Perimeter control, autonomous vehicle, and urban spatial structure

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In this study, we developed a land use model where hypercongestion occurs in the downtown area and interacts with land use by incorporating a bathtub model. We show the following effects of hypercongestion mitigation by perimeter control: perimeter control decreases commuting costs and results in a less dense urban spatial structure. Furthermore, we examined the effects of the introduction of autonomous vehicles. We find that the introduction of autonomous vehicles may increase the commuting cost due to a severe capacity drop by the temporal concentration of traffic demand and result in a denser urban spatial structure in the long run. This result contradicts that of the standard bottleneck model. When perimeter control is implemented, the introduction of autonomous vehicles decreases commuting cost and result in a less dense urban spatial structure. These results show that hypercongestion is a key that could change the urban spatial structure.

Key Words : *hypercongestion, perimeter control, autonomous vehicle, urban spatial structure*

1. Introduction

Peak-hour traffic congestion is a major problem in urban cities and alleviating traffic congestion could change spatial distribution of residents in the long-run. The bottleneck model (Vickrey [1]), Arnott et al. [2]), Arnott et al. [3])) is an effective tool for describing peak-hour traffic congestion and examining the resultant temporal distribution of traffic demand by commuters' choice of departure time. However, the bottleneck model misses a crucial property of urban congestion dynamics, namely hypercongestion where flow decreases with density. Recent research has shown that downtown areas experience network-wide hypercongestion (Daganzo [4]), Geroliminis and Daganzo [5])) and that the traffic demand concentration during peak period leads to the capacity drop of networks (Small and Chu [6]), Geroliminis and Levinson [7]), Arnott [8]), Fosgerau and Small [9]), Fosgerau [10]), Amirgholy and Gao [11]), Arnott and Buli [12]), Jin [13]), Bao et al. [14]), Chen et al. [15])). That is, the throughput decreases if traffic demand exceeds the capacity, which does not occur in the standard bottleneck model.

A number of studies have proposed traffic demand management (TDM) strategies, such as congestion pricing (e.g., Geroliminis and Levinson [7])) and perimeter control (e.g., Haddad and Geroliminis [16]), Tsekeris and Geroliminis [17])) to decentralize traffic demand during peak period to alleviate hypercongestion. However, most of them focused on problems under the assumption that commuters do not relocate (i.e., fixed origin-destination patterns). That is, they ignored changes in the spatial distribution of commuters in response to the commuting behavior changes and instead focused on the short-run effects. A suitable model is yet to be developed to examine long-run effectiveness of TDM strategies for alleviating hypercongestion.

Models of urban spatial structure can describe the interactions between commuting and residential locations (Alonso [18])). Traditional models that employ static congestion models (e.g., Kanemoto [19]), Wheaton [20]), Anas et al. [21])) have been successfully extended to models that incorporate the dynamic bottleneck congestion (e.g., Arnott [22]), Gubins and Verhoef [23]), Takayama and Kuwahara [24]), Fosgerau et al. [25]), Fosgerau and Kim [26]), Takayama [27])). They demonstrated the significance of the temporal distribution of traffic demand and dynamic congestion phenomena in a long-run equilibrium; however, they cannot incorporate hypercongestion, where the capacity could change over time unlike the bottleneck congestion, as discussed above.

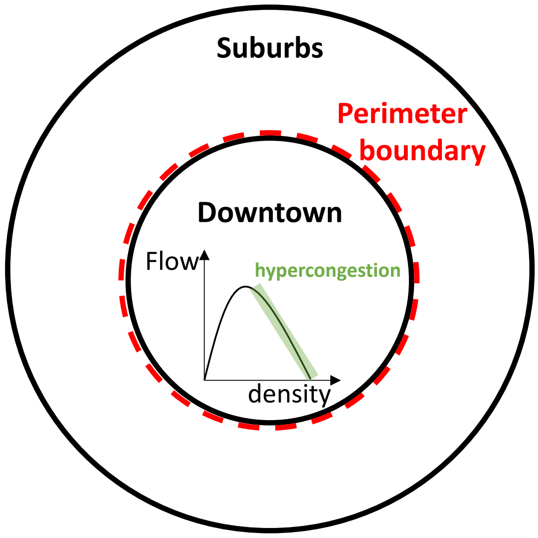
These studies focused on the problems related to 'normal vehicles' humans drive; however, the introduction of autonomous vehicles also influences the temporal distribution of traffic demand. According to van den Berg and Verhoef[28]), the network capacity is anticipated to increase by driving closer to each other than normal vehicles, whereas people care less about travel time because they do not need to drive anymore. It is crucial to develop a model that systematically analyzes those impacts on the temporal and spatial distributions of traffic demand to properly investigate the long-run effects of TDM strategies in a new era of autonomous vehicles. This is because the traffic demand patterns with autonomous vehicles in the presence of hypercongestion become more complex.

In this study, we developed an urban spatial model where hypercongestion occurs in the downtown area and interacts with land use. Then, we examined the long-run effects of hypercongestion mitigation by perimeter control and the introduction of autonomous vehicles. To this end, we combined the departure time choice model in the presence of hypercongestion, namely the bathtub model with the residential location choice model. Furthermore, we consider a situation where every vehicle is an autonomous vehicle. Our findings demonstrate that (I) the introduction of autonomous vehicles may result in a lesser or a denser urban spatial structure at user equilibrium in the presence of hypercongestion, (II) hypercongestion mitigation by perimeter control results in a less dense urban spatial structure, and (III) the introduction of autonomous vehicles always results in a less dense urban spatial structure when perimeter control is implemented. These results show that hypercongestion is a key factor that could change the urban spatial structure.

2. Model

(1) Model setting

As shown in Fig.1, consider a monocentric city that has downtown and suburban areas. The areas of downtown and suburban zones are A_d and A_s, respectively. The downtown area is where all job opportunities are found. We assume that the land is owned by absentee landlords, as it is common in literature. The downtown area has homogeneous topological characteristics by proper partitioning approaches, and thus shows the well-defined relationship between space-mean flow and density. The congestion dynamics in the downtown area are described as a bathtub model, whereas we assume that one can travel at the free-flow speed in the suburban area.



図–1 Model Structure

(2) Commuters preferences

There are N continuum of homogeneous commuters who have identical preferences and desired arrival times. The downtown area is where all commuters work. They choose their trip timing and residential location (i.e., downtown or suburban areas) as short-run and long-run decisions, respectively. The N_d who reside in the downtown area are assumed to commute by walk or bicycle, and thus incur constant commuting cost C_d, whereas the N_s $(= N - N_d)$ who live in the suburban area commute by their car and incur the commuting cost $C_s(t)$ when they arrive at work at time t based on their scheduling preferences represented by

$$C_s(t) = \begin{cases} \alpha\left(T(t) + T_s\right) + \beta\left(t^* - t\right) & \text{if} \quad t \leq t^* \\ \alpha\left(T(t) + T_s\right) + \gamma\left(t - t^*\right) & \text{if} \quad t > t^* \end{cases} \quad (1)$$

where $T(t)$ represents the travel time in the downtown area at time t, T_s represents the free-flow travel time in the suburban area, and t^* represents the desired arrival time. That is, we assume that commuters have "α-β-γ" type preference. The first and second terms of the RHS are the travel time cost and schedule delay cost, respectively.

Let $i \in \{d, s\}$ where d and s represent the downtown and suburban areas, respectively. The utility of commuters who live in area i and arrive at work at time t is given by the following Cobb-Douglas utility function.

$$u(z_i(t), a_i(t)) = \{z_i(t)\}^{1-\mu}\{a_i(t)\}^{\mu} \tag{2}$$

where $\mu \in (0, 1)$, $z_i(t)$ represents consumption of the numéraire good, and $a_i(t)$ represents the lot size of housing they consume. The budget constraint is given by

$$w = z_i(t) + (r_i + r_A)a_i(t) + C_i(t) \tag{3}$$

where w represents their income, $r_A > 0$ represents the exogenous agricultural rent and $r_i + r_A$ represents land rent at area i. The first-order conditions of the utility maximization problem give

$$z_i(t) = (1-\mu)\, I_i(t) \tag{4a}$$

$$a_i(t) = \frac{\mu I_i(t)}{r_i + r_A} \tag{4b}$$

$$I_i(t) = w - c_i(t) \tag{4c}$$

where $I_i(t)$ represents the income net of commuting cost earned by a commuter who lives at area i and arrives at work at time t. Substituting this into the utility function, we obtain the indirect utility function

$$v(I_i(t), r_i + r_A) = (1-\mu)^{1-\mu}\mu^{\mu} I_i(t)(r_i + r_A)^{-\mu}. \tag{5}$$

(3) Bathtub congestion in downtown area

To incorporate the bathtub model of the downtown area, we employ the Greenshields model for the space-mean speed as follows.

$$v(t) = v_f\left(1 - \frac{n(t)}{n_j}\right) \tag{6}$$

where $v(t)$ is the space-mean speed at time t, v_f is the free-flow space-mean speed, $n(t)$ is the car accumulation in the downtown area at time t and n_j is jam accumulation.

Since the downtown area is modeled as a system with inflow and outflow and whose traffic conditions are governed by bathtub congestion dynamics, the time evolution of car accumulation, $\dot{n}(t)$, is given by

$$\dot{n}(t) = I(t) - G(t) \tag{7}$$

where $I(t)$ is the inflow and $G(t)$ is the outflow at time t. The outflow is formulated by the network exit function (NEF) as

$$G(t) = \frac{n(t)v(t)}{L} \tag{8}$$

where L is the average trip length in the downtown area.

We assume that the travel time in the downtown area is determined by a single instant of time for the tractability (Small and Chu [6]), Geroliminis and Levinson [7]) and given by

$$T(t) \approx \frac{L}{v(t)} \tag{9}$$

Note that all suburban commuters have identical trip length L in the downtown area.

(4) Autonomous vehicle

We also consider a situation where every vehicle is an autonomous vehicle. Autonomous vehicles are expected to have two effects: commuters care less about the travel time (VOT effect hereafter) and autonomous vehicles travel closer to each other than normal vehicles (network capacity effect hereafter) (van den Berg and Verhoef [28])). In this study, the former effect is represented by the reduction in VOT. It is $\eta\alpha$ where η is the VOT effect parameter ($\frac{\beta}{\alpha} < \eta \leq 1$). The latter effect is captured by the increase in the network capacity, which is ξn_j where ξ is the network capacity effect parameter ($\xi \geq 1$). This effect increases not only the network capacity but also the critical accumulation, which is consistent with the simulation analysis by Lu et al. [29]).

3. Equilibrium

(1) Equilibrium conditions

At short-run equilibrium, no commuter who lives in the suburban area can reduce their travel cost by changing their departure time. The equilibrium conditions are

$$\begin{cases} C_s(t) = c_s^* & \text{if} \quad n(t) > 0 \\ C_s(t) \geq c_s^* & \text{if} \quad n(t) = 0 \end{cases} \quad \forall t \in \mathbb{R} \tag{10a}$$

$$\int_{t\in\mathbb{R}} \frac{n(t)v(t)}{L} = N_s \tag{10b}$$

where c_s^* is the short-run equilibrium cost of commuters who live in the suburban area. Condition (10a) states that if the commuting cost at time t is greater than the equilibrium cost, no one will arrive at their destination at time t. Condition (10b) is the conservation law for traffic demand in the suburban area.

Each commuter chooses residential area i to maximize indirect utility (5) in the long run. The equilibrium conditions are

$$\begin{cases} v(I_i, r_i + r_A) = v^* & \text{if} \quad N_i > 0 \\ v(I_i, r_i + r_A) \geq v^* & \text{if} \quad N_i = 0 \end{cases} \quad \forall i \in \{d, s\} \tag{11a}$$

$$\begin{cases} a_i(I_i, r_i + r_A)N_i = A_i & \text{if} \quad r_i > 0 \\ a_i(I_i, r_i + r_A)N_i \leq A_i & \text{if} \quad r_i = 0 \end{cases} \quad \forall i \in \{d, s\} \tag{11b}$$

$$N_d + N_s = N \tag{11c}$$

where v^* is the long-run equilibrium utility level and $a_i(I_i, r_i + r_A)$ denotes the lot size of commuters who live in area i, which is given by

$$a_i(I_i, r_i + r_A) = \frac{\mu I_i}{r_i + r_A} \tag{12}$$

Condition (11a) is the equilibrium condition for the residential location choices. This condition states that no commuter has the incentive to change residential locations unilaterally. Condition (11b) is the land market clearing condition, which requires that if total land demand for housing in area i, $a_i(I_i, r_i + r_A)N_i$, equals the residential area in area i, land rent $r_i + r_A$ is (weakly) larger than agricultural rent r_A. Condition (11c) shows the population constraint.

(2) Equilibrium properties

As derived in Small and Chu [6], the short-run equilibrium cost c_s^* of commuters who live in the suburban area satisfies

$$N_s = \alpha n_j \left(\frac{1}{\beta} + \frac{1}{\gamma}\right)\left(\ln\theta + \frac{1}{\theta} - 1\right) \tag{13}$$

where $\theta \equiv \frac{c_s^* v_f}{\alpha L}$. All variables except the equilibrium cost c_s^* are exogenous since the number of suburban commuters N_s is given exogenously at short-run equilibrium. From Eq. (13), it can be shown that the network capacity effect (i.e., the increase in n_j) always decreases the equilibrium cost when autonomous vehicles are introduced. This is because the network can process more vehicles, and then more commuters arrive at their destinations near the desired arrival time. On the other hand, *the VOT effect (i.e., the reduction in α) may increase or decrease the equilibrium cost since the reduction of the VOT simply decreases the travel time cost, whereas more traffic demand concentration near the desired arrival time results in a more severe capacity drop.* Thus, there are positive and negative impacts of the VOT effect.

At the long-run equilibrium, from conditions (11) and Eq. (12), the number of commuters who live in the suburban area is given by

$$N_s = N\left\{1 + \left(\frac{I_d}{I_s}\right)^{\frac{1-\mu}{\mu}} \frac{A_d}{A_s}\right\}^{-1} \tag{14}$$

In the long-run, the impacts of short-run equilibrium appear only in the income net of the commuting costs in the suburban area (i.e., $I_s = w - c_s^*$). The lower the commuting cost in the suburban area, the higher the number of commuters who live in the suburban area, as shown in Eq. (14). Thus, the following proposition can be presented.

Proposition 1 The introduction of autonomous vehicles may decrease or increase the short-run equilibrium cost and may result in a less or denser urban spatial structure in the long-run.

In the standard bottleneck model, the introduction of autonomous vehicles decreases the short-run equilibrium cost because the VOT effect only decreases the travel time cost van den Berg and Verhoef [28] and result in a less dense urban spatial structure in the long run. However, the urban spatial structure may be less or denser at long-run equilibrium in the presence of hypercongestion since the short-run equilibrium cost may decrease or increase depending on the magnitude of the network capacity and VOT effects of autonomous vehicles as discussed above.

In our numerical example illustrated in Fig. 2 (a), a high decrease in VOT leads to a high short-run equilibrium cost, resulting in a denser urban spatial structure, whereas a high increase in the network capacity leads to a low short-run equilibrium cost, resulting in a less dense urban spatial structure. This can be explained by the time evolution of the NEF, as shown in Fig. 2 (b). When the VOT effect is large ($\eta = 0.7$ and $\xi = 1.02$), commuters are less likely to avoid hypercongestion,[1] but the capacity effect is insufficient, leading to a longer rush hour, and then higher equilibrium cost. However, when the capacity effect is large ($\eta = 0.9$ and $\xi = 1.08$), the hypercongestion externality is relaxed due to the capacity effect, which leads to a shorter rush hour, and then lower equilibrium cost.

4. Perimeter control

(1) Perimeter control and queuing dynamics at perimeter boundaries

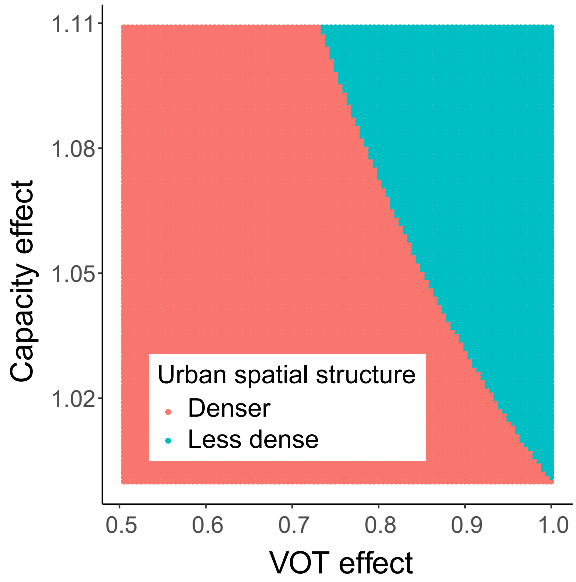
During perimeter control, the inflow rate to the downtown area is restricted at perimeter boundaries (see Fig. 1) to protect the area from hypercongestion. Since the critical accumulation is derived as $n_j/2$ from Eq.(6), the control scheme at time t can be written as

$$I(t) = \begin{cases} I_p & \text{if} \quad n(t) = \dfrac{n_j}{2} \\ A(t) & \text{if} \quad n(t) < \dfrac{n_j}{2} \end{cases} \tag{15}$$

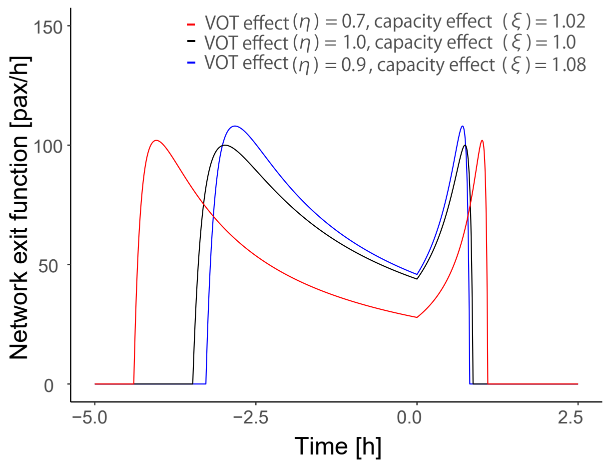
where I_p is the inflow rate during perimeter control and $A(t)$ is the arrival rate at the perimeter boundary at time t. There is no restriction if car accumulation is below the critical level; all vehicles at the boundary can enter the downtown area. The inflow rate is restricted to I_p once the car accumulation reaches the critical accumulation. To maintain the critical accumulation, the inflow rate during perimeter control is set to the value of the NEF at the critical accumulation and thus determined from Eqs. (6) - (8) by $I_p = n_j v_f / 4L$.

A queue will develop outward from the perimeter boundary if the car arrival rate at the perimeter boundary exceeds the inflow rate during perimeter control (i.e., $A(t) > I_p$). We model the queuing dynamics by the point queue and assume the first-arrived-first-in property. Thus, the waiting time of a commuter who arrives at their destination at time t,

[1] After the maximum NEF is reached, hypercongestion occurs until the maximum NEF is reached again



(a) Sensitivity with respect to the parameters ξ (capacity effect) and η (VOT effect)



(b) Time evolution of NEF with different VOT and capacity effects

図–2 Numerical example with parameters ($v_f = 20$ [mph], $n_j = 100$ [veh], $\alpha, \beta, \gamma = 20, 10, 40$ [\$/h], $T_s = 0$ [h], $L = 5$ [mile], $N_s = 300$ [pax], $t^* = 0$)

$T_b(t)$, is

$$T_b(t) = \frac{q(t)}{I_p} \tag{16}$$

where $q(t)$ is the number of cars queued at the perimeter boundary when a commuter who arrives at their destination at time t reaches the boundary.

(2) Commuting cost under perimeter control

Given the dynamics during perimeter control, the commuting cost incurred by a commuter who lives in the suburban area and arrives at their destination at time t is

$$C_s(t) = \begin{cases} \alpha\left(T(t)+T_s\right)+\beta\left(t^*-t\right) & \text{if} \quad t<t_s^p \\ \alpha\left(\frac{L}{v_f/2}+T_b\left(t\right)+T_s\right)+\beta\left(t^*-t\right) & \text{if} \quad t_s^p \leq t < t^* \\ \alpha\left(\frac{L}{v_f/2}+T_b\left(t\right)+T_s\right)+\gamma\left(t-t^*\right) & \text{if} \quad t^* \leq t < t_e^p \\ \alpha\left(T(t)+T_s\right)+\gamma\left(t-t^*\right) & \text{if} \quad t_e^p \leq t \end{cases} \tag{17}$$

where t_s^p and t_e^p are the start and end times of the perimeter control implementation, respectively. The commuting cost is the same as Eq. (1) before and after perimeter control is implemented. During perimeter control, the travel time in the downtown area is given by $2L/v_f$. In addition to the travel time cost, the cost of waiting at the perimeter boundary is incurred, as given by Eq. (16).

5. Equilibrium under perimeter control

(1) Equilibrium conditions

When perimeter control is implemented, the short-run equilibrium conditions are

$$\begin{cases} C_s(t)=c_s^* & \text{if} \quad n(t)>0 \\ C_s(t)\geq c_s^* & \text{if} \quad n(t)=0 \end{cases} \quad \forall t\in\mathbb{R} \tag{18a}$$

$$\begin{cases} n(t)=\frac{n_j}{2} & \text{if} \quad q(t)>0 \\ n(t)\leq \frac{n_j}{2} & \text{if} \quad q(t)=0 \end{cases} \quad \forall t\in\mathbb{R} \tag{18b}$$

$$\int_{t\in\mathbb{R}} \frac{n(t)v(t)}{L} = N_s \tag{18c}$$

In addition to the equilibrium conditions without perimeter control, we have equilibrium condition (18b), which reflects the restriction of inflow to the downtown area during perimeter control; if there is a queue at the perimeter boundary, car accumulation is at the critical accumulation. Otherwise, car accumulation is lower than the critical level.

The long-run equilibrium conditions are the same as conditions (11).

(2) Equilibrium properties

When perimeter control is implemented, similar to Dantsuji et al. [30] model, the short-run equilibrium cost c_s^* of commuters who live in the suburban area satisfies

$$N_s = \alpha n_j \left(\frac{1}{\beta}+\frac{1}{\gamma}\right)\left(\frac{\theta^p}{4}+\ln 2 - 1\right) \tag{19}$$

where $\theta^p \equiv \frac{c_s^* v_f}{\alpha L}$. Note that all variables except the equilibrium cost c_s^* are exogenous. If the number of commuters who live in the suburban area is sufficiently large ($N_s > \frac{n_j}{2}$), the equilibrium cost with perimeter control obtained from Eq. (19) is lower than that without perimeter control from Eq. (13). This is because the capacity drop of the network never occurs under perimeter control, and thus more commuters can arrive their destinations near the desired arrival time than at user equilibrium where the capacity drop occurs. Therefore, *even though queuing congestion at the perimeter boundary exists, the short-run equilibrium cost decreases.*

As the number of commuters who live in the suburban area at the long-run equilibrium is the same as Eq. (14), we have the following proposition.

Proposition 2 Hypercongestion mitigation by perimeter control decreases the short-run equilibrium cost and results in a less dense urban spatial structure in the long-run.

When autonomous vehicles are introduced, as shown in Eq. (19), *both the network capacity and VOT effects decrease the equilibrium cost under perimeter control,* i.e.,

$$\frac{\partial c_s^*}{\partial \eta} > 0 \quad \text{and} \quad \frac{\partial c_s^*}{\partial \xi} < 0. \tag{20}$$

Then, we have the following proposition.

Proposition 3 The introduction of autonomous vehicles under perimeter control decreases the short-run equilibrium cost and then results in a less dense urban spatial structure in the long-run.

This situation can be regarded as a case where there is a bottleneck with the fixed capacity (i.e., the value of NEF at critical accumulation) between the downtown and suburban areas. Thus, Proposition 1 and 3 show the long-run impacts of autonomous vehicles in the bathtub model and the standard bottleneck model, respectively. This fact indicates that the long-run impacts of autonomous vehicles in the presence of hypercongestion contradict those of the standard bottleneck model.

6. Conclusion

This study is the first in the literature to incorporate hypercongestion into an urban spatial structure where commuters can relocate. The findings demonstrated that hypercongestion is a crucial factor that can alter the urban spatial structure. Particularly, the long-run impacts of autonomous vehicles at user equilibrium by the developed model (Proposition 1) contradict those of the standard bottleneck model that the introduction of autonomous vehicles results in a less dense urban spatial structure.

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流入制御，自動運転自動車，都市空間構造

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本研究では，土地利用モデル (Alonso [18]) とバスタブモデル (Small and Chu [6]) を統合することで，都心における “超混雑現象” と “土地利用” の相互作用を考慮した理論モデルを構築した．そして，超混雑を緩和する方策として都心部への流入制御を取り上げ，その影響を調べた．その結果，流入制御は短期的には通勤費用を低下させ，長期的には都市を低密度化させることが明らかにされた．本稿では，次に，全ての自動車が自動運転となる影響を調べた．より具体的には，通勤者の所要時間価値の低下・道路容量の増加の影響を分析した．その結果，自動運転自動車の導入は，交通需要の時間的集中に伴う超混雑の悪化 (ピーク時の機能低下) をもたらす可能性があることが示された．これは，短期的には通勤費用の増加・長期的には都市の高密度化を生じさせる可能性があることを意味している．なお，この結果は，標準的なボトルネックモデルからは得られないものである．最後に，全ての自動車が自動運転である状況下で，流入制御の導入効果を検証した．その結果，流入制御の導入は，全ての自動車が手動運転の場合と比べても，通勤費用を低下させるため，都市の低密度化をもたらすことが明らかとなった．以上の結果は，超混雑現象が都市空間構造や交通施策の効果に重要な影響を与えることを示している．