map are defined as green space [23]. Green space represents mountains, rivers, inland, wetlands, lakes, farmland, and so on. The green accessibility of the cell is calculated as the distance from each green space. Figure 7 shows the green space data used in this study.

B. SCENARIOS

In this paper, two scenarios are chosen among Heinrichs’ scenarios [4]: the regenerative and the hypermobile cities. In this paper, the first scenario, i.e. the regenerative city assumes that semi-autonomous vehicles (autopilot) will play an important role in mobility, and semi-autonomous vehicles will drive on highways. In the scenario, semi-autonomous vehicles imply an autonomous vehicle at level 2 or higher.
The second scenario, i.e., the hypermobile city assumes that a highly networked (autonomous) mass taxi system will operate using autonomous vehicles, and that autonomous vehicles drive on highways. However, since our study seeks to identify changes in land use as a result of the introduction of autonomous vehicles, we do not consider the endless city scenario. The endless city in Heinrichs’s study illustrated that technological development would not take place, due to the huge cost involved in building the necessary infrastructure, and existing vehicles dominate, and the development of autonomous vehicles is consequently not expected. Accordingly, this study simulates land use changes by autonomous vehicles with Heinrich’s two scenarios of the regenerative city and the hypermobile city.

V. LAND USE CHANGES BY SCENARIOS

A. CURRENT STATUS

Figure 8 shows the current land use distribution in Seoul Capital Area. In Seoul, residential areas, commercial areas, and social areas are mainly distributed. Industrial and agricultural areas are distributed in Gyeonggi province, and the distributions of residential and commercial areas are identified. In addition, most of the land use in the Seoul Capital Area is green area, because of the many mountains in the region. Cells that do not overlap with green areas and building areas remain as vacant land use, and this could be developed for other land uses.

Figure 9 shows the distribution of land prices in the Seoul Capital Area. The natural breaks method is used to group land prices. When we refer to the land price histogram of cells in metropolitan areas, dividing the group by the method
of natural breaks could also identify the characteristics of each group. Land prices of each cell are divided into 10 groups. As the land price of the cell gets closer to “L1” (red in the figure), the cell has a higher land price. Figure 10 shows Gangnam, Jung-gu, Jamsil, and Yongsan districts in Seoul have the highest land prices. The other districts in Seoul, Incheon, and the newly developed towns along the Gyeongbu Expressway belong to the intermediate groups. Most cells in Gyeonggi province belong to low land price groups. Although Seoul and Gyeonggi province fall under the same metropolitan area, land prices in Seoul and Gyeonggi province differ greatly. The empty cells represent mountain areas where land price data do not exist. In this study, since the green area is not a changeable land use, it does not affect the result.

Figure 10 shows the distribution of accessibility to green areas in the Seoul Capital Area. The criteria for green areas are based on ecological naturalness level 1 and 2, and the green areas include mountains, lakes, and rivers. Most of Gyeonggi province is comprised of green spaces, such as mountains and lakes. Accordingly, most cells exist within a radius of 200 m of the green space. Much of Gyeonggi province has high accessibility to green areas, and relatively, the accessibility to green areas of Seoul is lower than that of Gyeonggi province.

**B. SCENARIO 1: REGENERATIVE CITY**

The first scenario is the regenerative city. In the scenario, accessibility is calculated by accessibility to major nodes. Since we assume that the role of the future node will play the same role as current subway stations, the land use distribution...
FIGURE 11. Accessibility to major nodes in Seoul Capital Area.

FIGURE 12. Land use potentials in Seoul Capital Area by Scenario 1.

FIGURE 13. The number of cells by residential, commercial, industrial, agricultural, and vacant land use.

by distance to subway stations is analyzed, in order to set the weight of accessibility to major nodes. In Korea, subway station areas are divided into three types: Residential-oriented area, commercial and leisure-oriented area, and employment-oriented area [31]. Since six subway stations, i.e. Gangnam, Express Bus Terminal, Sadang, Jamsil, Seoul Station, and Shinchon, include all three types of characteristics, the stations are determined as reference stations. The land use distributions within the distances of (200, 400, 600, 800, and 1,000) m are analyzed around these stations, and the average values are calculated. The average values are used for weight parameters for accessibility to major nodes. Figure 11 shows the accessibility of major nodes in Seoul Capital Area.

Figure 12 shows the first scenario simulation result showing the change of land use distribution. In the scenario, it is assumed that autonomous vehicles would be a backbone of urban mobility, and that semi-autonomous vehicles would drive on freeways. The results of the scenario illustrate that the city will grow around traffic centers such as transfer stations for autonomous vehicles, and become a polycentric city.

The results of simulation show three features. First, the number of agricultural cells decreases. Simulation results show that much of the agricultural cells change for residential and commercial cells. This implies that the situation in the first scenario will transform the agricultural region into urban areas. Second, the number of residential cells in Gyeonggi province increases. The vacant areas in Gyeonggi province change to residential areas, and commercial areas also change to residential areas. Third, in the Seoul area, the existing large commercial areas become larger, and small commercial districts convert into residential areas. Gangnam, Yeouido, and Jung-gu commercial districts, which are the existing large commercial areas, are maintained and become larger, and other commercial areas are transformed into residential areas.

Figure 13 shows the number of cells by land use distribution, and the number of cells of the first scenario. Since the vacant cells in current land use are assumed to change to another land use, the vacant cells in the first scenario are removed. Land use, where the difference in the number of cells between the first scenario and the current land use distribution is most prominent, is residential. The number of residential cells significantly increases, and the
difference is approximately 30,000 cells. In addition, the number of agricultural cells is halved, and the numbers of commercial and industrial cells are similar to the current ones. With the introduction of autonomous vehicles, the number of residential cells increases. At the same time, the number of agricultural cells may decrease, as many cities in Gyeonggi province expand.

### C. SCENARIO 2: HYPERMOBILE CITY

The second scenario is the hypermobile city. Figure 14 shows the distribution of accessibility to major routes and nodes in the Seoul Capital Area. Accessibility of cells is grouped by means of natural breaks. The natural break classification is applied, which minimizes the variance within the groups, and maximizes the variance among the groups [32]. When referring to the accessibility histogram of cells in the Seoul Capital Area, accessibility to major routes and nodes is divided into 20 groups by natural breaks. As the accessibility of the cell is closer to “a1” (red in the figure), the cell is closer to the node and the route. Seoul is mostly red, which shows cells in Seoul have high accessibility. In Gyeonggi province, most of the cells with high accessibility are located around roads.

Weights of accessibility to major routes and major nodes are calculated according to Stanilov’s [24] frequency distribution of land use by integral accessibility. Stanilov [24] illustrated the distribution of land use by accessibility during the period of suburbia in the United States. As mentioned earlier, Heinrichs [4] and Milakis et al. [6] asserted that when autonomous vehicles are introduced, suburbanization would occur. Therefore, the distribution of land use by accessibility in the suburbanization period is referred to as a distribution of land use by accessibility when autonomous vehicles are introduced. The weight parameters for commercial, residential, and industrial land use are set by referring to the study. The weight parameter for agricultural land use is set using the distribution of agricultural land use according to accessibility in the study areas.

Figure 15 shows the land use distribution as a result of the second scenario. The second scenario assumes that a highly networked mass taxi system is constructed with autonomous vehicles. Furthermore, autonomous vehicles act as commuters, and drive on the highways. The result of the
scenario is that the city would be suburbanized, and the city center would have high density.

The result reveals three interesting points. First, the land use in Gyeonggi province changes mainly for residential use and industrial use. The area where the existing industrial area is located is larger, and most of the cells in Gyeonggi province change to residential cells. This can be expected, because the use of autonomous vehicles will make it easier to move, eliminate restrictions on driving, and change many of the suburbs to residential areas. Moreover, with the assumption that people would choose residential areas where land prices are low and green areas are abundant, it can be identified that residential areas in Gyeonggi province will increase significantly, since the area is relatively cheaper, and more accessible to green areas than Seoul. This demonstrates the suburbanization of the Seoul Capital Area. Second, the current commercial areas in the central city area, that is, Seoul, remain, and commercial areas in Gyeonggi province change to almost all residential areas. As most commercial land uses are converted to residential uses, the ratio of commercial uses decreases significantly. This means that commercial areas in Gyeonggi province, where land prices are relatively low change to residential areas, rather than being used commercially. Since people can move conveniently by using autonomous vehicles and are not restricted by the location of shopping malls, commercial areas in Gyeonggi province turn into more favorable residential areas. In Gyeonggi province, it is predicted that a large-scale shopping mall, which can be easily accessed using a car, mostly remains. Accordingly, the results show that commercial areas such as Gangnam, Jung-gu, Yeouido, and Yongsan in Seoul will be more concentrated. Third, commercial use in Seoul also changes to residential use, except for commercial and business uses that are currently concentrated in Seoul. The use of autonomous vehicles changes commercial areas in Seoul to residential areas, except for current concentrated commercial areas.

Figure 16 shows the number of cells of current land use distribution and the number of cells of the second scenario. As mentioned earlier, we assume that the vacant cells would change to another land use, so the vacant cells disappear in the second scenario. Figure 16 illustrates that the number of agricultural and commercial cells significantly decreases, and the number of residential cells doubles. With the introduction of autonomous vehicles, convenient movement will be possible, which leaves only the central commercial areas in Seoul. Therefore, commercial areas will significantly decrease. In addition, since the land prices in Gyeonggi province are relatively cheap, land use in Gyeonggi province would be used for residential purposes.

VI. DISCUSSION

The simulation results of the first scenario demonstrate that commercial areas and residential areas are distributed around nodes, and many agricultural areas transform into commercial and residential areas. If the city changes as in the scenario, many agricultural areas would become urbanized. Residential areas and commercial areas increase in outskirt areas, i.e. Gyeonggi province in Seoul Capital Area. As the use of autonomous vehicles makes transportation more convenient and the restriction of driving is reduced, residential and commercial areas expand in Gyeonggi province. In Seoul, the central area of Seoul Capital Area, the existing large commercial areas such as Gangnam, Yeouido, and Jung-gu become larger, and small commercial districts convert into residential areas. Heinrichs’s scenario [4] predicted that if semi-autonomous vehicles are used, the form of a city will be polycentric, due to urban growth around a transportation center. The simulation results also support that the urban areas grow around nodes, where residential areas and commercial areas would be located. The possibilities of decrease in agricultural areas and increase in residential and commercial areas are identified, and it is expected that residential and commercial areas will be larger in Gyeonggi province than now. This is predicted as a result that the use of autonomous vehicles changes the perception of people’s travel cost, and that the use of autonomous vehicles changes the urban land use.

The simulation results of the second scenario demonstrate that cities become suburbanized, and city centers have high density. The residential areas become denser in Gyeonggi province and extend to the city centers and the suburbs, as the use of autonomous vehicles enables convenient movement. In Gyeonggi province, lands become used for residential purposes rather than for commercial purposes, due to its low land price and high accessibility to green areas. Accordingly, the proportion of commercial areas in the overall metropolitan area decrease, and the commercial areas in the main spots in Seoul become more concentrated. The distribution of changed land use is different from the current distribution of land use. Except for the major commercial areas, such as Gangnam, Jung-gu, Yongsan, and Yeouido, most of the commercial areas in Seoul change to residential areas. Even in the case of the Seoul area, since the use of autonomous vehicles relieves drivers, the non-intensive commercial areas could be used for residential areas. This explains that the concentrated commercial areas in Seoul would become more important in the future. In addition, the decrease of the commercial area ratio compared to the residential area makes the utilization of commercial areas less efficient, and the population could concentrate on such spaces. It would be necessary to develop appropriate planning for commercial and residential land uses in advance. According to the suburbanization and higher central densification, Heinrichs [4] predicted that younger people will prefer to live in urban centers, and high-income households will move to the suburbs, despite the distance to work. Although this study does not consider the specific ages for land use, the simulation results of the second scenarios support the density increase of residential areas in suburban areas and downtown around commercial areas increases. Additionally, Smith [13] predicted that travel costs would be zero when autonomous vehicles are introduced, because people could do other activities in autonomous vehicles. If
travel costs are reduced, people would choose a residential area regardless of their job, which makes a city suburbanized. By anticipating the suburbanization of the city, Smith [13] emphasized the need for smart growth when autonomous vehicles are introduced, suggesting that regulations to prevent unplanned suburbanization would be necessary. Milakis et al. [6] explained that fully autonomous vehicles could fetch groceries from the supermarket by themselves, or collect children from school. Milakis et al. [6] also explained that the use of autonomous vehicles improves accessibility, so that people can work, shop, and live at greater distances. These previous studies also supports land use changes in the simulation results. If autonomous vehicles fetch goods directly from supermarkets, many commercial facilities will not be needed. If the use of autonomous vehicles improve accessibility, people would choose to live or work further away, which is consistent with the simulation results. In particular, the proposed methods is helpful to illustrate geographical location and changes in a wide region.

Figure 17 illustrates the change in the number of land use cells according to the two scenarios when autonomous vehicles are mainly used. Since all of the existing vacant cells are assumed to be changed for other uses, vacant cells do not appear in the first and second scenarios. The number of agricultural cells is much smaller in the first and second scenarios. This is because the existing agricultural cells that are adjacent to green areas and have cheap land price change to other land use, due to the use of autonomous vehicles. By suburbanization, agricultural areas in Gyeonggi province would change to urban areas. The numbers of industrial cells remain similar in the two scenarios. In commercial land use, the number of cells in the first scenario hardly changes, but the number of cells in the second scenario is extremely low. In the first scenario, the distribution of commercial and residential areas similar to the current ones is formed around the roads in Gyeonggi province, so that the number of commercial cells is similar to the current one. However, as a result of the second scenario, the introduction of autonomous vehicles results in a change of commercial areas to residential areas. Most of the commercial areas with cheap land prices and high accessibility to green spaces in suburbs will change to residential areas, and only big shopping malls or neighborhood stores will remain. In addition, concentrated commercial areas in central city areas, such as Gangnam, Yeouido, Yongsan, and Jung-gu, will be dominant. Therefore, as the number of commercial cells in the suburbs decreases, the number of overall commercial cells also decreases. In residential areas, the number of residential cells is different according to the scenarios. In the first scenario, the number of residential cells increases, due to the large urban growth in Gyeonggi province, as well as in Seoul. In the second scenario, the number of residential cells greatly increases, because the current suburban commercial areas change to residential areas. This illustrates that much land in the Seoul Capital Area would be dedicated for residential areas, since many commercial facilities are not required in the era of autonomous vehicle. The city will grow around residential areas, rather than commercial areas. This situation could be a guideline in regulating a residential area as a suburban area when autonomous vehicles are introduced. In addition, the major commercial areas, such as Gangnam, Jung-gu, Yeouido will remain their locations, and other commercial areas near residential areas will significantly decrease. The residential area in Gyeonggi province will expand. It is necessary to prepare for how to manage existing commercial and residential areas in outskirt areas in advance for people and autonomous vehicle.

VII. CONCLUSION

This study proposed a simulation method to illustrate the effect of autonomous vehicles on land uses by adopting a cell-based approach and geographically demonstrated specific possible changes in land uses in Seoul Capitol Area. While many agricultural areas decrease in outskirt areas, residential and commercial areas will increase. Additionally, although those areas become suburbanized, the city centers will become denser. Even the commercial areas will become residential area if autonomous vehicles operate as a highly networked mass taxi system. Accordingly, because the use of autonomous vehicles lead to the huge growth of cities, it is necessary to expand and manage the infrastructure in outskirt areas, i.e. Gyeonggi province in Korea. Additionally, because it is expected that commercial areas significantly decrease compared to residential areas, currently existing commercial areas would become less efficient. It would be necessary to prepare for how to use commercial areas in the future.

The technology of autonomous vehicles continues to evolve, and people will surely start to use autonomous vehicles on a large scale in the near-term future, rather than the distant future. This study provides a promising result to predict the distribution of land use in future cities, when autonomous vehicles are one of the major transportation means. The result of this study will be a stepping-stone for future prediction, and act as a guideline for urban planning and design when autonomous vehicles start operating in a city.
However, because the results are based on the assumptions in this study, we do not claim that the results of this study will be the only city in the future. Rather, we suggest that this proposed approach would be an initial step to estimate significant effects of autonomous vehicles on urban areas and helpful for future city and regional planning to prepare for autonomous vehicles. Accordingly, further studies are suggested to conduct for strengthening the estimation of effects of autonomous vehicles. For example, a sensitivity analysis would be helpful to improve the propose model by clarifying more relevant attributes in land use potentials. Other attributes could be included in the proposed model, e.g. social or educational attributes.

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REFERENCES


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