How to Realize a Compact City: Street Activeness and Agent-based Urban Modeling

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Abstract: The purpose of this research is to verify the effectiveness of the combination of the introduction of tramway with introducing a public facility for urban residents and promoting street activeness around it, on urban sprawl. An agent-based model (ABM) for simulating the changes of urban structure through autonomous behavior of urban residents was designed, and the simulation experiments were conducted based on the assumption of combining these policies. As a result, this research clarified the following points and how they were. First, the synergistic effects of the introduction of tramway, the proper location of a public facility for urban residents, and the promotion of street activeness around it, are effective in maintaining a poly-centric compact urban structure. Second, the introduction of tramway targeting the urban sprawl can exert a profound effect only when combined with the above-mentioned policies, although it takes a long period. Third, a mono-centric compact urban structure is realized along with the above, while improving the living environment and revitalizing the urban central area.

1 INTRODUCTION

1.1 Urban Sprawl Issues and Shift into Compact City

The world population has rapidly increased during our current century along with the previous century, and rapid urbanization has continued at various places around the globe (UN, 2012). Under such circumstances, urban sprawl has attracted much attention, in the past few decades, and coming under fire as an unsustainable form of urbanization. Urban sprawl is commonly defined by the following land-use characteristics (Schneider and Woodcock, 2008) (Johnson, 2001):

- Expansion of urban area in outer fringe area
- Low-density development
- Scattered development (multi-direction)
- Leapfrog development (discontinuity)
- Commercial strip development

Urban sprawl is also often criticized because of its following negative impacts (Johnson, 2001) (Deal and Schunk, 2004):

- Increase in traffic congestion and commuting time, air pollution, and energy consumption
- Increase in infrastructure cost
- Hollowing out in urban central area, economic disparity, and loss of community
- Loss of agricultural and natural land

Researchers and experts have studied a shift into ”compact city”, as a countermeasure against such urban sprawl. Compact city is commonly defined by the following characteristics (Tsai, 2005) (Behan et al., 2008):

- High-density
- Concentration of development
- Development in public transportation network
- Mono-centric or poly-centric city center

It has been proved that compact city can overcome some of the negative impacts driven by urban sprawl and many studies have also indicated that it can enhance quality of life by offering a broad range of choices about lifestyle and behavior (Behan et al., 2008). Considering the urban dynamics including sprawl as complex phenomena of mutual interactions of a wide variety of autonomous entities, such as individuals, households, and firms (Batty, 2007) (Ligtenberg et al., 2001), however, highlights the difficulty in direct control of the urban dynamics.

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1.2 Purpose of this Research

With these in mind, this research designed an agent-based model (ABM) to simulate urban structure changes through the induction of autonomous behavior of urban residents rather than the compulsion, and this research verified the following points:

• Is the combination of a introduction of tramway with introducing a public facility for urban residents and promoting street activeness around it effective in controlling urban sprawl?

• Is the combination of these policies also effective in improving existent urban sprawl?

2 RELATED WORKS AND POSITION OF THIS RESEARCH

2.1 Agent-based LUTI Model

Urban sprawl is a special kind of land-use change, urban spatial expansion along a city boundary. And land-use changes come from its complex driving forces and their interactions (Ligtenberg et al., 2001). Above all, the fundamental principle that land-use impacts transport and vice versa has been acknowledged by many researchers and supported by empirical findings (Acheampong and Silva, 2015). These research efforts have culminated in the development of operational urban land-use/transport interaction (LUTI) models.

And recently, researchers have supported the modeling approach of an agent-based model (ABM) to express the real-world complicated system including a city as a macro-level state that is generated by micro-level collective interactions and adaptive behavior of multiple autonomous agents (Batty, 2007) (Railsback and Grimm, 2011).

A series of agent-based LUTI models, which is an integration of the above two concept, have contributed to express complicated macro-level land-use patterns of cities sprawl as self-organization through micro-level adaptive behavior of agents, such as households and firms. And such models have served to explore urban growth scenarios.

2.2 Revitalization of Urban Central Area

Jacobs (1969) has emphasized the attractiveness of a city as a lively and bustling place which has served as a market for exchange from the time before the establishment of the concept of nation or trading by currency (Jacobs, 1969). And researchers and experts have reevaluated the importance of informal public spaces for activities of local residents in the way of an antithesis to urban development on an inhuman scale as well as another way to regain people in urban central areas. The two factors are vital to forming such public space. First, such public space needs to serve as a hub for people in their daily lives so that they can visit there casually while they are out. As for such urban hubs, public complexes based mainly on a library have recently attracted much attention. The representative one is the series of Idea Store in London, U.K. Several pioneering libraries built and put into operation recently in Japan are also relevant to these cases [1]. These public complexes, while offering the library service as the core function, provide a wide variety of other services, such as cafe and support of learning and civic activities. They also try to enhance convenience by various policies such as an extension of opening time. By doing so, they play an important role to serve as a hub for local culture. Second, such public space needs to generate ”street activeness” set in an open space, such as a street or a plaza, around the public space. Street activeness indicates a lively situation where individuals gather and stroll around downtown while enjoying exchanges, such as encountering various people, contacting various shopping goods, and experiencing other services (Nagai and Kurahashi, 2017). It has been long argued that such interactions propel economic activity, and recent researches have also indicated that such interactions can enhance economic productivity through creative knowledge spillover (Landry, 2012). Furthermore, the following positive feedback has been demonstrated empirically: the number of people that visited a certain place including their sojourn time they spent there can derive attract further activeness (Kakoi et al., 2010).

2.3 Position of this Research

By integrating the above-mentioned conceptual framework, Nagai (2017) built the agent-based model (ABM) to consider qualitative benefit obtained by visiting informal public space along with the daily travel of urban residents. And they clarified that the synergistic effects of policies of locating of the public space and promoting street activeness in such a place, are effective to maintain a compact urban structure (Nagai and Kurahashi, 2017). On the other hand, an introduction of tramway is well known as one of the measures to improve urban environment. Tramway has

[1]e.g., Gifu Media Cosmos in Gifu, Japan (2015), Art Museum & Library, Ota in Gunma, Japan (2017).

been introduced especially in many European cities (De Bruijn and Veeneman, 2009), and in recent years momentum for introduction of tramway has also been raised in Japan. Additionally, especially in Japan, a large part of the land is mountainous, thus the area suitable for urbanization is relatively small. And the population is also declining (MLIT, 2016). For these reasons, improvement of many cities that have already sprawled is considered to be more important. With these in mind, this research develops the conceptual framework introduced by Nagai (2017) (Nagai and Kurahashi, 2017) to verify whether the introduction of tramway is effective in maintaining compact urban structure, and whether it is also effective in improving sprawled urban structure.

3 SIMULATION MODEL

The overview of the experimental model was described below according to the ODD (Overview, Design concepts, and Details) protocol.

3.1 Purpose

By simulation experiments by the ABM that abstracted a city and behavior of the residents in the city, this research verified the effects of controlling the urban structure, which was planned according to the zoning, based on the combination of the introduction of tramway with introducing a public facility for urban residents and promoting street activeness around it. Additionally, this research verified the effects of improving the urban structure, which has already sprawled, based on the combination.

3.2 Entities and Scales

Entities are a planar urban schematic and household agents who act in the urban schematic. Both are spatially-explicitly expressed. Fig. 1 shows the urban schematic. This is the abstraction of a part of typical regional cities in Japan, where a central business district (CBD) and bedroom towns connected by railway. They were planned according to the zoning with separation between residences and job locations. Therefore, they are also regarded as the poly-centric compact city, which is composed of multiple hubs linked with traffic networks and sharing their own role (Tsai, 2005). In the urban schematic, two domains are located: a residence district and a central business district (CBD). The residence district is the aggregation of residences, which are the starting point and the final destination of each household agent's daily travel which corresponds to commuting. CBD is the aggregation of job locations, which are also a halfway point of the travel. Two railway stations are located at each center. Additionally, a highway is located 500 meters north of the railway. Furthermore, three tramway routes are radially installed around the central station as a hub (see next section for details). To simplify the simulation, this schematic is assumed to have uniform and high-density sidewalks and roads overall and household agents can freely travel on this space on foot, by bicycle or private automobile.

In the residence district, residences of the same number as household agents: 1,000 are located randomly based on normal distribution centering on the residence station. Similarly, job locations of the same number are also located in CBD. Additionally, one public facility such as a complex mentioned in the previous section: a public facility for stopping off (PFS), is located in the central area of CBD.

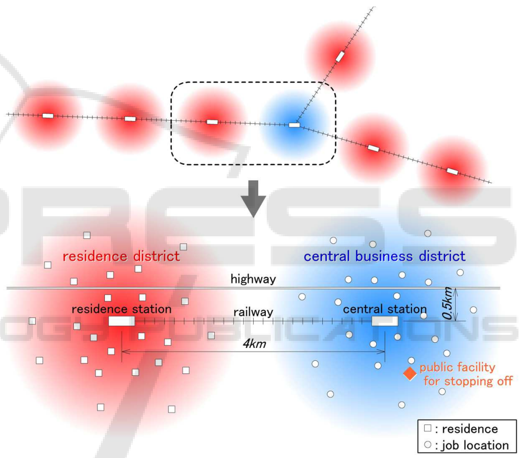

Figure 1: Urban Schematic.

3.3 State Variables of Household Agent

State variables of household agent are as follows:

- Position of the residence
- Position of the job location
- Type of linked trip selected currently
- Value list of linked trips

A linked trip indicates the series of travels of each household agent from the starting point to the destination.

3.4 Process Overview and Scheduling

Each household agent repeats daily travel based on the value list of linked trips, and fixes travel mode in one way through the learning period. After that, a part of all household agents randomly chosen relocate their residences. In this research, after the loop process of residential relocation is repeated 20 times, the simulation stops processing. [2]

3.5 Sub-model of Daily Travel

Each household agent repeats daily travel according to the selected linked trip. The representative travel mode is either of the following: on foot, by bicycle, train, private automobile, or tramway. The initial representative travel mode of all household agents is train according to the original urban planning philosophy. Each household agent leaves the residence for the job location. And after all household agents arrive at each job location, they leave for PFS. After arriving and staying there, finally they return to the residence. When returning, the total travel cost C is calculated according to the equation below.

$$C = w_t C_t + w_c C_c + w_f C_f - w_P P$$

C_t, C_c, C_f, and P indicate time cost, charge cost, fatigue cost, and activeness value. w_t, w_c, w_f, and w_P indicate each preference bias. The preference biases of all agents are assumed to be equal. According to this cost, the household agent updates the value V_i of the selected i-th linked trip, according to the equation below.

$$V_i \longleftarrow \alpha(-C) + (1-\alpha)V_i$$

The following travel is done according to the linked trip selected by the ε-greedy method based on this value. And each household agent fixes their travel mode in one way through the learning period of 30 times' daily travel. This setting is based on the findings that individuals choose travel modes and routes rather boundedly rationally and habitually (Ramming, 2001).

3.5.1 Activeness Value

Within 500 meters radius around PFS, a promotion of street activeness is considered. Here, it is assumed that street activeness can be generated when household agents traveling on foot or by bicycle within this range interact face-to-face. During this time, relevant household agents acquire benefit brought about by the street activeness as activeness value P according to the equation below.

$$P = \eta_{ac} D_{ac}$$

$D_{ac}(agent)$ indicates the number of other household agents traveling on foot or by bicycle within 100 meters radius centering on the relevant household agent. η_{ac} indicates coefficient of activeness. The total travel cost is reduced by the amount obtained by multiplying the activeness value P with preference bias w_P. The coefficient of activeness can be regarded as a level of effort to bring further street activeness within the relevant range according to the agglomeration of pedestrians. This coefficient is enhanced by projects such as arranging comfortable sidewalks and cycling roads, arranging attractive retail stores, or holding attractive events. Improvement in this coefficient enhances the benefit for travel on foot or by bicycle and increases a balanced total travel cost. Therefore, this coefficient can be regarded as a coefficient of gain.

3.6 Sub-model of Residential Relocation

After all household agents fix their travel mode in one way, 1/10 of all household agents randomly chosen relocate their residence. To the relevant household agents, 10 of candidate residences are presented randomly. Each household agents relocate to the candidate residence of which total living cost is the minimum. Travel cost (time) and rent are particularly significant constraints for those that households face on relocation (Acheampong and Silva, 2015) (Taniguchi and Takahashi, 2011). Based on these findings, the total living cost of these candidates is set as sum of total travel cost and land rent. The total travel cost is calculated by conducting virtual daily travel from a candidate residence based on the fixed travel mode fixed through learning. The land rent for the candidate residence increases corresponding to the agglomeration of neighboring residences and job locations. In other words, the local interactions between households, and between a household and an environment, also impact the change in land-use pattern through the change in land rent.

3.7 Initialization and Input Data

Setting values of parameters of the urban schematic and household agent were set carefully based on the various materials such as statistical data published by public authorities e.g., the ministry of land, infrastructure and transport (MLIT, 2016), and previous studies, while assuming a regional city in Japan.

[2]This model assumes that a single loop process of residential relocation represent two years in the real-world. Therefore, 20 loop processes correspond to simulating 40 years of urban dynamics in the real-world.

3.8 Indicators to Estimate Experimental Result

By observing the result of each experimental scenario according to the indicators shown below.
• Percentage of each representative travel mode
• Total CO_2 emission (expressed as percentage relative to the basic scenario)
• Average travel time
• Distribution map of residences

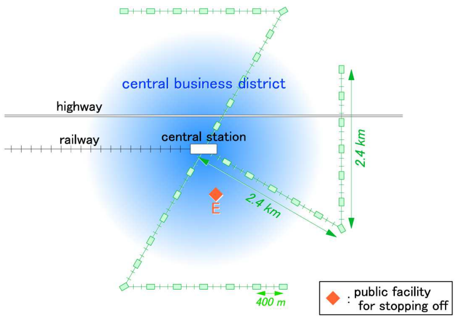

Figure 2: Schematic of tramway routes.

4 EXPERIMENT 1 - INTRODUCTION OF TRAMWAY

4.1 Conditions of Experiment 1

The simulation here assumes that the tramway routes imitate the "Karlsruhe Model" (De Bruijn and Veeneman, 2009), where the routes are shared with ordinary railway. Therefore, three routes are radially installed centering on the central station as shown on Fig. 2, and the routes pass through CBD. Each route has tramway stops at 400 meters intervals. Along with this, residents can also choose the additional two types of linked trips. The first is by train and tramway in combination, and the other is by tramway. The experiments were conducted under the conditions of the following two types for the location of a public facility for stopping off (PFS).
• A : none (no promotion of street activeness)
• E : urban central area, 0.5km south and 0.5km east from the central station

And the four types, 0, 10, 20, and 30, for coefficient of activeness. Hereinafter, each of these experiments is expressed e.g., scenario At, Et0 - 30, by combining the symbols of A and E indicating the location of PFS, the initial letter t for the word of tram, and the coefficient of activeness. Additionally, this section reproduces scenario A, where tramway and PFS were not introduced, and a promotion of street activeness was also not implemented, to compare with the new scenarios and validate the simulation model.

4.2 Results of Experiment 1

Table 1 shows the quantitative result of scenario A, At, and Et0 - 30. Fig. 3 shows the final distributions of residences of the same scenarios.

The result of scenario At, when compared with scenario A, shows that private automobile users decreased by close to 30 points, while train (and tramway in combination) users increased accordingly. Along with this, the sprawl on the periphery of CBD was improved, and the total CO_2 emission also reduced considerably.

The results of scenario Et0 - 30 show that, in scenario Et0, the percentages of each travel mode and the sprawl level were almost the same as scenario At. As advancing the promotion of street activeness, however, private automobile users got decreasing gradually. When the scenario reached Et30, private automobile users decreased to less than 10%, and train (and tramway in combination) users increased to more than 75%. Along with this, the cluster of residences of train users around the residence station was maintained quite clearly. Additionally, tramway users increased to more than 15%. And the total CO_2 emission also reduced to less than 30%.

Table 1: result of Experiment 1.

scenario	percentage of representative travel modes						CO_2 emission	travel time (min)
	walk	bicycle	train	auto-mobile	train + tram	tram		
A	1.3%	2.4%	7.3%	89.0%	0.0%	0.0%	100.0%	9.3
At	1.4%	2.6%	15.0%	49.7%	27.9%	3.5%	66.6%	20.6
Et0	1.1%	2.3%	14.4%	53.7%	25.3%	3.2%	91.1%	33.5
Et10	1.2%	1.5%	11.3%	21.6%	57.1%	7.4%	48.1%	39.4
Et20	1.2%	1.3%	9.5%	10.4%	65.7%	11.9%	32.9%	44.7
Et30	1.0%	1.1%	7.9%	7.1%	67.6%	15.3%	28.6%	47.6

5 EXPERIMENT 2 - SETTING URBAN SPRAWL AS INITIAL STATE

5.1 Conditions of Experiment 2

This section sets the final state of scenario A as the experimental initial state. Most of the residences were distributed on the periphery of CBD as sprawl, and private automobile users reached close to 90%. This shows the state after 20 loop processes of residential relocation (corresponding to 40 years) from the zoning between residences and job locations. The edge

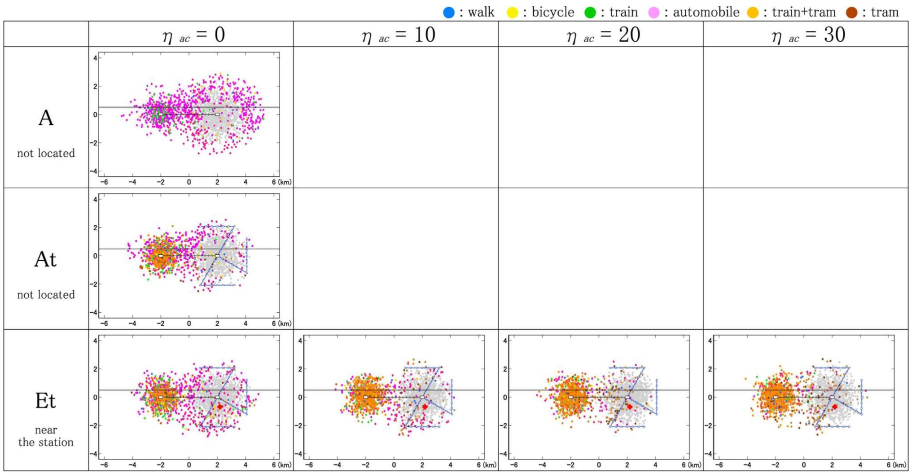

Figure 3: Residences' final distribution of Experiment 1.

routes of tramway also pass through the suburb area with sprawled residences.

The experiments were conducted under the conditions of the two types for the location of PFS and the four types for coefficient of activeness, like the previous section. Hereinafter, each of these experiments is expressed e.g., scenario SAt, SEt0 - 30, by combining the initial letter S for the word of sprawl, the symbols of A and E indicating the location of PFS, the initial letter t for the word of tram, and the coefficient of activeness. Additionally, scenario SEt30+, which was run for twice as long as SEt30, was executed.

5.2 Results of Experiment 2

Table 2 shows the quantitative result of scenario SAt, SEt0 - 30, and SEt30+. Fig. 4 shows the final distributions of residences of the same scenarios.

The result of scenario SAt shows that private automobile users increased further, and the sprawl of their residences on the periphery of CBD also advanced further, unlike scenario At.

The results of scenario SE0 - 30 also show that both the decrease in the private automobile users and the cluster of residences of train users around the residence station were not observed, unlike the series of Et. Particularly in scenario SEt0 - 20, private automobile users increased further, and the sprawl also advanced further, like scenario SAt. In advancing the promotion of street activeness, however, private automobile users decreased, and tramway (and train in combination) users increased and reached close to 50% in total in scenario SEt30.

Furthermore, the results of scenario SEt30+, where scenario SEt30 was run further, shows that tramway (and train in combination) users reached close to 90% in total. Along with this, the total CO_2 emission also reduced considerably, and the following two clusters of residences were emerged. One is the cluster by residents commuting by train and tramway in combination (about 20%), on centering the residence station. The other is the cluster by residents commuting by tramway alone (about 70%), along tramway routes from the center to the periphery of CBD.

Table 2: Result of Experiment 2.

scenario	percentage of representative travel modes: walk	bicycle	train	auto-mobile	train + tram	tram	CO_2 emission	travel time (min)
SAt	0.8%	1.3%	1.5%	93.4%	1.3%	1.7%	89.3%	7.5
SEt0	0.7%	0.9%	1.7%	94.1%	1.5%	1.2%	95.4%	20.9
SEt10	0.6%	0.6%	1.7%	94.5%	1.4%	1.2%	97.1%	21.1
SEt20	0.8%	0.7%	1.4%	91.8%	1.9%	3.3%	94.8%	21.3
SEt30	2.3%	0.9%	4.1%	44.9%	12.3%	35.6%	54.2%	37.4
SEt30+	0.8%	0.9%	1.4%	10.0%	19.4%	67.5%	20.6%	43.7

6 DISCUSSION

6.1 Estimation of Experimental Results

By combining the introduction of tramway with introducing a public facility for stopping off (PFS) and promoting street activeness around it, private automobile users decreased, when compared with the cases when no policies were implemented. And train (and tramway in combination) users increased accordingly. Along with this, the total CO_2 emission reduced, and the compact urban structure, which was formed according to the zoning, was maintained. These suggest that the synergistic effects of the above-mentioned policies could impact positively on a both static and dynamic urban environment. This also seems to be because the promotion of street activeness, which is

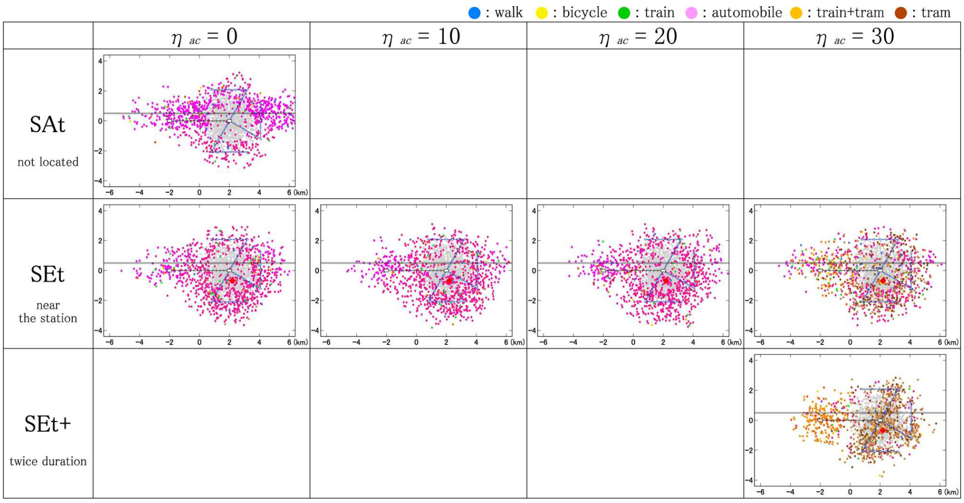

Figure 4: Residences' final distribution of Experiment 2.

incentive to stroll about downtown, was effective to increase tramway users.

On the other hand, where the initial state was sprawl mainly with use of private automobiles, the introduction of tramway could not serve to control further sprawl and use of private automobiles. When combined with the introduction of the public facility and the promotion of street activeness, however, most of private automobile users switched to tramway use, although it took a long period. This suggests that once residents established the lifestyle of low-density residence in suburb and commuting by private automobile, that becomes robust, irreversible, and very difficult to be upset. As for the residence distribution in the same scenario, most of the residences that are distributed along the tramway routes deviated from the initial poly-centric compact city. This, however, can gain the following positive evaluations of a mono-centric compact city. First, the residents can live where residences and job locations are nearby based mainly on use of public transportations, resulting in being free from traffic congestion and air pollution. Second, mixed land-use provides the residents with a broad range of social activities, while revitalizing the central urban area.

Simply put, the promotion of street activeness is a policy to lead people to walk by giving them incentives. On the other hand, many successful cases of introducing tramway in the real world are characterized with combining the introduction of tramway with other policies which serve as a benefit for people traveling on foot. That is, this experiment clarified that the introduction of tramway can exert a profound effect only when combined with policies, which lead tramway users' stroll before and after they use a tramway, and how it can offer great benefits.

6.2 Validation of the Simulation Model

Because of the property of emergence in complex self-organizing systems, ABMs should be validated in terms of whether it can capture the basic features of the system in the real-world (Wu, 2002). Pattern-Oriented Modeling (POM) procedure is an effective validation procedure. In POM procedure, after identifying the observed patterns in the real-world characterizing the system to be modeled, an ABM is evaluated by whether the observed patterns are reproduced (Railsback and Grimm, 2011).

First, the history of urban area in Japan for 40 years based on 1970 and the history of residential area in scenario A for the first experiment are very similar, so this scenario can be regarded as reproducing the fact of the constant expansion of urban area in many cities in Japan (Eaton and Eckstein, 1997). Additionally in this scenario, the residence distribution significantly changed from separation between residences and job locations to sprawl on the periphery of CBD. This can be regarded as the reproduction of the growth process of a concentric low-density suburb based on the mono-centric urban model proposed by Alonso (1964) (Alonso, 1964), and subsequently supported by many related researches. Next, the travel mode used by most of the household agents has switched from train to private automobiles. This can be also regarded as the reproduction of the fact that the main travel mode in commuting has switched from train to private automobiles (MLIT, 2016).

Our highly abstracted urban dynamics model based on a small number of elements and simple rules reproduced the above multiple social phenomena which were not directly incorporated into the model. These reproductions demonstrate that the simulation model can explain the real society to a certain level, and the experimental results of this research are valid.

7 CONCLUSION

The purpose of this research was to verify the effectiveness of the combination of the introduction of tramway with introducing a public facility for urban residents and promoting street activeness around it, on urban sprawl. An agent-based model (ABM) for simulating the changes of urban structure through autonomous behavior of urban residents was designed. Then the simulations were conducted based on the assumption of zoning between residences and job locations as the initial state and combining these policies. These were followed by other simulations based on the assumption of setting urban sprawl as the initial state. As a result, this research clarified the following points and how they were. First, the synergistic effects of the introduction of tramway, the proper location of a public facility, and the promotion of street activeness around it, are effective in maintaining a poly-centric compact city in accordance with the initial plan. Second, the introduction of tramway targeting the urban sprawl can exert a profound effect only when combined with the above-mentioned policies, which lead tramway users' stroll before and after riding the tramway, although it takes a long period. Third, a mono-centric compact city is realized along with the above-mentioned point, while improving the living environment for the residents and revitalizing the urban central area.

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