Empirical Study on Optimum Commuting Allocation toward Reducing the Length of Journey-to-Work Trip: The case of Sapporo city

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Abstract: Many cities recently have initiated efforts in the formation and development of sustainable cities through transport policies as a means to realize a low carbon city. But changes in the urban structure and transport as a result of the urban growth are not sufficiently analyzed and established including its evaluation methods as a result of such changes. The study aims to evaluate the changes in urban structure and transportation in a target city-wide two million people in Japan, in an era of depopulation in the country. Thus, an empirical analysis was performed to clarify the changes in the urban structure and journey-to-work travel characteristics. Also, in order to realize the formation of a low carbon sustainable city, an optimum commuting allocation solution was formulated by estimating reduction in the form of commuter trip length. As a result, by evaluating the changes of urban structures and transportation, estimation of the journey-to-work trip length reduction was analyzed.

Key Words: Journey-to-work Trip Lengths, Urban Structure, Optimum Commuting Allocation Solution

1. INTRODUCTION

In many East Asian cities, urban sprawl and the decline of urban centers continue to develop. In metropolitan areas of Bangkok, Manila and other major cities, urban redevelopment plans are being implemented through the introduction of public transport systems. Creating a sustainable and low-carbon society through the urban development has been a general trend. However, to evaluate the impact of the urban structure and transport changes as a result of the urban growth are not sufficiently established.

In this study, targeting Sapporo as a local city with a population of two million in Japan (a country where the population has recently been on a downward trend), this study was conducted with two objectives. The first was to empirically analyze the transition of the changes in urban structures and transportation following urban growth. We focused on Journey-to-work trip for showing the situation of urban structures and transportation which is
based on the Person-Trip (PT) surveys conducted in 1972, 1983, 1994 and 2006. The second was to develop a tool for analyzing the possibility of changes in the characteristic of journey-to-work travel within a certain area (e.g., the extent to which journey-to-work distances can be shortened) by formulating an optimum commuting allocation solution.

Journey-to-work travel consists of vehicles originating in residential areas and ending in workplace areas. Accordingly, journey-to-work trip lengths are influenced by the scale of residential and workplace areas and by urban structure (e.g., the geographical relationship between two areas). Also, journey-to-work trip lengths vary greatly depending on where commuters choose to live and work. In this study, when formulating an optimum commuting allocation solution, focus was placed on trying to bring about changes in journey-to-work travel characteristics rather than the more difficult changes in urban structure, thereby reducing journey-to-work trip lengths. In other words, by setting generated traffic and that arriving at the workplace and in residential areas as fixed variables the possibility of reducing journey-to-work trip length was examined through simulation of different origin-destination (OD) trip patterns.

2. LITERATURE REVIEW

Literature review was undertaken from two viewpoints. First, studies that empirically analyzed the relationship between the development of public traffic systems and changes in urban structure/journey-to-work travel characteristics were also reviewed. Second, studies concerning optimum commuting allocation solutions were reviewed.

For the former, Nakagawa et al. (1993), focusing on the effects of railway development on cities and towns, conducted analysis on changes in the population growth rate before and after the opening of a train station, and showed that railway development influenced the subsequent population growth rate. Additionally, Suzuki (2009) conducted a microstudy on populations involving detailed analysis of residential density in areas around train stations, and showed that most of the dense residential areas studied were situated within a 3-km radius of a train station. Furthermore, extremely high levels of density were confirmed in areas within 1 km of a station, indicating the significant effect of railway development on the distribution structure of urban residential areas.

Other investigations have dealt with population changes as an index of urban transformation or changes in the distribution structure of residential areas, as exemplified by these studies. However, few studies have focused on changes in the distribution structure of workplace areas – an important element of cities along with residential areas.

In the field of studies concerning optimum commuting allocation solutions, Suzuki (1994) and Maruyama (2003) achieved results showing a reduction in the length of journey-to-work trip through efforts to bring about changes in journey-to-work travel characteristics. However, these studies, both based on the optimum commuting allocation solution, did not sufficiently analyze actual journey-to-work travel characteristics or the distribution of workplace and residential areas in each zone (i.e., urban structure). Also, Morimoto (2002) concluded the effective policies to reduce journey-to-work trip length, and suggesting development creating residence area nearby workplace area like a Compact City.

Accordingly, by formulating optimum commuting allocation solutions using cumulative
frequency distribution curves to represent the actual characteristics of journey-to-work travel, we calculated the possible reduction of journey-to-work distances that could be achieved by altering commuting allocation. Additionally, the relationship between possible reduction length of journey-to-work trip and the actual details of urban structure was examined.

The data used were OD traffic figures from four PT surveys conducted in the Sapporo urban area in 1972, 1983, 1994 and 2006. As another characteristic of this study, changes between 1972 and 2006 in the population and the distribution structure of residential and workplace areas were compared using cumulative ratio distribution curves.

3. PERSON TRIP SURVEY DATA AND POPULATION CHANGES

This section deals with the person-trip (PT) survey data used and changes in the population of Sapporo City. PT surveys are regularly conducted by prefectures to monitor the movement of people – the main influences behind traffic – by surveying the status of traffic within certain areas.

Sapporo City’s OD traffic related to commuting and all purposes was analyzed in this study using data from PT surveys conducted in 1972, 1983, 1994 and 2006 in seven cities and three towns located in the central urban area of Hokkaido with Sapporo City at its center (Sapporo City, Kitahiroshima City, the former Ishikari City, Chitose City, Eniwa City, Otaru City, Ebetsu City, Namporo Town, Naganuma Town and Tobetsu Town). Table 1 shows the years in which the four PT surveys were conducted, the numbers of target zones, the nighttime population figures and the total numbers of trips made for commuting purposes.

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</thead>
<tbody>
<tr>
<td>No. of zones</td>
<td>53</td>
<td>70</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Nighttime population</td>
<td>1,010,123</td>
<td>1,176,236</td>
<td>1,733,860</td>
<td>1,880,863</td>
</tr>
<tr>
<td>No. of journey-to-work trips</td>
<td>355,218</td>
<td>498,438</td>
<td>606,021</td>
<td>643,778</td>
</tr>
</tbody>
</table>

To enable time-series comparisons in this study, the OD tables were retabulated to adjust the number of target zones to match the zoning situation of 1972 (53 zones). Figure 1 shows the zoning of Sapporo City.
This is followed by examining changes in the population of Sapporo City between the surveys. Figures 2 and 3 show population changes in the zones between 1983 (the year the Toho Subway Line was opened) and 1994 and between 1994 (the year the Tozai Subway Line was extended) and 2006, respectively.
Figure 2 shows that between 1983 and 1994, populations in suburban areas along the newly opened Toho Line grew significantly, and those in areas centering on Zone 1 (the central workplace area) decreased by between 1,000 and 5,000 people. This may be because in the urban center (where businesses are concentrated), residential areas – meaning the population – decreased in relative terms due to limitations of the zone area and the living environment despite a well-developed public transport infrastructure.

On the other hand, a marked decrease of over 20,000 people was observed in the Jozankei area (Zone 53). Since the population of Sapporo City continued to grow, it appears that people moved toward inner parts of the city, where life is more convenient and there are more employment opportunities, rather than moving out of the city.

Figure 3 shows phenomenon between 1994 and 2006, contrary to the trend observed between 1983 and 1994, people moved toward the city center. This suggests that during the 23 years between 1983 and 2006, people initially dispersed toward the outer suburbs, resulting in a reduction of residential areas in the central region, and that later, many high-rise condominiums were constructed in the urban center, thereby promoting a shift to a high-density, compact residential style.
Table 2 shows the trip share of each year. Comparing with Subway and Automobile share from 1972 to 2006, in Sapporo city, subway extensions contributed to attracting people to urban area, and at the same time suppressing the demand for automobile.

### 4. FORMURATION OF THE OPTIMUM COMMUTING ALLOCATION SOLUTION

Commuting allocation patterns based on the optimum commuting allocation solution can be obtained from a solution that minimizes objective function (4) (the total journey-to-work distance) under constraint conditions (1), (2) and (3).

\[
\begin{align*}
\sum_{j=1}^{n} x_{ij} &= F_i \quad (i = 1, \ldots, n) \\
\sum_{j=1}^{n} x_{ij} &= G_i \quad (i = 1, \ldots, n) \\
d_{ij} &\geq 0 \\
\sum_{i=1}^{n} \sum_{j=1}^{n} d_{ij} \cdot x_{ij} &\rightarrow \text{min}
\end{align*}
\]

Where,
- \(x_{ij}\): OD traffic from Zone i to Zone j
- \(F_i\): Traffic generated in Zone i (a residential area)
- \(G_i\): Traffic attracted to Zone i (a workplace area)
- \(d_{ij}\): Distance between zones i and j

By solving this problem, the commuting allocation pattern that gives the minimum total journey-to-work distance can be obtained from among the many patterns possible under the traffic generated and arriving in a given zone. Additionally, to show the flow range of journey-to-work travel in a city, the value that maximizes objective function (4) was determined.
Table 3 Results of applying the optimum commuting allocation solution

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</thead>
<tbody>
<tr>
<td>Total no. of trips</td>
<td>335,218</td>
<td>498,438</td>
<td>606,021</td>
<td>643,778</td>
</tr>
<tr>
<td>Average trip length (km/person)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>2.836</td>
<td>2.944</td>
<td>3.066</td>
<td>2.909</td>
</tr>
<tr>
<td>Actual</td>
<td>4.850</td>
<td>5.622</td>
<td>5.966</td>
<td>5.921</td>
</tr>
<tr>
<td>Max</td>
<td>8.850</td>
<td>10.538</td>
<td>11.609</td>
<td>11.565</td>
</tr>
<tr>
<td>Flow range</td>
<td>6.014</td>
<td>7.594</td>
<td>8.544</td>
<td>8.656</td>
</tr>
<tr>
<td>Possible reduction in distance</td>
<td>2.014</td>
<td>2.679</td>
<td>2.900</td>
<td>3.012</td>
</tr>
</tbody>
</table>

Table 3 shows that in Sapporo City, the length of journey-to-work trip increased as the total number of trips rose. Considering the suburbanization observed in Figure 2, it can be thought that the progress of motorization between 1983 and 1994 expanded people’s sphere of living, prompting many of them to move toward outer parts of the city (where land prices are low) and commute to the city center. On the other hand, between 1994 and 2006, due at least in part to the increased population in the city center where businesses are concentrated, average trip lengths decreased slightly.

The possible reduction of journey-to-work trip length per person was taken as the difference between the actual and minimum journey-to-work trip lengths. The results obtained were 2.0 km for 1972, 2.7 km for 1983, 2.9 km for 1994 and 3.0 km for 2006. The possible reduction in distance for 2006 increased from the previous survey year despite a fall in the average trip length. This was due to a decrease in the value obtained by the optimization of the commuting allocation pattern (minimization of the length of journey-to-work trip).

Next, a cumulative frequency distribution curve (Blunden and Black, 1984) was used to compare and analyze commuter OD traffic (traffic flow) and distance (traffic friction) based on the OD traffic patterns obtained from actual commuter OD traffic and the application of the optimum commuting allocation solution. Figure 4 shows a schematic diagram of this.

![Cumulative Ratio Distribution Curve](image)

**Figure 4 Schematic diagram of the cumulative ratio distribution curve**

The horizontal axis in Figure 4 shows each OD traffic distance, and the vertical axis shows the cumulative ratio of the OD traffic amount achievable within a certain distance from
among all the target OD traffic figures. Using this curve, the spatial distribution of commuter traffic flow in an actual city can be determined. The actual length of journey-to-work for each city can also be calculated based on this curve.

Figure 5 shows the cumulative frequency distribution curve created based on actual commuter OD traffic and the cumulative frequency distribution curve created based on OD traffic patterns to which the optimum commuting allocation solution was applied.
Table 4 Numerical indices (actual values)

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</tr>
</thead>
<tbody>
<tr>
<td>Average trip length (km)</td>
<td>4.850</td>
<td>5.622</td>
<td>5.966</td>
<td>5.921</td>
</tr>
<tr>
<td>5km cumulative ratio</td>
<td>0.5992</td>
<td>0.5148</td>
<td>0.4890</td>
<td>0.5038</td>
</tr>
<tr>
<td>10km cumulative ratio</td>
<td>0.9095</td>
<td>0.8660</td>
<td>0.8330</td>
<td>0.8358</td>
</tr>
<tr>
<td>50% OD distance (km)</td>
<td>4.08</td>
<td>4.84</td>
<td>5.26</td>
<td>4.93</td>
</tr>
<tr>
<td>80% OD distance (km)</td>
<td>7.29</td>
<td>8.45</td>
<td>9.19</td>
<td>9.07</td>
</tr>
</tbody>
</table>

Table 4 shows the details. In the upper graph (actual values), the cumulative ratio of generated traffic (0.8) corresponds to the OD distances of 7.3 km for 1972, 8.5 km for 1983, 9.2 km for 1994 and 9.1 km for 2006, showing the same trend as that seen in Table 4, where the length of journey-to-work trip in Sapporo City increased between 1972 and 1994 and decreased slightly in 2006.

Further, over 80% of trips were completed within 10 km in all four of the survey years. The OD traffic patterns for 1983, 1994 and 2006 are also similar, whereas that for 1972 shows a distinct pattern. This may be because a significant change in the distribution structure of workplaces in Sapporo City between 1972 and 1983 (outlined later) influenced the characteristics of journey-to-work travel.

5. INDICATORS USED AND THE RESULTS OF ANALYSIS

(1) Urban consolidation index
The urban consolidation index can be formulated as Equation 5 using the minimum value $T_{\text{min}}$ and maximum value $T_{\text{max}}$ of the total length of journey-to-work trip calculated based on the optimum commuting allocation solution for an urban structure:

$$\text{Urban consolidation index} = \frac{T_{\text{min}}}{T_{\text{max}}}$$ (5)

This is an index that describes the distribution structure of workplaces in a city. Its value is 0 when workplaces are dispersed equally in all zones, and approaches 1 as workplaces become increasingly concentrated in one zone.

(2) Excess rate and traffic flow rate
The excess rate is calculated by dividing the difference between the actual and minimum total lengths of journey-to-work trip by the actual length. The value of this index is 0 when the actual length is equal to the minimum length, and approaches 1 as the total length exceeds the minimum. Using this rate, the difference between the actual and minimum (optimum) lengths of journey-to-work trip (i.e., the unnecessary journey-to-work distance) can be ascertained.

On the other hand, the traffic flow rate is calculated based on the actual value and the minimum and maximum values of the total length of journey-to-work trip. The value of this index is 0 when the actual length is equal to the minimum value, and is 1 when it is equal to the maximum value. Accordingly, the closer the traffic flow rate comes to 0, the more traffic characteristics reduce the actual length of journey-to-work trip toward the minimum;
conversely, the closer it comes to 1, the more these characteristics increase the journey-to-work trip length toward the maximum. In other words, the traffic flow rate indicates where the actual journey-to-work trip length in a city is between the minimum and maximum levels. With this knowledge, it is possible to ascertain how actual journey-to-work distances are influenced by factors such as urban structure changes and the development of traffic facilities.

The excess rate and traffic flow rate can be formulated as equations (6) and (7) using the actual journey-to-work trip length $T_{act}$ and the minimum value $T_{min}$ and maximum value $T_{max}$ of the length calculated based on the optimum commuting allocation problem:

$$\text{Excess rate} = \frac{T_{act} - T_{min}}{T_{act}}$$

$$\text{Traffic flow rate} = \frac{T_{act} - T_{min}}{T_{max} - T_{min}}$$

Table 5 shows index values obtained using equations (5), (6) and (7).

<table>
<thead>
<tr>
<th>Year</th>
<th>Total no. of trips</th>
<th>Average trip length (km / person)</th>
<th>Urban consolidation index</th>
<th>Excess rate</th>
<th>Traffic flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase / decrease in total no. of trips</td>
<td>163,220</td>
<td>107,583</td>
<td>37,757</td>
<td>Increase / decrease in average trip length</td>
<td>0.772</td>
</tr>
</tbody>
</table>

The urban consolidation index continued to decrease from 0.3204 in 1972 to 0.2515 in 2006. Accordingly, it is indicating that workplaces in Sapporo City dispersed from the central area to all zones. This change was especially noticeable between 1972 and 1983, indicating a great change in the distribution structure of workplaces during the period.

The large fluctuation in the maximum values of the optimized journey-to-work trip length (as seen in the cumulative frequency distribution curves in Fig. 5) may be due to the range of commuter traffic flow expanding in response to the dispersal of workplaces, thereby increasing the complexity of the commuting allocation pattern. On the other hand, it was suggested that the minimum values were constant, arguably due to fluctuation limits in initial conditions such as area and urban structure.

The excess rate, which is the theoretically possible reduction in workplace journey-to-work trip length, gradually increased from 42% in 1972 to 51% in 2006. However, the traffic flow rate, in which the maximum lengths of journey-to-work trip are considered, was between 33%
and 35% (i.e., close to the minimum values) in the four survey years. The realistically possible reduction in trip lengths as a result of traffic measures and other efforts would therefore be less than those indicated by the excess rate.

Additionally, considering the increase in the total number of trips in response to the higher population of Sapporo City, the rate of increase in the average trip length as part of the higher total number of trips gradually fell during the study period. Furthermore, in 2006, despite an increase in the total number of trips, the average length of journey-to-work trip took a downward turn. Accordingly, it is suggested that Sapporo City’s urban structure is now increasingly taking on a polycentric form along subway line.

6. CONCLUSIONS

Based on an optimum commuting allocation solution, calculations and time-series comparisons of possible reduction of journey-to-work trip lengths were made in this study. The steps taken can be summarized as follows:

- Targeting the Sapporo urban area, time-series changes in journey-to-work trip lengths were determined using cumulative frequency distribution curves, which were used for comparing data from four PT surveys conducted in 1972, 1983, 1994 and 2006.
- An optimum commuting allocation solution was formulated to develop a tool for analyzing the possibility of changes in journey-to-work travel characteristics within certain areas.
- The possible reductions in the length of journey-to-work trip were 2.0 km for 1972, 2.7 km for 1983, 2.9 km for 1994 and 3.0 km for 2006.
- The cumulative frequency distribution curves and the urban consolidation indexes showed that the journey-to-work travel pattern in 1972 was different from those in the other three survey years.
- Traffic flow rates in the four survey years were between 33% and 35%, which were close to the minimum values; realistic reductions in the length of journey-to-work trip as a result of traffic measures and other efforts would be lower than the levels indicated by the excess rate (42% – 51%).

Suggestions for future reduction of green-house gas emission from automobile will be that it is highly important not only to reduce Journey-to-work trip length but also promoting the shift from automobile trip into subway trip by land-use control. Simultaneously, the countermeasures to encourage ZEV/EV usage should be considered in the outside of the subway areas where had been commuting by vehicles mainly and widely spread as the result of urban sprawl.

As a future issue, the resolution of problems identified by the excess rate and the traffic flow rate will require the development of optimum commuting allocation solutions into a more realistic model and further analysis similar to that conducted in the present study.

REFERENCES


