A NOTE ON ADOPTION OF AUTONOMOUS VEHICLES WITH THE DECREASE IN PARKING SPACES AT SHOPPING AREAS

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In this research, we are going to explore Autonomous vehicles (AVs) adoption through its effect of reducing city parking spaces. The representative consumer derives utility from consumption of a group of differentiated goods. They live in outskirts and travel to shopping areas located in city center to purchase all the goods they need under budget constraint. There are two available transportation modes which are AVs and general vehicles (GVs). AVs can park themselves away from the city center after dropping off passengers. If more people choose to use AVs as their travel mode, there will be less demand of parking at shopping areas. Those lands formerly used for parking can then be converted to commercial land. The increased commercial land will have effects on retails price and goods variety. This paper presents a framework to obtain land rent, retail price, and number of varieties at market equilibrium. Base on that, we analyze consumer's choice behavior and develop social welfare function which can be used by urban planners to find optimal level of AVs adoption. Finally, we discussed the characteristics of the regions where AVs adoption is more preferred.

Key Words : *Autonomous vehicles, adoption, parking spaces*

1. INTRODUCTION

Automakers have successfully brought tre`mendous computerization and electrification into modern vehicles. With greatly improved artificial intelligence technologies, the autonomous vehicle (AV, also called automated or self-driving vehicle) is expected to hit the road in the next decade (C. Liu et al., 2017). By 2018, Google's self-driving cars have driven more than 10 million miles on multiple cities. Tesla has offered auto-pilot to their customers and has the capability to update the software remotely. AVs are getting familiar to the public and expected to become commercialized in near future. Expert members of the Institute of Electrical and Electronics Engineers (IEEE) have predicted that up to 75% of all vehicles will be autonomous by 2040 (IEEE, 2012). AVs are expected to improve in efficiency, convenience, comfort, safety and mobility compared to general vehicles (GVs).

AVs use sensing and communication technologies to navigate safely and efficiently with little or no input from the driver. These driverless technologies will create an unprecedented revolution in how people move, and policy makers will need appropriate tools to plan for and analyze the large impacts of novel navigation systems (R.A. Daziano et al., 2017). AVs use laser and radar to detect the surroundings and the vehicles react according to the system. It can see at night the same as that in the day and thus reducing the frequency of crashes. Many people do not drive because they are disabled or too young. AVs will increase mobility and social interaction of those people. With less crashes and more efficient vehicle operation, congestion might also be relieved. Moreover, AVs have the ability to simply drop off passengers in urban centers and drive away to satellite parking area, which may result in lower parking demand in the downtown areas and more space could be redeveloped for other activities. AVs require less maintenance than GVs, which will translate to a greatly reduced demand for automobile repair and maintenance use. This in turn will free up a large amount of land for redevelopment. Moreover, there will be no need for curbside parking or sprawling garage in city centers. Some remote centralized garages can serve as recharging station because AVs require much more intensive electrical infrastructure. However, cities must proactively plan for this transition. Pilot projects dedicated to reducing or reallocating parking can help cities test strategies for location. For example, shopping areas usually require three times parking land compared with retailer floor land. If parking lands at shopping areas will be released after introduction of AVs, there will be more space for entertainments and commercial activities.

AVs adoption, defined as people switch from GVs to AVs, has been admitted to have a great benefit to the society. But the process still has some barriers. For example, due to the new technologies used in AVs such as sensors, navigation and communication systems, software, and Light Detection and Ranging systems (LIDAR), AVs will be more expensive (Fagnant and Kockelman, 2015). Our research is going to study on the AVs adoption in the beginning stage when the price of AVs is expensive. We build a model to explain consumers' choice behavior between AVs and GVs. Incorporate with the effect of reducing parking spaces in city center, we would be able to explain how AVs adoptions become possible in spite of the high costs of AVs.

In this research, we focus mainly on three points. First, we propose a model to describe consumers' utilities with the decrease in parking spaces. Second, through the process of maximizing utility we analyze AVs adoption from both individual level and social level under certain conditions. Third, we summarize the characteristics of regions where AVs adoption is preferred.

The thesis is structured as follows. Section 2 explains the basic ideas on AVs and adoption theory, based on which the basic model is structured and explained in section 3. The fourth section analyzes consumers' choice behavior and social welfare. It shows the influence of some important parameters on AVs adoption. Finally, conclusions and discussions are presented at section 5.

2. BASIC IDEAS

(1) Impacts of autonomous vehicles

AVs are expected to have various impact on transportation system including improved road safety, enhanced mobility, increased road capacity, more efficient traffic operations, and new patterns for urban parking (M. Noruzoliaee et al., 2018). AVs will also affect travel demand because travelers can use their in-vehicle time more productively (Jamson et al., 2013; Fagnant and Kokelman, 2015; van den Berg and Verhoef, 2016), which results in reduced generalized cost of travel. In addition, AVs can accelerate and deaccelerate more smoothly so that they will decrease energy consumption and emissions and shape land use in the long run.

AVs have the potential to dramatically reduce crashes. According to NHTSA (2008), 94 percent of accidents in the U.S., as well as over 40 percent of the fatal crashes among them, are related with human errors including speeding, drunk, tired driving, or use of mobile phone. Self-driven vehicles would not fall prey to human failings, suggesting the potential for at least a 40 percent fatal crashes reduction. This is because AVs are designed to never speed, always keep a safe distance to other vehicles, be equipped with accurate detection system, and react quickly, and so on. Humans by contrast are fallible. This is why majority of crashes involve the human factor, either the driver or another road user. AVs can save millions of people's lives every year from accidents caused by human errors. We can now understand why the safety benefits of AVs are paramount.

Road capacity is expected to be improved by AVs. The capacity impact of AVs comes from the reduction in vehicle headways. M. Noruzoliaee et al. (2018) modeled the average vehicle space in mixed flow as the weighted averaged of vehicles space with only AVs and only GVs. Mahmassani (2016) found that as AVs market share increases, AVs will have a greater influence on capacity because this allows AVs to cooperate more efficiently. Raphael E. Stern et al. (2018) demonstrated experimentally that intelligent control of AVs is able to dampen stop-and-go waves. When perturbation happens in front of the AVs, the system could estimate the average velocity of the vehicle ahead thus they could drive at an optimal velocity to stabilize the traffic flow.

AVs may affect the value of travel time (VOTT). The concept of valuation of travel time is based on the fact that time is considered to have some value. Hence, people choose whether they spend their time on one activity compared to another or how much are they willing to pay to save the time spent in one particular activity (Hensher, 2011). VOTT may depend on the enjoyment of the travel, the use of the travel time to conduct other activities, the comfort and reliability of the mode, the time pressure, and the affordability of the travel cost (M. Abou-Zeid et al., 2010). VOTT losses will be reduced because AVs allow users to perform other activities in the vehicle (V.A.C van den Berg et al., 2016).

Parking space could be saved especially in city center where the land is very limited. In the downtown area of numerous large cities, parking spaces are insufficient due to scarcity of land (Shoup, 2006). Roadways and parking facilities consume over 30 percent of the developed land in most American cities and in excess of 75 percent of the land in many big city downtowns (Jackle et al., 2004). After introduction of AVs, vehicles could drop off users before autonomously travelling empty to a peripheral parking space if an adjacent parking space is unavailable (Levin and Boyles, 2015). The vehicle could even park back home if fuel costs less than parking, which is likely for commuting into city with expensive parking (Fagnant and Kockelman, 2015). There exist some concerns that AVs self-parking trips might increase congestion. However, this negative influence is relatively insignificant compared with the benefits AVs adoption brings, not to mention that sharing AVs will sharply reduce vehicle ownership. R.P.D. Vivacqua (2009) pointed out advanced high-accuracy localization method for outdoor vehicles is capable of performing autonomous driving in narrow two-way roads. Both the number of parking spaces and the size of a single parking slot could be reduced with more AVs adoption. AVs are expected to have a considerable influence on urban transport and layout of city in the long run (V.A.C van den Berg et al., 2016). The land previously used for lanes and parking facilities could be saved for other purposes so as to improve the city life.

(2) Adoption models

The adoption of new technologies has received attention across multiple disciplines within economics and social science over the years (F. El Zarwi et al, 2017). Adoption models are popular in a variety of disciplines such as agriculture, consumer durables, pharmaceutical industry, and the automobile industry estimation. Rogers (1962) divided potential adopters in five classes: innovators, early adopters, early majority, late majority and laggards. And this classification is based upon the timing of adoption by the various group.

Later Bass (1969) combined the last four classes and divided potential adopters into two distinct groups: innovators and imitators. He defined innovators as individuals that "decide to adopt an innovation independently of the decisions of other individuals in a social system" while imitators are adopters that "are influenced in the timing of adoption by the pressures of the social system".

Aggregate models such as Bass model in the marketing science literature using mathematical formulation to show that the probability of a certain consumer will make an initial purchase at a given time as a linear function of the number of previous buyers. However, this kind of imitation model describes users or adopters not as groups thus lacks a clear microeconomic foundation, namely do not explicitly consider consumers' heterogeneity. (E. Kiesling et al., 2011)

Disaggregate models were designed to overcome the shortcoming of the imitation model. Introduced by David (1975), the threshold model of adoption assumes that individuals make adoption decisions using economic decision-making rules, heterogeneity of potential adopters, and dynamic processes. The micro-level economic decision-making emphasizes the expected-utility maximization. Some studies focus on dynamic optimization, whereby the threshold changes overtime because some learning process or technology price decreases.

Disaggregate models are of interest to researchers in transportation adoption studies. These models formulate the probability that an individual or household adopts a transportation innovation as some function of the characteristics of the decision maker, attributes of the alternative and social effect (F. El Zarwi et al., 2016). One of the dominate disaggregate adoption model is the threshold model. Studying the market adoption of electric vehicles has received worldwide attention in the past few years. A probit model for plug-in electric vehicles (PEV) adoption would calculate the average ownership cost difference between conventional and electric vehicles and estimate a PEV market share based on this difference. As fuel and battery prices change over time, these cost differences change and with the estimated PEV market share (T. Gnann et al., 2015). Plotz et al. (2014) estimated an agent-based simulation model of the adoption of electric vehicles using real-world driving data that captured heterogeneity among decision-makers, psychological factors and attributes of the new technology. Eppstein et al. (2011) using an integrated agent-based and consumer choice model to capture the effect of social interactions and media on the market penetration of PEV.

As for other transportation innovation adoption models, J. Struben (2008) modeled the adoption of the alternative fuel vehicles focusing on the generation of consumer awareness of alternatives through feedback from consumers' experience, word of mouth, and marketing, with a reduced-form treatment of network effects and other positive feedbacks. And he demonstrated the existence of a critical threshold for sustained adoption of alternative technologies, and showed how the threshold depends on economic and behavioral parameters. H. Yang (2000) models the growth rate and the saturation market penetration level for advanced traveler information system (ATIS) with heterogeneous drivers. He used price of using and benefit gained from ATIS as two factors in explaining the growth of adoption. F. El Zarwi (2016) developed a new technology adoption model for new transportation service to predict the probability that a certain individual will adopt the service at a certain time period, which is explained by social influences, network effect, social demographics and level of service attributes. He assumes all individuals are utility maximizers and described how the utility is influenced by involved variables.

Research on adoption of AVs has been based on empirical evidence of adoption of earlier vehicles technologies, stated-preference surveys, and simulation techniques. Fagnant and Kockelman (2015) highlight that a comprehensive market penetration analysis should consider the interactions between traveler willingness-to-pay and AV prices. Some papers studied on transportation issues under a mixed traffic condition of both AVs and GVs with exogenous penetration rate (V.A.C. van den Berg and E.T. Verhoef, 2016). L. Tian et al. (2019) used a bottleneck model to study a morning commute problem and drive penetration rate endogenously based on the number of available parking spaces.

() Points of the research

Even though the technology adoption theory has been widely developed, research studies concerning AVs adoption are limited. Since AVs are not available on the market, the existing literature is mostly based on empirical evidence observed from earlier vehicle technologies, stated-preference surveys, and simulation techniques. Unlike other commodities, vehicles adoption takes a long time because of the long lifetime cycle and high price. AVs adoption has been proved to have greater impact on safety, road capacity, people's lifestyle, parking issues, and even urban layout in the long run. Prediction of AVs adoption based on the current transportation network is suspectable.

In this study, we focus on the effect of reducing parking spaces during the AVs adoption process because we believe this will have a huge impact on urban planning. As more and more people choose AVs, some parking spaces will become unoccupied so as to increase land supply in the city. The increase of land supply will have great influence on city life. We built a theoretical model to explain how the land rent, goods price, and varieties of goods change along with AVs adoption, based on which we maximize consumers' utilities under their budget constraints. Using the model, we analyze consumers' choice behavior and optimal AVs adoption level for social optimal.

3. THE MODEL

(1) Assumptions

Consumers in our model live in outskirts and they derive utility by shopping at some shopping areas located in the city center. A consumer has to own one vehicle as his/her transportation mode for shopping. The choice set of their transportation modes includes only GVs and AVs. They have the same income level which we assume to be exogenously given. All their income will be spent on vehicle ownership and shopping at city center. Ownership cost here consists of all the costs needed for owning a vehicle, like purchasing price, insurance cost, maintenance and repair cost, etc. And consumers are able to purchase a variety of differentiated goods at shopping areas located in the city center. Lands in shopping areas are developed only for parking purpose and commercial purpose. Parking land is used to build parking facilities in order to serve those who drive GVs. And commercial land is rented by retailers to sell differentiated retail goods. Meanwhile GVs users need to pay parking fee because they occupy some parking lands. AVs users have no need to park because their vehicles are able to drop off passengers in shopping areas and drive away to satellite free parking spaces away from the city center. In our model, if more people use AVs, the demand for parking will decrease so the land owner could provide land at a lower rent. As a result, retailers could provide goods at lower price so consumers will increase their consumption. This increase in consumption will in return attract more entries of retailers. As a consequence, the consumers' utilities change in the process. We will derive the market equilibrium at the end of this section.

The model considers a city with N potential adopters, in which the number of AVs users is N^A and the number of GVs users is N^G. People in this city live in outskirts and make one trip to the shopping areas located in city center to purchase all the goods they need under budget constraints. All their incomes after paying vehicle ownership will be used for shopping. As the new technologies used on AVs are always expensive at beginning stage because the effects of scale economy are small, we here assume the ownership cost of AVs is higher than that of GVs. Of course, this difference in cost might be mitigated by economics of scale principle. AVs users can spend all those incomes on shopping because they have no need to parking at the shopping areas. However, GVs users need to pay an extra fixed amount of parking fee because they occupy some land for parking. The lands in shopping areas are used for commercial purpose and parking purpose. The land development rules of land owners are that they will first guarantee enough parking land required by GVs users and the rest of land could then be developed to satisfy commercial demand, here again, we mean selling a variety of differentiated goods. The retailers at shopping areas provide differentiated goods under increasing return using commercial lands as the only input. Retailers pay rent to land owner and the land owner would adjust the rent according to land demand. If there appears more unoccupied land. The land owner will decrease the rent so as to attract more entries of retailers. In this model, the rent is endogenously derived through supply-demand balance in land market.

(2) Consumers

A consumer resides in outskirts and makes a shopping trip to the city center by transportation mode M, where $M = G$ denotes general vehicle and $M = A$ denotes autonomous vehicle. When shopping areas provides a group of differentiated goods, the consumer's utility function is given by

$$U = \left[\sum_i \left(x_i^M\right)^\rho\right]^{1/\rho} \qquad 0 < \rho < 1 \qquad (1)$$

where x_i^M represents the consumption of variety i by consumer using transportation mode M. Here the utility function is of the Dixit-Stiglitz form with constant elasticity of substitution (CES). The parameter ρ stands for the inverse of the intensity of desires for variety over the differentiated products. When ρ is close to 1, varieties are close to perfect substitutes; when ρ decreases, the desire to spread consumption over all varieties increases. If we set

$$\sigma \equiv \frac{1}{1-\rho} \qquad (2)$$

then σ is the elasticity of substitution between any two varieties, which varies between 1 and ∞.

The budget constraint for a GV user is

$$\sum_i p_i x_i^G + r_0 h + O^G = I \qquad ()$$

where p_i are the prices of the goods sold in market, r_0 is the fixed rent for parking land at shopping areas and h denotes the average land occupied for parking by a GV user, O^G is the ownership cost of a general vehicle and I is the exogenous income for all individuals.

The budget constraint for an AV user is

$$\sum_i p_i x_i^A + O^A = I \qquad (4)$$

where x_i^A denotes the consumption of product variety i by an AV user, O^A is the ownership cost of an autonomous vehicle. Note here an AV user has no expenditure on parking purpose.

Given the utility function and budget constraint, the problem for a GV user is to maximum (1) under the constraint of (), which is,

$$\max y^G = \left[\sum_i \left(x_i^G\right)^\rho\right]^{1/\rho}$$
$$\text{s.t.} \sum_i p_i x_i^G + r_0 h + O^G = I$$

The Lagrangian $\mathcal{L} = \left[\sum_i \left(x_i^G\right)^\rho\right]^{1/\rho} - \lambda\left(\sum_i p_i x_i^G + r_0 h + O^G - I\right)$ yields the first-order conditions

$$\frac{\partial \mathcal{L}}{\partial x_i^G} = \mathrm{y}^{1-\rho}\left(x_i^G\right)^{\rho-1} - \lambda p_i = 0 \qquad (5)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = \sum_i p_i x_i^G - \left(I - r_0 h - O^G\right) = 0 \qquad (6)$$

Solving (5) for x_i gives

$$x_i^M = y(\lambda p_i)^{1/(\rho-1)} \qquad (7)$$

Inserting this into (6) and solving for λ we get

$$\lambda^{1/(\rho-1)} = \frac{I - r_0 h - O^G}{y}\left[\sum_i p_i^{\rho/(\rho-1)}\right]^{-1} \qquad (8)$$

Finally, plugging (8) back into (7) we get the preliminary demand function of a single variety of product i for a GV user,

$$x_i^{\mathrm{G}} = (I - r_0 h - O^G) p_i^{1/(\rho-1)}\left[\sum_i p_i^{\rho/(\rho-1)}\right]^{-1} \qquad (9)$$

Take (9) to the power of ρ and sum over i

$$\sum_i \left(x_i^G\right)^\rho = \left[\sum_i p_i^{\rho/(\rho-1)}\right]^{-\rho} (I - r_0 h - O^G)^\rho \sum_i p_i^{\rho/(\rho-1)}$$

$$y^G = \left[\sum_i \left(x_i^G\right)^\rho\right]^{1/\rho} = \left[\sum_i p_i^{\rho/(\rho-1)}\right]^{-1} (I - r_0 h - O^G)\left[\sum_i p_i^{\rho/(\rho-1)}\right]^{1/\rho}$$

$$y^G = \frac{I - r_0 h - O^G}{\left[\sum_i p_i^{\rho/(\rho-1)}\right]^{(\rho-1)/\rho}} \qquad (10)$$

Fourth, in the case all varieties are equally weighted, the price should be in the same level, i.e. $p_i = p_e$ and hence $x_i^G = x^G$. Then the expenditure is equally divided over all varieties since they symmetrically contribute to the utility function. If there exists n_e varieties, the demand function (9) and indirect utility function (10) are simplified to

$$x_i^G = x^G = \frac{I - rh - O^G}{n_e p_e} \qquad (11)$$

$$V^G = y^G = \frac{I - rh - O^G}{n_e^{(\rho-1)/\rho} p_e} \qquad (12)$$

From above we can understand why CES utility function is often referred to as "love of variety" preferences. As there exists a large number of varieties in the market, each retailer is negligible. Increasing or decreasing of one retailer may have little influence on the price level which suggests a fixed product price. When the price level is constant, consumer's utility increases with the number of varieties n_e and this is how "love of variety" works. From the figure below we can examine how indirect utility changes with n_e.

Next, let us look at the consumers who choose to own AVs. Similar to the discussion above, the problem an AV user facing is to maximum (1) under the constraint of (4) which gives,

$$\max y^A = \left[\sum_i \left(x_i^A\right)^\rho\right]^{1/\rho}$$

$$\text{s.t.} \sum_i p_i x_i^A + O^A = I$$

where x_i^A is the consumption of product variety i by an AV user and O^A is the ownership cost of an autonomous vehicle. No parking fee is charged.

Following the same optimization process as we did for GV users before, we can get the demand function and indirect function for an AV user,

$$x_i^{\mathrm{A}} = (I - O^A) p_i^{1/(\rho-1)} \left[\sum_i p_i^{\rho/(\rho-1)}\right]^{-1} \quad (13)$$

$$y^A = \frac{I - O^A}{\left[\sum_i p_i^{\rho/(\rho-1)}\right]^{(\rho-1)/\rho}} \quad (14)$$

Under symmetrical situation, the above functions can be simplified to

$$x_i^A = \frac{I - O^A}{n_e p_e} \quad (15)$$

$$V^A = \frac{I - O^A}{n_e^{(\rho-1)/\rho} p_e} \quad (16)$$

Let us think about the results in (10) and (14), the numerators are disposable income spent on purchasing the differentiated goods after paying the vehicle ownership cost and parking fee (if charged). As $y^M = \left[\sum_i \left(x_i^M\right)^\rho\right]^{1/\rho}$ stands for an index of consumption of the goods market, we can now define the denominators in (10) and (14) as price index of the differentiated products which is given by,

$$q = \left[\sum_i p_i^{\rho/(\rho-1)}\right]^{(\rho-1)/\rho} \quad (17)$$

Using the price index, the demand function (9) and (13) can be simplified to

$$x_i^G = y^G \left(\frac{q}{p_i}\right)^{1/(1-\rho)} \quad (18)$$

$$x_i^A = y^A \left(\frac{q}{p_i}\right)^{1/(1-\rho)} \quad (19)$$

Some remarks are required hereafter. Since the results will be the same for both AVs users and GVs users, only AVs case will be presented. Let us rewrite expression (.13) in the following format,

$$x_i^{\mathrm{A}} = (I - O^A) p_i^{1/(\rho-1)} q^{\rho/(1-\rho)} \quad (20)$$

Then take the logarithm,

$$\log x_i^A = \log(I - O^A) + \frac{1}{\rho - 1}\log p_i + \frac{\rho}{1-\rho}\log q \quad (21)$$

we could get two useful results from this equation. First, we assume there is a sufficiently large number of varieties so each firm has a negligible impact on the market. This means the pricing decision of a single retailer do not affect the general price index. So, the price elasticity of demand for product i is

$$\varepsilon_d = \left.\frac{\partial \log x_i^A}{\partial \log p_i}\right|_{q\ const.} = \frac{1}{\rho - 1} \quad (22)$$

Second, we can obtain the elasticity of substitution by

$$\varepsilon_s = \frac{\partial \log\left(x_j/x_i\right)}{\partial \log\left(MRS_{ij}\right)} = \frac{\partial \log\left(x_j/x_i\right)}{\partial \log\left(MU_i/MU_j\right)} = \frac{\partial \log\left(x_j/x_i\right)}{\partial \log\left(p_i/p_j\right)} \quad (23)$$

From (.20) we can get

$$\frac{x_j}{x_i} = \left(\frac{p_i}{p_j}\right)^{1/(1-\rho)} \quad (24)$$

Substituting (24) to (23)

$$\varepsilon_s = \frac{\partial \log\left(p_i/p_j\right)^{1/(1-\rho)}}{\partial \log\left(p_i/p_j\right)} = \frac{1}{1-\rho} = \sigma \quad (25)$$

At this point, we can understand why $1/(1-\rho)$ was set as elasticity of substitution in (2).

() Consumers

The market in the shopping areas is such that the sale of goods requires identical fixed and marginal land input. This is because products need space for exhibition. Each variety of goods is sold in the same way that the display of quantity x requires l_c square meters of commercial land,

$$l_c = f + cx \quad (26)$$

where f is the fixed land input and c is the marginal land input. Clearly, this kind of market shows scale economies. Since consumers demand all existing varieties symmetrically, any new retailer entering the market will choose to sell a unique variety instead of replicating an existing one. Also, every retailer will choose to sell only one variety. Therefore, the number of varieties should equal the number of retailers on the goods market.

The profit function of a retailer in shopping areas is

$$\pi = px - r(cx + f) \qquad (27)$$

where p is the price of goods under symmetrical condition and r is the rent fee of commercial land. As we mentioned before, varieties are equally weighted in the utility function, the equilibrium price is the same for all varieties of commodities. And we also notice that there exists a sufficiently large number of retailers so we ignore the effects of a single retailer's price strategy on the price index q. From (20) we can know that p is a function of x, so we mark as $p = f(x)$. The revenue function of a retailer can be written as

$$R = px = f(x) \cdot x \qquad (28)$$

Then we take the derivative of revenue with respect to x to get marginal revenue

$$MR = \frac{dR}{dx} = \frac{d(p \cdot x)}{dx} = \frac{dx}{dx}p + \frac{dp}{dx}x = p + \frac{dp}{dx}x = p\left(1 + \frac{dp/dx}{p/x}\right)$$

Then we take the derivative of revenue with respect to x to get marginal revenue

$$MR = \frac{dR}{dx} = \frac{d(p \cdot x)}{dx} = \frac{dx}{dx}p + \frac{dp}{dx}x = p + \frac{dp}{dx}x = p\left(1 + \frac{dp/dx}{p/x}\right)$$

From the definition of elasticity of demand, the above equation can be simplified into

$$MR = p\left(1 + \frac{1}{\varepsilon_d}\right) \qquad (29)$$

We know the optimal price can be derived when marginal revenue equals marginal cost which gives

$$p\left(1 + \frac{1}{\varepsilon_d}\right) = c \quad (30)$$

Substituting (22) into (0) gives the optimal price,

$$p_e = \frac{rc}{\rho} \qquad (31)$$

This means the optimal price is set as a constant mark-up $1/\rho$ over marginal land rent cost rc, which is independent of consumer's choice. We also find that p_e increases when ρ decreases. This shows more desire for goods differentiation leads to a higher price in equilibrium.

Substituting (1) into the profit function,

$$\pi = \left(\frac{rc}{\rho} - rc\right)x - rf = \frac{rc}{\sigma - 1}x - rf \qquad (32)$$

This model assumes free entry so that new retailers will enter the market and sell a new variety as long as the profit is positive. When a new variety of product shows up on the market, consumers will divert some of the expenditure previously spent on the existing varieties to purchase the new one. The quantity sold of each variety decreases, as does profit due to rising average land cost. As we can see from equation (32), profit has a positive relationship with quantities they sold. This kind of entry behavior stops until each retailer's profit reaches zero. As a consequence, the free entry condition states that in equilibrium the marginal retailer operating at zero-profit. Set $\pi = 0$

$$x_e = \frac{f}{c}(\sigma - 1) = \frac{f}{c}\left(\frac{\rho}{1-\rho}\right) \qquad (33)$$

Under free entry, we can see the equilibrium output of a retailer is a constant independent of consumers' behavior. As a result, the equilibrium land input of each retailer should also keep constant,

$$l_e = f + cx_e = \sigma f = \frac{f}{1-\rho} \qquad (34)$$

This means each retailer rents the same size of commercial land under free entry condition. As each retailer will sell a unique kind of variety, the land requirement for each variety is equal to the land requirement for each retailer. Now we have the demand quantity of each consumer and the supply quantity of each retailer. In equilibrium the quantity supplied by each retailer should satisfy the consumers' demand, which gives,

$$x_e = N^G x_i^G + N^A x_i^A \qquad (35)$$

Substituting (11), (15), (33) into (35) and replacing N^G with $N - N^A$, we can get,

$$\frac{f}{c}\left(\frac{\rho}{1-\rho}\right) = (N - N^A) \cdot \frac{I - r_0 h - O^G}{n_e p_e} + N^A \cdot \frac{I - O^A}{n_e p_e} \qquad (36)$$

We've already known from (31) that $p_e = rc/\rho$, substitute into equation (35) and solve the number of varieties n_e when supply equals demand,

$$n_e = \frac{1-\rho}{fr}[(N - N^A)(I - r_0 h - O^G) + N^A(I - O^A)] \qquad (37)$$

In the expression above, the part in square brackets presents overall income spent on retail markets. We could find that the equilibrium number of varieties is decided by consumers' disposable income spent on retail market and the commercial land rent on market. As the number of AVs users increases, people will have less disposable income because the technology used on AVs are always more expensive. However, adoption will cause less parking demand which means there will be more unoccupied land for commercial activities. The land owner will be able to provide the land with lower rent which will result in lower price level according to (31). Decrease in price level will lead to more consumption which has a positive influence on consumers' utility. In the next section, land rent for commercial areas will be endogenously determined through the land market equilibrium.

(4) Land Market

The land in these shopping areas is owned by government. The land development rules are such that the requirement for parking and commercial purpose should first be satisfied and the rest stay undeveloped as recreational land. The rent for parking land is set to be fixed as r_0 while the rent for commercial, or retailers, is decided by the following equation,

$$Z_c = Z_m\left(1-\frac{\beta}{r}\right) \tag{38}$$

where Z_c is the commercial land demand by retailers, Z_m is the maximum land supply for retailers which equals to the total land minus parking land, r is the rent for retailers and β is a parameter. Here we notice that the part in parentheses means to what percentage will the land be used for commercial purpose so $\beta < r$ always holds. When β has a larger value, the land provided to retailer is smaller. This equation is based on the principle that the land price is determined by the relation of land's supply and demand. We could find from the equation that when the commercial land demand is fixed, more supply will lead to lower rent.

As we can see from (34) that the land requirement for each retailer is the same which is equal to a markup over fixed land input. So, the commercial land demand for all retailers is calculated in the following equation,

$$Z_c = n_e l_e = \frac{n_e f}{1-\rho} \tag{39}$$

If we assume the size of all the lands in shopping areas is L, the maximum land supply for retailers is expressed by,

$$Z_m = L - L_p \tag{40}$$

where L_p is the parking land requirement. We assume that each GV user occupied a fixed amount of land for parking. Thus, the overall parking land requirement is,

$$L_p = N^G \cdot h = (N-N^A)h \tag{41}$$

By substituting (9) and (40) into (38), we can get the land balance equation for commercial purpose,

$$Z_m\left(1-\frac{\beta}{r}\right) = \frac{n_e f}{1-\rho} \tag{42}$$

Then substituting (37) into (42), we can solve the endogenous commercial land rent at equilibrium

$$r_e = \beta + \frac{[N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)]}{L-(N-N^A)h} \tag{43}$$

As we could see from the equation above, the commercial land rent is changing with the retailers' total revenue and the maximum commercial land supply. If we take the derivative of r_e with respect to N^A, we can get

$$\frac{dr_e}{dN^A} = \frac{(r_0h+O^G-O^A)[L-(N-N^A)h]}{[L-(N-N^A)h]^2} - \frac{[(N-N^A)(I-r_0h-O^G)\ \ +N^A(I-O^A)]h}{[L-(N-N^A)h]^2} \tag{44}$$

As we assume new technologies used on AVs are always expensive at the beginning stage, here we can say O^A is much larger than O^G compared with the parking fee rh GVs users are charged. Therefore $(r_0h+O^G-O^A)<0$ holds. And we know the land in shopping areas must at least be enough for parking so $[L-(N-N^A)h]>0$. As $[(N-N^A)(I-r_0h-O^G)\ \ +N^A(I-O^A)]$ shows all the disposable incomes for consumers to spend in retail markets, this value should also be positive. In a word, $dr_e/dN^A < 0$ always holds. As a result, we could say rent has a decreasing relationship with the number of AVs adoption.

Substituting (43) into (31) and (37), we can get endogenous optimal price and the number of varieties at equilibrium,

$$p_e = \frac{c}{\rho}\left[\beta + \frac{N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)}{L-(N-N^A)h}\right] \tag{45}$$

$$n_e = \frac{(1-\rho)[(N-N^A)(I-r_0h-O^G)\ \ +N^A(I-O^A)]}{f\left[\beta+\frac{N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)}{L-(N-N^A)h}\right]} \tag{46}$$

4. ADOPTION PROCESS

(1) Consumr's Choice

With endogenous r_e derived from (43), we could get the indirect utility of a consumer who chooses GV by plugging (31) and (37) into (12),

$$V^G(N^A) = \frac{[I-r_0h-O^G]}{\left\{\frac{1-\rho}{fr_e}[N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)]\right\}^{\frac{(\rho-1)}{\rho}}\frac{r_ec}{\rho}} \tag{47}$$

Similarly, we can get the indirect utility if the consumer chooses an AV,

$$V^A(N^A) = \frac{[I-O^A]}{\left\{\frac{1-\rho}{fr_e}[N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)]\right\}^{\frac{(\rho-1)}{\rho}}\frac{r_ec}{\rho}} \tag{48}$$

The number of varieties is affected by two values: disposable income spent on retail market $[N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)]$ & retail goods prices $\frac{r_ec}{\rho}$. These two values have opposite effects on

n_e as N^A increases, which makes the monotonicity of V^G and V^A unclear. If we take the difference of these two utilities,

$$V^G(N^A)-V^A(N^A)=\frac{[O^A-O^G-r_0h]}{\left\{\frac{1-\rho}{fr_e}[N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)]\right\}^{\frac{(\rho-1)}{\rho}}\frac{r_ec}{\rho}} \quad (49)$$

It's apparent that $V^G(N^A)-V^A(N^A)>0$ always holds. We got the same result with 4.2.1 that the indirect utility for using a GV is always larger than the indirect utility for using an AV so that consumers have no incentive to adopt AVs.

(2) Utility

Overall utility is calculated by taking the aggregate sum of consumers' indirect utilities. If we assume there are N^A autonomous vehicle users in the city, the overall utility of consumers is calculated by the following equation,

$$V(N^A)=(N-N^A)V^G+N^AV^A \qquad (50)$$

We can get

$$V(N^A)=\frac{[(N-N^A)(I-r_0h-O^G)\ \ +N^A(I-O^A)]\rho\cdot r_e^{-\frac{1}{\rho}}}{c\cdot\left\{\frac{1-\rho}{f}[N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)]\right\}^{\frac{(\rho-1)}{\rho}}} \quad (51)$$

Rearranging the function, we can get

$$V(N^A)=\frac{\rho}{c\left(\frac{1-\rho}{f}\right)\left\{\frac{1-\rho}{fr_e}[N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)]\right\}^{-\frac{1}{\rho}}} \quad (52)$$

Substituting (.37) into (4.12), we can have

$$V(N^A)=\frac{\rho}{c}\left(\frac{f}{1-\rho}\right)^{\frac{(\rho-1)}{\rho}}\left[\frac{\beta}{N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)}+\frac{1}{L-(N-N^A)h}\right]^{-\frac{1}{\rho}} \quad (53)$$

As $\frac{\rho}{c}\left(\frac{f}{1-\rho}\right)^{(\rho-1)/\rho}>0$ always holds, let us define the following function,

$$F_1(N^A)=\frac{\beta}{N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)}+\frac{1}{L-(N-N^A)h} \quad (54)$$

Then we have

$$n_e=\frac{1-\rho}{f}[F_1(N^A)]^{-1} \qquad (55)$$

If we take the first derivative of $F_1(N^A)$ with respect to N^A, we can get

$$\frac{dF_1(N^A)}{dN^A}=\frac{-\beta(r_0h+O^G-O^A)}{[N(I-r_0h-O^G)\ \ +N^A(r_0h+O^G-O^A)]^2}+\frac{-h}{[L-(N-N^A)h]^2} \quad (56)$$

As we already know that $r_0h+O^G-O^A<0$, the monotonicity of $F_1(N^A)$ is not explicit. If we set $\frac{dF_1(N^A)}{dN^A}=0$, we can solve the critical size of AVs users when monotonicity changes,

$$N^{A*}=\frac{(L-Nh)\sqrt{-\beta(r_0h+O^G-O^A)}-N\sqrt{h}(I-r_0h-O^G)}{(r_0h+O^G-O^A)\sqrt{h}-h\sqrt{-\beta(r_0h+O^G-O^A)}} \quad (57)$$

(3) Comparative Statistics

The last section provided us how consumers' overall utility changes with the level of AVs adoption. We found the monotonicity of $V(N^A)$ is dependent on the value of N^{A*}. In this section, we are going to make comparative statics analysis on N^{A*} to explore how the change in AV's ownership cost, population size, income level, total land size and rent parameter may have influence on overall utility.

a) The influence of AV's ownership cost O^A

In this model we assume the ownership cost of AV is much higher than GV at early stage because the effects of scale economy are small. When O^A is too high that more AVs adoption will reduce the overall utility because the effect of reducing income for retail market is too strong, even though the land rent also decreases. Only an acceptable O^A could make adoption beneficial. Then we will analyze the influence of O^A on N^{A*} by defining the follow function,

$$\sigma(O^A)=\frac{\sigma_1(O^A)}{\sigma_2(O^A)}=\frac{(L-Nh)\sqrt{-\beta(r_0h+O^G-O^A)}-N\sqrt{h}(I-r_0h-O^G)}{(r_0h+O^G-O^A)\sqrt{h}-h\sqrt{-\beta(r_0h+O^G-O^A)}} \quad (58)$$

When O^A is not that expensive so $\sigma(O^A)>0$ holds, which make adoption possible because the overall utility may increase as adoption happens. Let's take the derivative of $\sigma(O^A)$ with respect to O^A,

$$\frac{d\sigma(O^A)}{dO^A}=\frac{\left[\frac{1}{2}\beta(L-Nh)[-\beta(r_0h+O^G-O^A)]^{-\frac{1}{2}}\right]\sigma_2(O^A)}{[\sigma_2(O^A)]^2}-\frac{\sigma_1(O^A)\left[-\sqrt{h}-\frac{1}{2}h\beta[-\beta(r_0h+O^G-O^A)]^{-\frac{1}{2}}\right]}{[\sigma_2(O^A)]^2}$$

As $\sigma_2(O^A)<0$ and $\sigma(O^A)=\frac{\sigma_1(O^A)}{\sigma_2(O^A)}>0$, we have $\frac{d\sigma(O^A)}{dO^A}<0$. This means when the ownership is not too high, $\sigma(O^A)$ has a negative relationship with

O^A. When O^A decreases, the adoption level for maximal overall utility increases. AVs are more preferable in the process. According to economics of scale, O^A will gradually decrease during the adoption process. The reduced ownership cost will continuously increase the optimal adoption level that maximize overall utility.

b) The influence of population size N

Let's define N^{A*} as a function of population size N,

$$\varphi(N) = \frac{(L-Nh)\sqrt{-\beta(r_0h+O^G-O^A)}-N\sqrt{h}(I-r_0h-O^G)}{(r_0h+O^G-O^A)\sqrt{h}-h\sqrt{-\beta(r_0h+O^G-O^A)}} \tag{59}$$

Taking the derivative of $\varphi(N)$ with respect of N,

$$\frac{d\varphi(N)}{dN} = \frac{\left[-h\sqrt{-\beta(r_0h+O^G-O^A)}-\sqrt{h}(I-r_0h-O^G)\right]}{(r_0h+O^G-O^A)\sqrt{h}-h\sqrt{-\beta(r_0h+O^G-O^A)}}$$

It's easy to find that $\frac{d\varphi(N)}{dN}>0$ always holds, which means the value of N^{A*} will increase if the city's population increases. This implies that even though AVs adoption might not be preferred in small cities, it may be promoted in big cities with large population. This is because the effect of decreasing parking spaces effect is prominent with large population.

c) The influence of income level I

In this model, consumers derive their utilities through consumption of differentiated retail goods. Higher income level generally leads more utility. In order to analyze its effect to N^{A*}, we define the following function,

$$\zeta(I) = \frac{(L-Nh)\sqrt{-\beta(r_0h+O^G-O^A)}-N\sqrt{h}(I-r_0h-O^G)}{(r_0h+O^G-O^A)\sqrt{h}-h\sqrt{-\beta(r_0h+O^G-O^A)}} \tag{60}$$

Let's take the derivative of $\zeta(I)$ with respect of I,

$$\frac{d\zeta(I)}{dI} = \frac{-N\sqrt{h}}{(r_0h+O^G-O^A)\sqrt{h}-h\sqrt{-\beta(r_0h+O^G-O^A)}}$$

As $\frac{d\zeta(I)}{dI}>0$, the value of N^{A*} will increase if people have a higher income level. This shows that AVs adoption will be more likely to be preferred in a high income society. This is reasonable because when consumers have a higher income level, the difference in vehicles ownership cost is insignificant. And the effect of decreasing in land rent become more obvious.

d) The influence of total land size L

Land in city center is always limited. Larger available land size will lead to lower rent for retailers which make retailers possible to provide goods at a lower price level. Lower price might be beneficial to consumers. We want to know if larger land size will also benefit consumers. Defining the following function,

$$\tau(L) = \frac{(L-Nh)\sqrt{-\beta(r_0h+O^G-O^A)}-N\sqrt{h}(I-r_0h-O^G)}{(r_0h+O^G-O^A)\sqrt{h}-h\sqrt{-\beta(r_0h+O^G-O^A)}} \tag{61}$$

Taking the derivative of $\tau(L)$ with respect of L,

$$\frac{d\tau(L)}{dL} = \frac{\sqrt{-\beta(r_0h+O^G-O^A)}}{(r_0h+O^G-O^A)\sqrt{h}-h\sqrt{-\beta(r_0h+O^G-O^A)}}$$

It's obvious that $\frac{d\tau(L)}{dL}<0$, which means AVs adoption is not preferred in areas with larger land. In our model, AVs is beneficial for the reason that the decreased parking spaces lower the rent for commercial land. However, in the areas with enough land, rent cannot be reduced effectively through AVs adoption. Decreasing in consumption of retail goods again dominate during the process. In an extreme situation where a city has very large L, $\tau(L)$ becomes negative so AVs adoption will never be encouraged in that city.

e) The influence of rent parameter β

As we know from equation (38), β would have a lower value if the land owner is willing to provide a larger percentage of land to retailers. In general, land owner in highly commercialized regions would like to develop more proportion of land for retailers. Thus, the developed regions are supposed to have a lower value in β. We define the following function,

$$\lambda(\beta) = \frac{\lambda_1(\beta)}{\lambda_2(\beta)} = \frac{(L-Nh)\sqrt{-\beta(r_0h+O^G-O^A)}-N\sqrt{h}(I-r_0h-O^G)}{(r_0h+O^G-O^A)\sqrt{h}-h\sqrt{-\beta(r_0h+O^G-O^A)}} \tag{62}$$

Similar to the analysis for $\sigma(O^A)$, the AVs adoption is not preferred with a large β which makes $\lambda(\beta)\le 0$. Therefore, we only consider the case when $\lambda(\beta)>0$ holds. Let's take the derivative of $\lambda(\beta)$ with respect to β,

$$\frac{d\lambda(\beta)}{d\beta} = \frac{\left[-\frac{1}{2}(L-Nh)(r_0h+O^G-O^A)[-\beta(r_0h+O^G-O^A)]^{-\frac{1}{2}}\right]\lambda_2(\beta)}{[\lambda_2(\beta)]^2} - \frac{\lambda_1(\beta)\left[\frac{1}{2}h(r_0h+O^G-O^A)[-\beta(r_0h+O^G-O^A)]^{-\frac{1}{2}}\right]}{[\lambda_2(\beta)]^2}$$

As $\lambda_2(\beta)<0$ and $\lambda(\beta)=\frac{\lambda_1(\beta)}{\lambda_2(\beta)}>0$, we have $\frac{d\lambda(\beta)}{d\beta}<0$. This means when β is not too high, $\lambda(\beta)$ has a negative relationship with β. When β decreases, N^{A*} increases. This means AVs adoption is preferred in developed regions with lower value of β.

(4) Social Welfare

As free entry condition requires retailers to operate at zero profit, we define social welfare function to be the sum of overall utility and the profit of land owner. We've already known how overall utility is derived and had a deep analysis in the previous two sections. The land owner, if we ignore the costs, gets positive profits from the rent paid by both GVs users and retailers, which can be calculated by,

$$\Pi = r_0 L_p + r_e L_c = r_0 \cdot h(N - N^A) + r_e \cdot n_e l_e \quad (63)$$

Plugging (33) and (37) into (63) and simplify the equation,

$$\Pi = (N - N^A)(I - O^G) + N^A(I - O^A) \quad (64)$$

We could find that the value of land owner's profit equals total disposable income after paying vehicle ownership cost. This is reasonable as we assumed free entry condition. All the cash paid to retailers finally flows to the land owner. Then we could get the function of social welfare,

$$W = V + \Pi = \frac{\rho}{c}\left(\frac{f}{1-\rho}\right)^{\frac{(\rho-1)}{\rho}} \left[\frac{\beta}{N(I - r_0 h - O^G) + N^A(r_0 h + O^G - O^A)} + \frac{1}{L - (N - N^A)h}\right]^{-\frac{1}{\rho}} + N(I - O^G) - N^A(O^A - O^G) \quad (65)$$

The social optimal could be derived by solving the first-order condition of W. And the analyses would be similar to what we did for overall utility. However, the solution of $\frac{dW(N^A)}{dN^A} = 0$ depends on several parameters, $\rho, \beta, f, c, N, I, L, O^G, O^A, r_0$ interacting in a more complex way, so that the result of first-order condition turns out to be ambiguous. From an economic point of view, this ambiguity stems from the existence of relative impacts of overall utility and profit on social welfare. The impact of overall utility has been clarified in previous two sections. Furthermore, if we take the first derivative of land owner's profit, we have $\frac{d\Pi}{\mathrm{d}N^A} = -(O^A - O^G)$. Thus, the loss in profits might be mitigated if the difference in ownership cost decreases. Using the social welfare function, urban planner could find the optimal level of adoption which is best for society.

(5) Discussion

We found that if an individual could get more utility in a society of full adoption, that is $V^G(0) < V^A(N)$, it will be beneficial to realize AVs adoption. However, from individual perspective, a consumer would always have no incentive to adopt AVs because $V^G(N^A) > V^A(N^A)$ holds. This is because the utility was derived from consumption in retail market and AVs users have less disposable income due to the relatively higher vehicles ownership cost.

From the viewpoint of urban planners, the social optimal could be found through the welfare function. They could introduce some policies to move adoption to the optimal level which maximizes the social welfare. We also did some comparative statics analysis for overall utility to study the influence of AVs ownership cost, consumer's income level, population, total land size, and rent parameter on AVs adoption. The results provide us some interesting implications. First, we found that AVs adoption tends to be preferred at regions with high income level, large population, and limited land resource. The consumers preference towards AVs adoption is decided by two opposite effects. On the one hand, decreasing in parking demand will increase land supply, which may reduce the land rent. In our model, decreased land rent will further reduce goods price and increase goods variety. This effect will have a positive impact on consumers' overall utility. However, on the other hand, the higher cost for AVs will reduce the disposable income spent on retail market which may reduce goods variety. This has a negative effect on overall utility. As a result, overall utility is decided by the dominant effect. High income makes consumers insensitive to the ownership cost. And limited land or low development rate makes the effects of decreasing in price and increasing in variety become prominent.

5. CONCLUSIONS

This paper represents a theoretical model to describe consumers' utility with decrease in parking spaces in shopping areas. Optimal level of adoption could also be derived by maximizing the consumers social welfare. Policy makers can introduce appropriate policies based on the results. The model was built based on the behaviors of three sectors which were consumer, retailer, and land owner. In this section, we derived endogenous commercial land rent, retail goods price, and number of varieties. We analyzed consumers' choice behavior and social optimal condition of AVs adoption. We also did comparative statics analysis on some important values to find their influence on AVs adoption. Based on the results we summarized that AVs adoption is more preferred at regions with high income level, large population, and limited land resources. We found that lower AVs ownership cost is of great significance for adoption. Limitations of this study was also explained at the end of this section.

As for future work, we want to include AVs ownership cost and time constraint into the model to conquer the limitation of this study. On the one hand, the AVs price will decrease if the number of AVs users increases. This could be explained by the economics of scale. On the other hand, by increasing productivity and mobility, consumers could get more utility using AVs under their time constraint. Through these improvements, we expect to explain AVs adoption at individual level and find a critical threshold for sustainable AVs adoption.

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