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# AN ANALYSIS OF EXPECTED EFFECTS OF THE AUTONOMOUS VEHICLES ON TRANSPORT AND LAND USE IN KOREA

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## ABSTRACT

This paper aims to examine the existing studies to extract the expected effects of the autonomous vehicle system and quantify its impact on transport and land use through a spatial impact simulation based on South Korean data. The paper starts with a review of the literature with a specific focus on the expected effects of autonomous vehicle on traffic safety, travel demand, roadway capacity, and land use. Secondly, the development stage towards complete autonomous driving is examined with the reviews on projected timeframe as well as optimistic and pessimistic views. The third section specifies the expected effects by applying an analysis to the existing transportation network and the land use pattern in South Korea. Finally, the paper concludes with suggestions for further studies.

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# I. Introduction

Recent studies report that the technology of vehicle-automation has become matured enough to enable the commercialization of autonomous vehicles, possibly by the 2020s (Litman, 2013). Recent demonstrations of autonomous vehicles on the public roads also allude drastic changes in the auto industry (Dokic et al., 2015). Even if the commercialization of autonomous vehicles gets delayed up to several decades due to liability and safety issues, highly-automated vehicles are expected to pick up their market-share in the meantime.

In response to the above trend, the U.S. NHTSA (National Highway Traffic Safety Administration) published a guideline entitled "Preliminary Statement of Policy Concerning Automated Vehicles"; see NHTSA (2013) which furnishes research plans and policy recommendations for automated vehicles. For conceptual clarification, this statement categorizes the operations of vehicle into 5 levels, from fully-manual (0) to fully-automated driving (4), depending on the level of automation. This statement also reveals the NHTSA's intention to prevent autonomous vehicles (classified as level-4 automation) from operating on the public roads except under restrictive conditions in consideration of the state-of-art automation technologies.

Public and private stakeholders of other OECD (Organization for Economic Cooperation and Development) member states have also promoted implementation of automated vehicles. For example, a technology roadmap for automated driving has been recently established with the participation of major European automotive manufacturers and suppliers (Dokic et al., 2015). This roadmap is intended to aid the European Commission and Member States to make decisions on either policy actions or research plans to facilitate the penetration of highly-automated vehicles into the market. Likewise, Japanese "Autopilot System Council" has announced roadmaps to realize general-purpose driving of highly-automated vehicles on highways until 2020 (Dokic et al., 2015). In South Korea, MOLIT (Ministry of Land, Infrastructure and Transport) has recently established Auto-Road ITS (Intelligent Transportation Systems) Plan 2020 (MOLIT, 2012). It includes a component called

"Intelligent Vehicle and Road Service" which aims at enhancing traffic safety by promoting highly-automated driving.

In this context, this paper aims to examine the existing studies to extract the expected effects of the autonomous vehicle system and quantify its impact on transport and land use through a spatial impact simulation based on South Korean data. The paper starts with a review of the literature with a specific focus on the expected effects of autonomous vehicle on traffic safety, travel demand, roadway capacity, and land use. Secondly, the development stage towards complete autonomous driving is examined with the reviews on projected timeframe as well as optimistic and pessimistic views. The third section specifies the expected effects by applying an analysis to the existing transportation network and the land use pattern in South Korea. Finally, the paper concludes with suggestions for further studies.

## II. A Review of the Literature

The operation of automated vehicles is expected to influence traffic safety, mobility, and land-use. Most existing studies (e.g. Anderson et al., 2014; Dokic et al., 2015) report such potential impacts of automated vehicles in rather speculative ways due to unknown human factors and unresolved legal issues attendant to the general-purpose operations of automated vehicles. The extent to which automated vehicles benefit the society as a whole will also largely depend on their share in the total vehicle fleets (see e.g. Pinjari et al.,2013; Litman, 2013).

IIHS (2010) reports that even the vehicles classified as NHTSA's level 1, if operated with 100% market-penetration, can prevent one third of crashes and fatalities. Such partially-automated vehicles are equipped with safety functions such as lane departure warning, and dynamic brake support, etc. Anderson et al. (2014) report that highly-automated vehicles of level 3 or 4 might enhance traffic safety particularly by reducing alcohol-related crashes or fatalities. Such promising predictions should be taken with caution because the benefit of safety innovations might not fully materialize due to drivers' offsetting behavior seen in the operations of vehicles equipped with advanced safety functions (Litman, 2013). Moreover, there is no guarantee that automated vehicles would perform perfectly safe in all complicated situations (Goodall, 2014). In this vein, human factors related to operating highly-automated vehicles under crash-prone conditions have been investigated mostly through driving simulator or surveys; see the review of Merat and de Waard (2014).

Automated vehicles might also bring positive operational impacts by reducing crash-related congestions; see e.g. Pinjari et al., (2013) and Anderson et al. (2014). In addition, Tientrakool et al., (2011) report that 100% market-penetration of vehicles equipped with automated braking capability and acceleration/deceleration decisions are expected to improve the capacity of typical existing highways by up to 40%. Such capacity improvement shall be maximized if the technology of automated vehicles is combined with V2V (vehicle-to-vehicle) or V2I (vehicle-to-infrastructure) communication; see e.g. Shladover et al. (2012) and Pinjari et al. (2013).

The potential capacity gains brought by the implementation of automated vehicles, however, are likely to induce further vehicle travel; see Pinjari et al. (2013) for this so-called rebound effect. Automated vehicles may also encourage longer travel distances by enabling commuting times to be used more productively (ITF, 2015). In addition, automated vehicles would significantly affect household vehicle demand and usage if prevalently used for car-sharing or taxis (see e.g. Fagnant and Kockelman, 2014; Schoettle and Sivak, 2015; Alessandrini et al., 2015).

As autonomous vehicles render commuting times more productive, businesses are likely to move further from city centers. In this way, implementation of automated vehicles can result in more dispersed land-use patterns surrounding metropolitan regions (Anderson et al., 2014). On the other hand, driverless parking via automated vehicles can de-couple parking spaces from most buildings and thus would form more compact urban cores (Anderson et al., 2014). Implementation of automated vehicles might even reduce required parking spaces themselves (ITF, 2015).

# III. Prediction of the pace of the Advancement of Autonomous Vehicles

Some vehicles are currently manufactured with partially-automated features of NHTSA's level 1 or 2. Google Corporation has even demonstrated self-driving along specially designated routes under good weather conditions (Muller 2013). Despite such breakthroughs of self-driving technologies, there remain many technical issues to be resolved so that unrestricted self-driving should play its role as one of the most robust travel options under the real-world urban environment (Luettel et al., 2013).

Litman (2013) predicted how automated vehicles would develop, commercialize and eventually fill the market. This prediction is based on the implementation patterns of both previous vehicle technologies (e.g. vehicle navigation systems, hybrid vehicles, etc.) and vehicle fleet turnover rates. The underlying assumption of the prediction is that fully-automated vehicles shall be manufactured for sale from the beginning of the 2020s and thereafter become operational for general-purposes on the public roads.

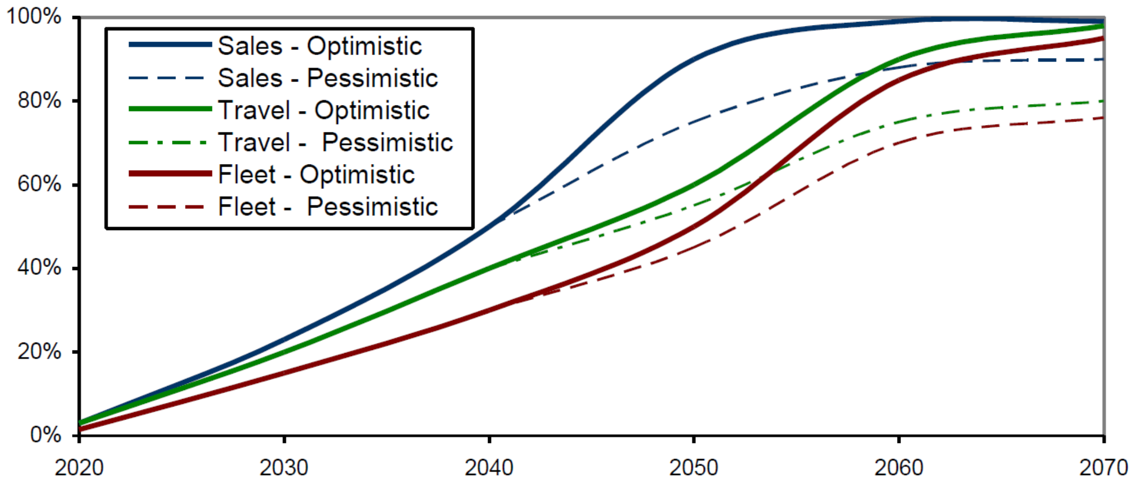



**Figure 1 Projected Autonomous Vehicle Sales, Travel, and Fleet adopted from Litman (2013)**

If an optimistic view is taken on various influential factors such as technical constraints and consumer acceptance, etc., one can arrive at projections about the sales of vehicles, their fleet and usage as illustrated by the three bold lines, respectively in **Error! Reference source not found.**. A pessimistic view, however, results in projections showing slower implementation of automated vehicles in comparison with those under optimistic assumptions as indicated by dashed lines. The optimistic projections by Litman (2013) shall be used as inputs into the case study in the next section.

## IV. Analysis of Expected Effects of Autonomous Vehicles in Korea

While the previous section conceptually attends the expected effects of the autonomous vehicle system in terms of traffic safety, traffic throughput, capacity increase, and the changes on land use; this section seeks to assess the expected impact using the data on the existing transportation network and the land use pattern in South Korea. Since we need to analyze what will happen during the transition period where the autonomous and conventional vehicles share the road space, the analysis posits several scenarios that assume different proportions of autonomous vehicles as their market share increases. It should also be noted that the current structure of car ownership is assumed to continue because our analysis is focused on evaluating the impact of autonomous vehicles on the performance of the existing transportation network rather than investigating the change on travel demand caused by the introduction of autonomous vehicles. Additional assumptions will be made depending on data availability. .

This section is divided into two subsections. The first subsection directly investigates the expected benefits from the improved performance of the existing transportation system while the second subsection analyzes the change in the spatial pattern of land use caused by the autonomous vehicle system that re-defines the concept of distance.

## 1. Transportation

### A. Assumptions

#### i. Future road condition

The advancement of the autonomous vehicle system is expected to increase travel speed and enhance the roadway capacity. These improvements can be reflected on the widely used Bureau of Public Roads (BPR) function that relates the traffic volume to the travel time on the roads in transportation planning. The travel time estimated using the function provides the basis for quantifying the expected social benefits resulting from accommodating the autonomous vehicles in the future road networks. The basic functional form is specified by equation (1) and its shape is depicted in Figure 2.

$$T_f = T_0(1 + \alpha[V/C]^{\beta}) \tag{1}$$

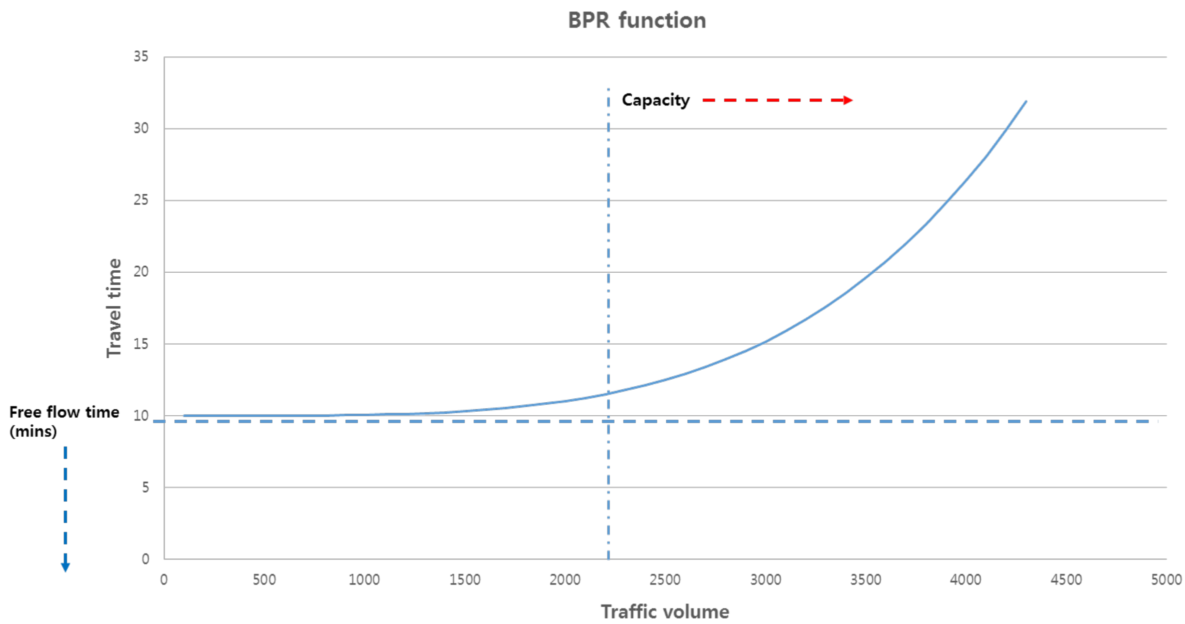



**Figure 2 Typical function form of the BPR function**

The graph shows that travel time ($T_f$) is the function of traffic volume (V) and the free flow travel time ($T_0$) is maintained until traffic volume reaches a threshold level. As traffic volume approaches the capacity (C) of the road (2200 vehicles per lane), travel time increases non-linearly.

The future road condition following the introduction of autonomous vehicles can be specified in terms of increases in the capacity and the free flow speed. As the number of autonomous vehicles on the road increases, travel time and the traffic throughput are enhanced, which yields an effect equivalent to lowering the free flow time (blue dotted arrow) and extending the flat portion (capacity increase) further right along the X-axis (red dotted arrow).

Since the number of autonomous vehicles is the first and foremost important factor affecting travel time and roadway capacity, it is necessary to estimate its coefficient using a reasonable functional form.

We follow Yokota et al. (1998) that postulate the capacity enhancement as a function of the proportion of autonomous vehicles on the roads.

$$Q_d = 3600/(h_i d + h_{manual}(1-d)) \qquad (2)$$

where,

$Q_d$ = capacity of the mixed traffic when the percentage of autonomous vehicle is d%.

$h_i$ = target headway of autonomous vehicle

$h_{manual}$ = an average headway of the conventional vehicles

d = percentage of autonomous vehicles

We calculate the capacity enhancement due to the penetration of the autonomous vehicles on top of the capacity of the existing roads. The average headway for the conventional vehicle ($h_{manual}$) depends on the designed capacity of the road. For example, if one directional link (road) is designed to support 1800 vehicles/hour then, the minimum headway allowed to a conventional vehicle is 3600/1800 = 2.0 seconds.

Yokota et al (1998) also estimated the multiplication factor in order to model enhancement of the travel speed that consequently reduces travel time due to the autonomous vehicles. For example, if the current free flow travel speed is 60mph, then the speed increases by a factor of 1.67, which is equivalent to 100mph when the 0.5s headway is assumed on the national highways. The travel time reduction and the multiplication factors are estimated by road type including the national highway and the express way and by the proportion of autonomous vehicles. The national highways in Korea are compatible with the interstate highways in the U.S. while the express ways provide the similar level of service to the major arterials such as belt routes and city expressways. The results are presented in Table 1.

**Table 1 Evaluation of macroscopic effect on travel time reduction**

| Road type | Target headway | Proportion of the autonomous vehicles | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0% | 20% | 40% | 60% | 80% | 100% |
| National highways | 0.5s | 1.00 | 1.07 | 1.15 | 1.26 | 1.42 | 1.67 |
| Express ways | 0.5s | 1.00 | 1.04 | 1.10 | 1.18 | 1.25 | 1.39 |

ii. Step-by-step adoption by road type

It would be reasonable to assume that the autonomous vehicle system will be gradually introduced to existing facilities according to the hierarchy of road types. We assume that highways, major arterials, minor arterials and the rest will be ready to accommodate the autonomous vehicles in the year of 2020, 2050, 2050, respectively. We also assume that no adjustments will be made to accommodate autonomous vehicles such as the dedicated lane system and that the existing road facilities are open to the autonomous vehicles as well as the conventional vehicles.

iii. Travel demand

Projecting travel demand is the most challenging part of our analysis due to limited information about the future. It is known that several issues associated with travel demand such as the social and economic characteristics of individuals, education level, income level, number of children, and car ownership etc. However, the data are not available for the given time span and it would not be meaningful to estimate the data with extra assumption. In addition, as previously described, there are positive and negative factors that would induce or reduce the travel demand following the introduction of the autonomous vehicle system and its relative strengths are not known. We utilize the Origin-Destination (O/D) trip data obtained from Korea Transport DataBase (KTDB, 2015) which is authorized to estimate and publish the O/D table for all travel forecasting projects. No alternation has been made on the given O/D table. However, it should be noted that the effects of population aging and the decrease in young drivers have been reflected on the travel demand.

#### iv. Distribution of travel demand into the network

There are several ways to assign the travel demand, or constructed trips for each O/D pair, into the network. The simplest way would be to assign all trips to the shortest path for each corresponding O/D pair. However, this method does not consider the congestion effects at different traffic volumes. Wardrop (1952) suggested an assignment principle based on the behavior of travelers who want to minimize their travel time. When the trips are assigned to the network according to his principle, all travelers cannot reduce their travel time by unilaterally changing their routes, which is called the User Equilibrium (UE). As the reasoning behind Wardrop's principle reflects the travelers' basic characteristics, the UE assignment will produce realistic travel behavior. We assign the constructed travel demand to the existing road network according to Wardrop's principle and the congestion functions derived in equation (1) above.

### B. Study Area

Our analysis is focused on the Seoul Metropolitan Area (SMA) consisting of Seoul, the capital city of Korea, Incheon, a major port city west to Seoul, and Gyeonngi Province that surround the two cities. The land area of the SMA is about 11,700 square kilometers and it holds 24 million people and several major cities. Figure 3 shows SMA with Seoul's major satellite cities of 50,000 population or more highlighted.

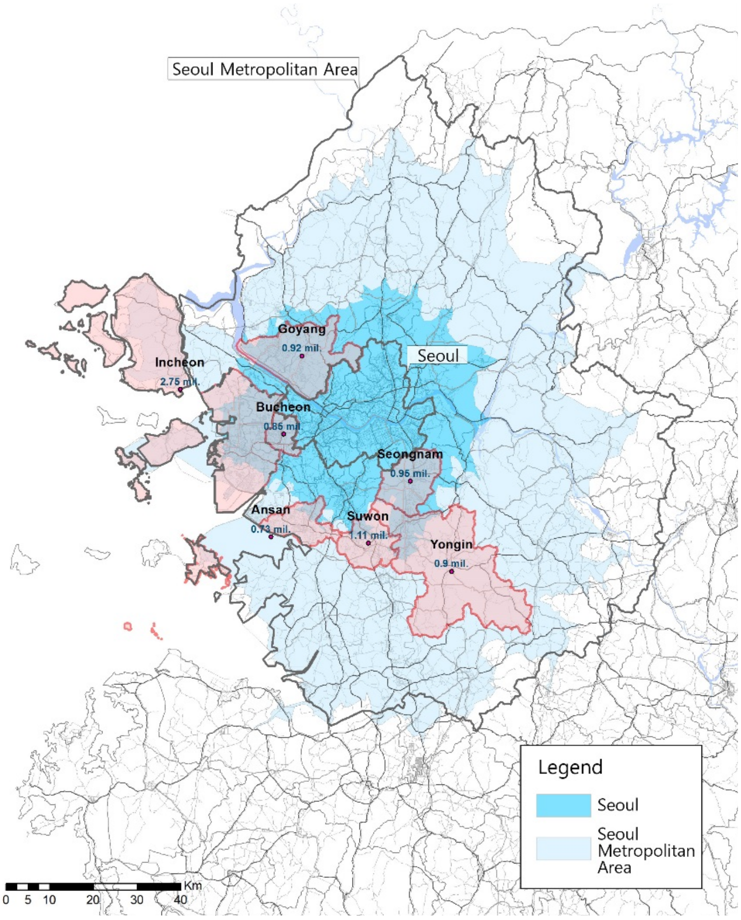



**Figure 3 Seoul Metropolitan Area**

According to the household travel survey by the Seoul Development Institute (SDI 2013), approximately 58 million trips were generated in the SMA in 2013. These trips serve several purposes such as commuting, school related, business, and returning to home with corresponding percentages 19.1%, 7.7%, 9.2%, 42.6% respectively. Figure 4 shows top ten districts in the SMA attracting trips during peak hours.

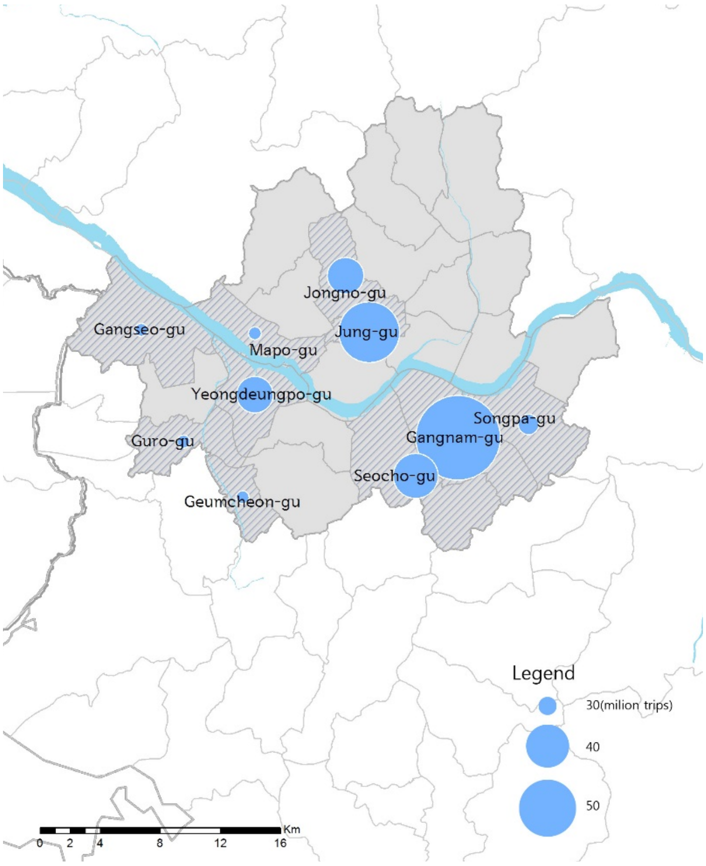



**Figure 4 Top ten districts attracting trips in SMA**

## C. Results

### i. Traffic safety enhancement

A major benefit from the autonomous vehicle system comes from decreases in traffic accidents. Consequently, the social costs associated with accidents, often termed as pain, grief, and suffering (PGS), and the costs from the property damage will be reduced. Quantifying the benefits from enhanced traffic safety is equivalent to valuing PGS and rehabilitation costs of the property damage from traffic accidents. According to the manual for the preliminary feasibility study of roadway investment project proposals (KDI, 2008), the Accident Cost Savings (ACS) from the reduced number of accidents are measured in the differences of ACS between 'do' and 'do-not' scenarios. In this case, the study assumes that the autonomous vehicles will be an accident free system such that the ACS is dependent only on the proportion of the conventional vehicles. This assumption implies that accident cost will be zero when an autonomous vehicle world is realized. Thus, the total ACS is computed by subtracting the reduced ACS of the conventional vehicles from the ACS of no-autonomous vehicle system in 2020. The benefits from a partial introduction of autonomous vehicles can be calculated by

$$\mathrm{VACS} = VAC_{no-automation} - VAC_{conventional} \qquad (3)$$

where,

$$\mathrm{VAC} = \sum_{t=1}^{3}\sum_{s=1}^{2}(A_{ts} \times P_s \times VL_t)$$

$A_{ts}$= number of injuries and deaths per 100 million-km by accident type

$P_s$= accident cost by accident type

$VL_t$= yearly 100 million-km by road type

$t$=road type (1: highway, 2: major arterials, 3: minor arterials)

$s$= accident type (1: dead, 2: injured)

**Table 2 Accident cost by accident type**

| | | death (1,000$) | injury (1,000$) |
|---|---|---|---|
| For 1 dead person | PGS excluded | 387 | 4.80 |
| | PGS included | 487 | 19.9 |
| For 1 injured person | PGS excluded | 24.0 | |
| | PGS included | 38.4 | |

Source; Manual for the Preliminary Feasibility Study for Roadway Investment Project, KDI (2008)

The estimated ACS is presented in Table 3. We follow the optimistic perspective on the projected advancement of the autonomous vehicle system proposed by Litman (2013). As mentioned earlier, the benefits of ACS in the year 2070 are the same as the total accident costs from the system available in the year 2020. The ACS is significantly lower than the national statistics because the scope for the feasibility study is limited to the accidents occurring on highways, major and minor arterials, and excludes all accidents occurring in most intersections in urban areas.

**Table 3 Estimated Accident Cost Savings from Autonomous Vehicles**

| Year | Market share of autonomous vehicles | ACS (million $) | Rate of increase in ACS (%) |
|---|---|---|---|
| 2020 | 3% | 14.2 | - |
| 2030 | 20% | 30.3 | 213 |
| 2040 | 38% | 137.5 | 454 |
| 2050 | 58% | 170.5 | 124 |
| 2060 | 86% | 294.6 | 173 |
| 2070 | 100% | 435.2 | 148 |

According to the National Roadway Accident Statistics (2015) of Korea, the number of fatalities in traffic accidents fell by 50 % from 12,603 to 5,092 between 1990 and 2013. A similar statistic can be found in the U.S. on the reduction of fatalities from 1960 to 2011 where it took two decades to halve the rate of fatalities. However, the introduction of autonomous vehicles may lead to a drastic reduction of the ACS within a shorter time period compared to the lengthy time that it took to halve the number of crashes in the past.

ii. Travel time savings & congestion reduction

Since the effective roadway capacity is approximately tripled by the autonomous vehicle system, we examine the impact on the relationship between service supply and the travel demand observed in the transportation network using the Volume/Capacity (V/C) ratio, a widely used measure of service level of a transportation system. The definition of each level of service is provided in Table 4.

**Table 4 Level of service definitions (HCM, 2000)**

| Level of service | Definition | V/C ratio |
|---|---|---|
| A | Conditions of free flow; speed is controlled by driver's desires, speed limits, or physical roadway conditions | 0.0~0.34 |
| B | Conditions of stable flow, operating speeds beginning to be restricted; little or no restrictions on maneuverability from other vehicles | 0.35~0.54 |
| C | Conditions of stable flow, speed and maneuverability more closely restricted | 0.55~0.77 |
| D | Conditions approach unstable flow, tolerable speeds can be maintained but temporary restrictions my cause extensive delays, little freedom to maneuver, comfort and convenience low | 0.78~0.93 |
| E | Conditions approach capacity, unstable flow with stoppages of momentary duration, maneuverability severely limited | 0.94~0.99 |
| F | Forced flow conditions, stoppages for long periods, low operating speeds | 1.00 or > |

We compare the distribution of V/C ratio, which is a measure of overall network congestion of the transportation system between, the year 2020 and 2070 when all vehicles are expected to operate with 0.5s headways (See Figure 5). When just a small portion of the autonomous vehicles is introduced in 2020, the V/C ratio exceeds 0.5 on at least 1/3 of the links. Since these links are in condition of service level 'C' or worse, the road capacity is still insufficient to accommodate the travel demand. On the contrary, the V/C ratio larger than 0.5 almost disappears when all vehicles are replaced with autonomous vehicles. According to Table 4 and the V/C distribution, most vehicles will run under free flow condition by 2070.

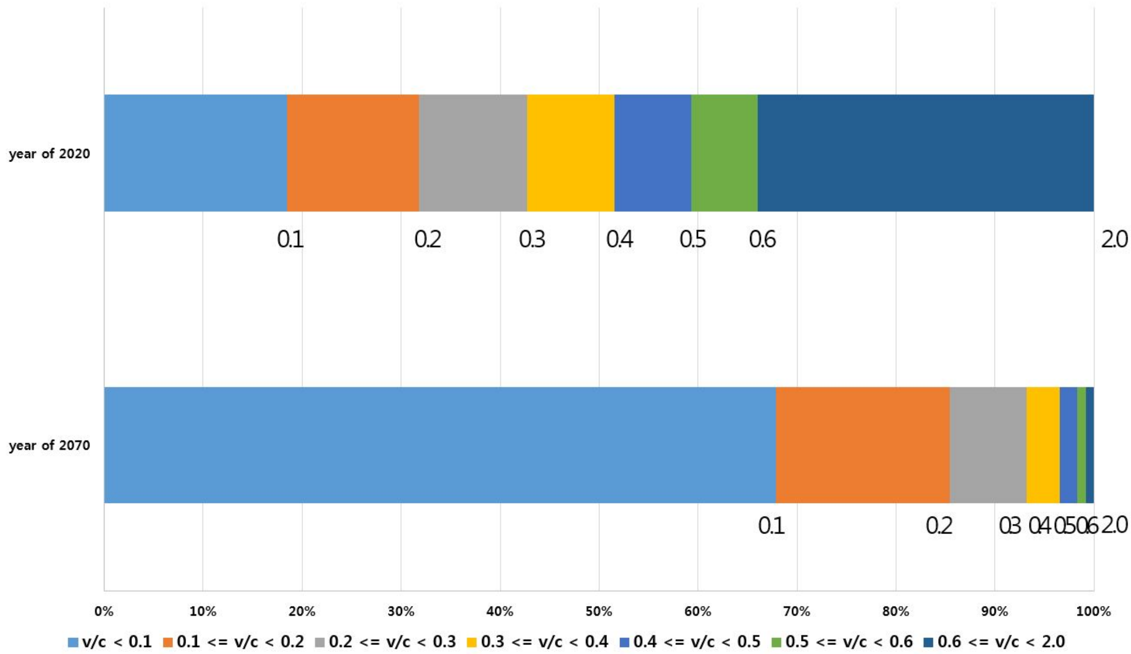



**Figure 5 Comparison of V/C Ratio Distribution between Year 2020 and 2070**

The effects of the increased road capacity combined with speed enhancement would be reflected on travel time savings. This section tries to specify the speed and capacity enhancement and to estimate the social benefits from increased market share of the autonomous vehicles in terms of aggregated travel time savings. Figure 6 shows the reduced vehicle-hours in the SMA (top) and the whole country (bottom) as the market share of the autonomous vehicles increases. When all vehicles are replaced with autonomous vehicles, the expected savings are estimated to be approximately 3 million vehicle-hours in the SMA which is equivalent to saving one hour for each commuting trip to SMA in 2013.

In addition, we can see that the pace of increase is almost linear in the SMA while it is exponential for the whole country. This implies that the effect of the autonomous vehicle system is expected to show up earlier in the SMA than in the inter-regional transportation network. The beginning point of the non-linear section appears earlier in the SMA than in the nationwide network where the network performance enhancement may be limited to specific inter-regional O/D pairs. This might explain the projected exponential increase in travel time savings in the nationwide network after 2050. Prior to the year 2050 the impact of the autonomous vehicles is likely to be scattered among the isolated O/D pairs while these scattered impacts will begin to generate synergy effects with newly introduced autonomous vehicles after the year 2050.

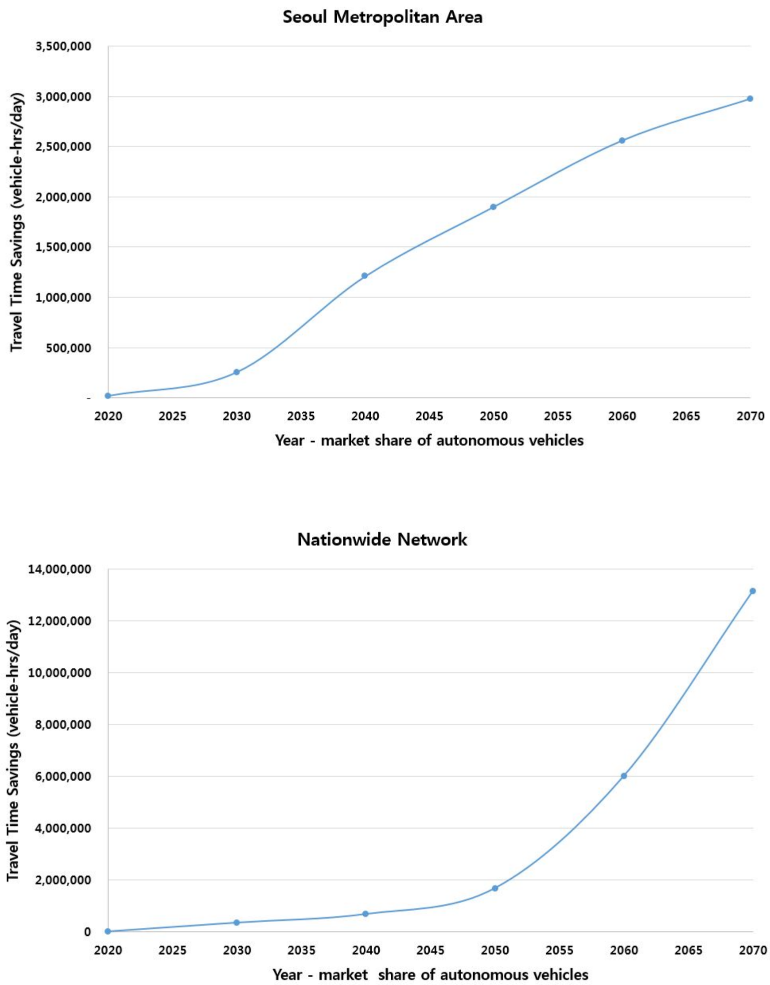



**Figure 6 Expected Travel Time Savings (in the SMA and the Nationwide Network)**

The faster realization of the effect of autonomous vehicle system in the SMA may be attributable to the current congestion level of the study areas. Since the congestion level is the function of the available capacity and travel demand, we analyze the demand pattern in the SMA and the whole country. Table 5 shows that travel demand is very much concentrated in the SMA; approximately 45% (18% + 27%) of the trips are generated in the whole country (See Table 5).

**Table 5 Total trips per day generated in Korea**

| Areas | All trips produced (million) | share (%) | trips to Seoul (million) | share (%) |
|---|---|---|---|---|
| Seoul | 12.45 | 18 | 10.02 | 82 |
| SMA Excluding. Seoul | 19.28 | 27 | 2.04 | 17 |
| Other areas | 39.32 | 55 | 0.22 | 2 |
| Sum | 71.05 | 100 | 12.28 | 100 |

On the other hand, the total capacity of the roads for the SMA represents just about 7% of that of the nationwide network. This means that only a small fraction of road space is available for each trip in the SMA which itself gives an indication as to how congested the SMA is.

**Table 6 Available road capacity for each trip in SMA and Korea**

| | SMA | Nationwide | Unit |
|---|---|---|---|
| total capacity of roads | 5,692 | 82,339 | km |
| total trips produced | 31.73 | 39.32 | Trips (million) |
| available capacity per trip | 0.179 | 2.094 | meters/trip |

In addition, as a more realistic example, we compare the travel time gap between passenger cars and Korea Train Express (KTX) connecting Seoul and Busan, the second largest city, in South Korea. Currently, the KTX is the fastest ground transportation for inter-regional trips. Assuming that the travel time of KTX is fixed during the time span as two hours and 45minutes, the two travel time curves are expected to cross around 2060 when the market share of the autonomous vehicles reaches approximately 80%.

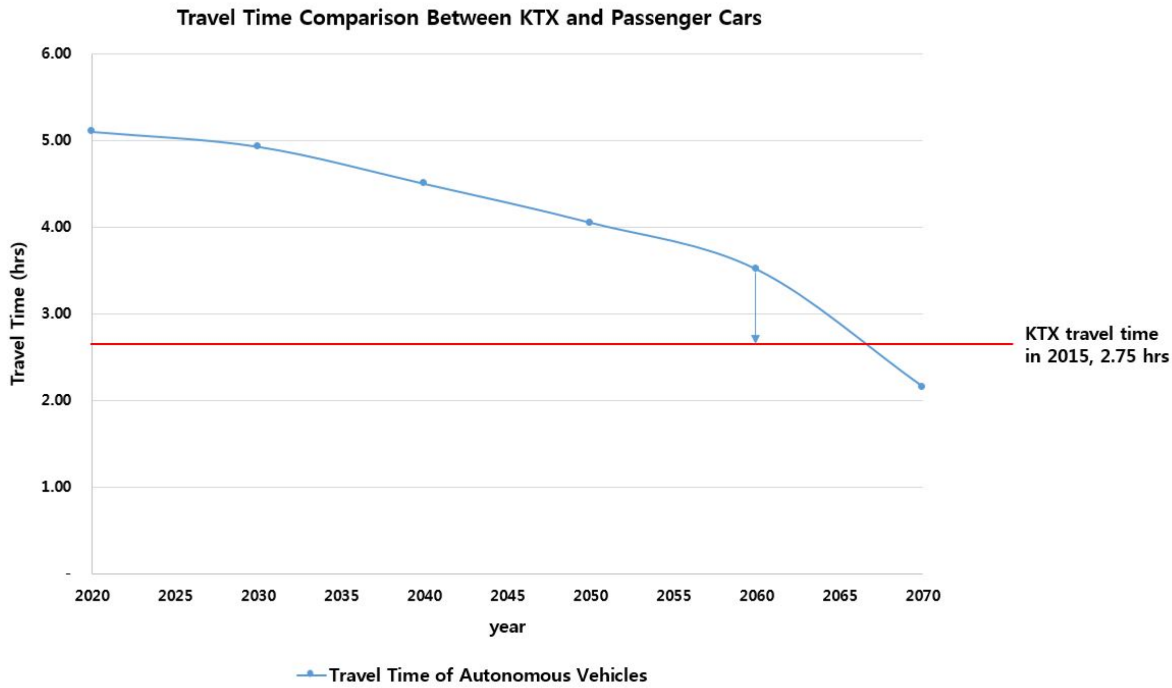



**Figure 7 Travel time comparison between KTX and passenger cars**

We have so far quantified the expected effects of the autonomous vehicle system in South Korea on traffic safety, travel time savings and traffic throughput. The travel pattern in the SMA is such that more than a quarter of all generated trips are bounded for Seoul, and the public transit network is well developed to support travel demand to and from Seoul as well as much of circumferential trips in the areas surrounding Seoul. This is quite different from some metropolitan regions in the U.S. and would produce a land use pattern different from the U.S case when the autonomous vehicle system is introduced. Next section explores the possible changes in land use pattern that can be brought by the autonomous vehicle system.

## 2. Land use

### A. Simulation of Spatial Impact of Autonomous Vehicle

It is expected that the introduction of autonomous vehicles would change the way of utilizing and developing urban space. In this section, the change in land use is presented using a simulation model that compares the spatial structure with and without autonomous vehicles. However, there exist limitations in specifying the values of some input variables and model parameters through empirical analysis, hence the variables and parameters were set under reasonable assumptions.

### A. Methodology and Model

There are many different types of urban models, and the classification of urban models also varies. Yet, disaggregate and dynamic urban models are gaining popularity as a new means to study urban development and land use change (Iacono, Levinson and El-Geidy, 2008; Batty, 2009). In order to compare the pattern of spatial dispersal and agglomeration following the introduction of autonomous vehicles, it is more suitable to employ a disaggregate model which extracts results in cell or parcel unit than an aggregate model that extracts results in administrative district unit. The two representative disaggregate urban models are cellular automat and agent based model.

We employ our own agent based model to simulate the spatial impact of autonomous vehicles, assuming that the introduction of autonomous vehicles would change the locational choices by the various agents as well as the attractiveness of regions. The model can simulate the changes in urban land use through the locational choice of utility maximizing individual agents such as households and business firms. It integrates the random utility theory (Mcfadden, 1973) into the agent based model framework, and the utility that individual *i* is associating with alternative *a* is defined by:

$$U_{ai} = \sum_{s=1}^{S} \beta_s x_{ai} + \varepsilon_{ai},$$

Where S is a choice set, $\beta_s$is a vector of s estimable coefficients,$x_{ai}$ is a vector of observed independent attributes of individual *i* derives from alternative *a*, and $\varepsilon_{ai}$ is an unobserved random disturbance term that follows a Gumbel distribution.

The basic behavioral configuration of the model conforms to the fundamental assumptions of the random utility theory. However, urban systems are affected not only by the location-choice behavior of individual agents but also by various socio-economic factors. Thus, the model is designed to also consider the relevant exogenous variables such as regional potentials and total development demand.

**B. Assumptions of the Simulation**

i. Only household agents are considered.

ii. Each household is located at space that maximizes utility.

iii. All land except in legal protection zones or undevelopable, can be developed without additional development cost.

iv. Only two land uses (urban and non-urban) are considered.

**C. Main Input Variables**

i. Macro: Total amount of expected development in the future – calculated exogenously on the basis of current urban land area per capita etc.

ii. Meso: Regional potential – utilize accessibility information by transportation zone calculated from the traffic model.

iii. Micro: Agents' locational preference factors: Physical factors (elevation, slope), accessibility factors (distance to road, distance to city center), humanities and socioeconomic factors (population density, distance to educational, cultural and distribution facilities, official land price) etc.

**D. Scope**

i. Study area: The Seoul Metropolitan Area

ii. Spatial unit: The region is represented by a discrete space composed of 100m x 100m grid cells. Each cell is the basic unit of locational choice and spatial change. Statistical data on the administrative districts or traffic zones are used as reference in the calculating of regional attractiveness and so on.

iii. Time horizon: From the year 2010 till 2070

**E. Scenarios**

i. Scenario A (business as usual): Urban growth continues in a pattern that is similar to the present without the introduction of autonomous vehicles.

ii. Scenario B (autonomous vehicle system): The share of the autonomous vehicles will reach 100%.

**F. Scenario-Specific Configuration of Parameters and Coefficients**

Generally, empirical evidences such as survey data are required for determining model parameters and calibrating the model. Since our simulation aims to explore the possible outcomes in the uncertain future, we need to make reasonable assumptions. Our assumptions are presented in Table 7.

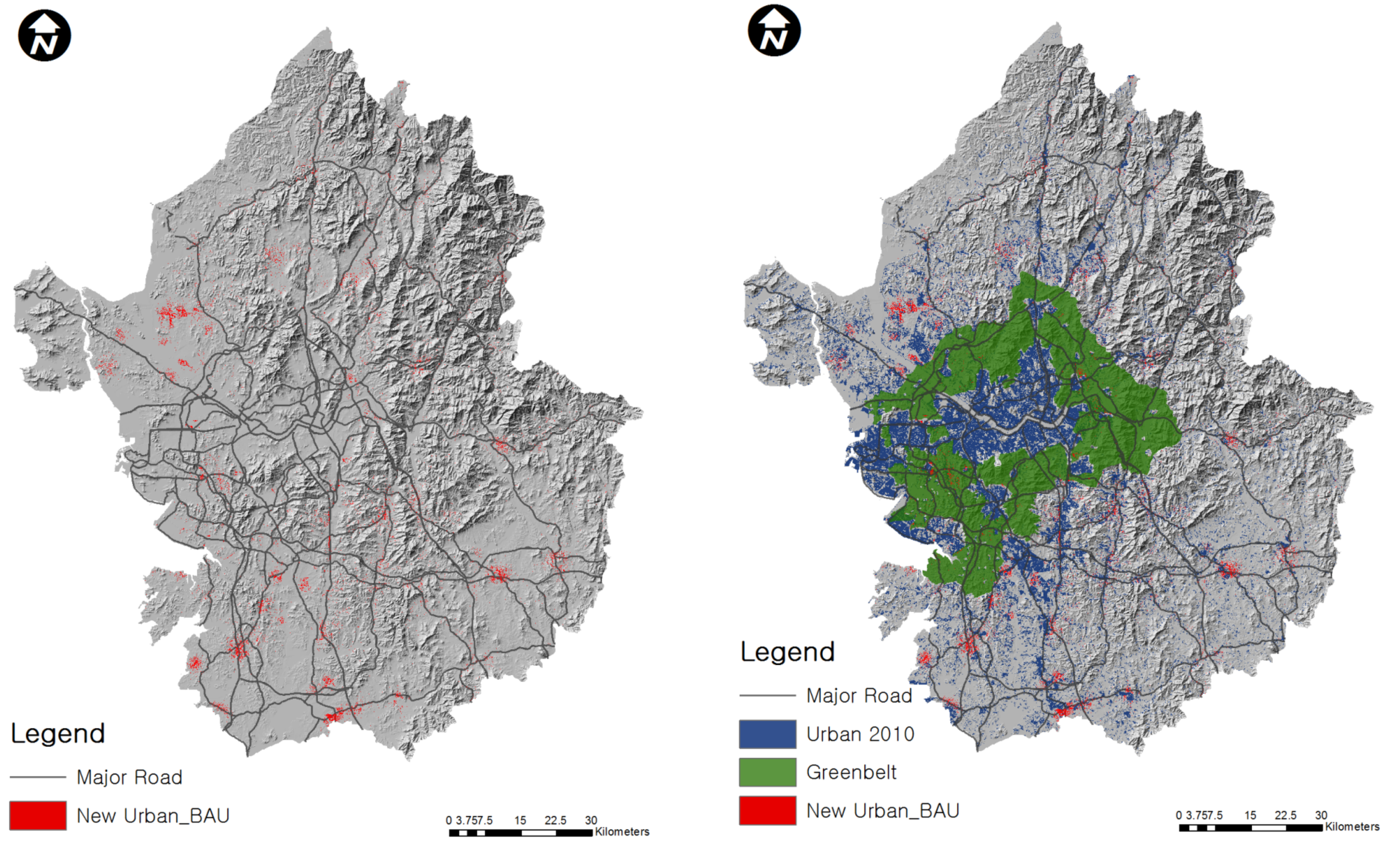
**G. Simulation Results by Scenario**

The simulations conducted under the assumptions specified in Table 7. We explore the likely extent of urban spatial growth in the (SMA) over the next five decades. Scenario A assumes that the underlying urban growth pattern of the SMA will continue in the future. It is noteworthy to mention that new developments are regulated around the two major cities, Seoul and Incheon, by greenbelts. Thus, new urban growth is likely to take place in the unprotected outer areas in the SMA, resulting in a leap-frogging development pattern. However, such new developments tend to form some local agglomerations around urban service centers due to agents' preferences for urban amenity. Scenario B assumes a complete introduction of autonomous vehicles. Agents no longer prefer to locate near urban centers under this scenario. This results in a much more dispersed and scattered urban growth pattern throughout the region. Figure 8 shows the result of simulation under Scenario A, and Figure 9 illustrates the growth pattern under Scenario B. The two figures suggest that the advancement of self-driving or the autonomous vehicles system will lead to a more dispersed development of urban space in the SMA.

**Table 7 Assumptions in Scenario A (business as usual) and Scenario B (autonomous vehicle system)**

| | Factors | Scenario A | Scenario B |
|---|---|---|---|
| Macro | Total amount of spatial change | Identical | Identical |
| Meso | Regional potential | High accessibility in regions near city center | Increasing accessibility in regions far away from city center |
| Micro | Elevation | No change | No change |
| | Slope | No change | No change |
| | Distance to road | Business as usual | Increased preference for road accessibility |
| | Distance to city center | Business as usual | Increased preference for city center accessibility |
| | Population density | Business as usual | Increased preference for regions with lower population density |
| | Distance to neighborhood facilities (education, culture, distribution etc.) | Business as usual | Increased preference for accessibility to neighborhood facilities |
| | Land price | Business as usual | Increased preference for low-price regions |

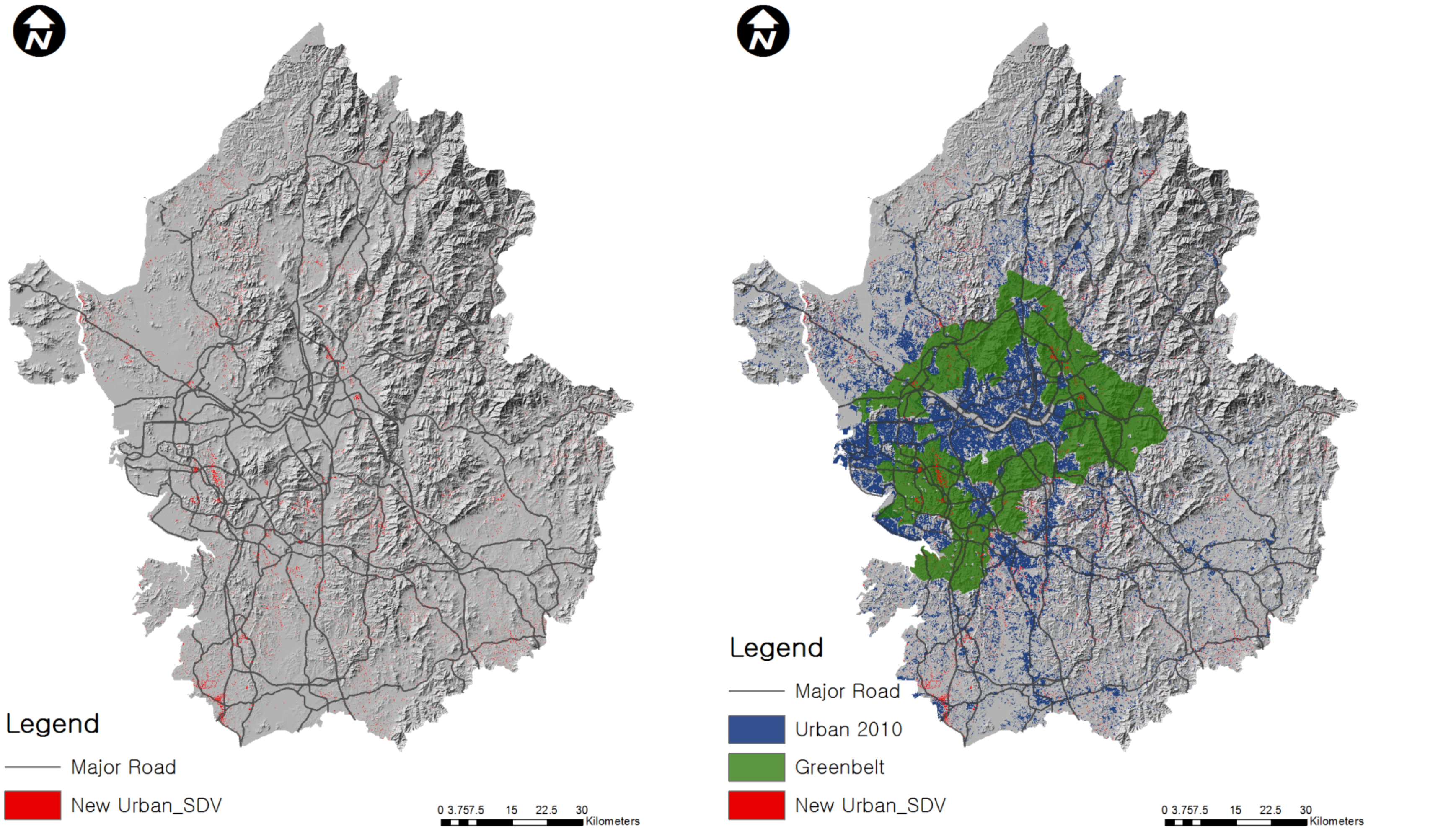
Area.




(a) new urban land

(b) new urban and current urban land

**Figure 8 Location of urban development under Scenario A**




(a) new urban land

(b) new urban and current urban land

**Figure** 9 **Location of urban development under Scenario B**

## V. Conclusions and Suggestions for Further Research

The paper started with a critical review of the existing studies on the prospect of and the expected effects of introducing an autonomous vehicle system. We then presented a projection of the timeframe for the advancement of autonomous vehicles towards complete autonomous driving under optimistic and pessimistic assumptions. The main part of the paper consists of an effort to quantify the expected effects of the autonomous vehicles system on transport and land use using data on South Korea. To be specific, the effect of autonomous driving was specified by item through an analysis taking into effect the actual transportation and land use system in South Korea. As a realistic example, the study compared the travel time gap between passenger cars and Korea Train Express (KTX) and predicted the two travel time curves to crossover around 2060 when the market share of the autonomous vehicles is projected to reach approximately 60%. Also, simulation of spatial impact of autonomous vehicles system was conducted under two scenarios: Scenario A status quo and Scenario B with the 100% autonomous vehicles. Our simulation results suggest that a more dispersed spatial structure is more likely to emerge under Scenario B than Scenario A.

The advancement of a fully operating autonomous vehicle system might be a fundamental technological breakthrough comparable to the third industrial revolution. That said, it must be difficult and incomplete to understand the expected impact of such a change in the framework of current analytical methodologies. The successful introduction of the autonomous vehicle system is likely to bring revolutionary changes to transportation and land use but our predictions rely on the analytic framework representing the travel behavior of present generation and current land use pattern. Hence the current approaches are limited to providing projections according to the visible development of autonomous driving technology in a reactive manner. It is difficult at present to forecast the changes in utility that the introduction of autonomous vehicles will bring about by examining time and costs only. This is also true in projecting changes in land use where the changes of spatial structure are estimated by examining the locational choices by businesses or individuals faced with the tradeoff between transportation cost and land price. However, viewing travels as derived demands to fulfil objectives such as business or leisure, there lacks rational inferences on human behavioral changes on objectives linked with space, which also deserves attention for further studies. In short, the validity of our analysis is conditioned by assumptions and inferences we made based on the understanding of the current system and institutions. Further studies are needed as better methodologies and more realistic scenarios become available.

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