Optimal Commuting Assignment Problem with Travel Preference Functions: A Study of the Location of Residences and Employment and Trip Lengths in Cities of Hokkaido, Japan

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Abstract: Sustainable cities are those where journey-to-work trip lengths (and hence their ecological footprints) are stabilizing or decreasing. The control of residential and employment locations are two appropriate policy instruments. As the journey-to-work trip length depends both on urban structure and travel behavior, a mathematical model based on the optimal commuting assignment problem is proposed to test different policy scenarios. This model is based on behavioral zonal travel preference functions. The preference functions are transformed into quadratic functions using data for the journey to work in the major four cities of Hokkaido, Japan. The optimization model is applied to estimate mean trip lengths from different hypothetical zonal distributions of residences and employment.

Key words: Optimal Commuting Assignment Problem, Journey-to-work Travel, Re-location of Residences and Employment

1. INTRODUCTION

Sprawling, low-density, cities, as typified in Australia, New Zealand and North America, are unsustainable when private transportation is the dominant mode of commuting (Newman and Kenworthy, 1999). A key planning policy response is to achieve more compact cities with a better spatial distribution of homes and workplace (Alpkokin, et al., 2008). Post-war metropolitan planning in many cities of the developed world, and increasingly in cities of
Asia (Alpkokin, et al, 2007), has aimed at poly-centric employment growth with its implicit assumption of containing commuting trip lengths.

The fundamental importance of the length of commuting trips as a measure of sustainability is widely recognized in the literature. However, the journey-to-work trip length depends not only on urban structure but on the travel behavioral response of commuters given the employment opportunity surface that is presented to commuters in the metropolitan region, and this is the focus of this theoretical paper. During the past three decades our research has addressed various components of this issue, and we are now confident that we have constructed a general model for any distribution of homes and work-places, or for any city where authentic data are available, that can estimate mean trip lengths for various metrics such as minimum, maximum, actual, and random. With hypothetical changes to urban form and travel behavior (or for any proposed plan) our model can estimate the dynamical response of these metrics over time. This mathematical model is based on the optimal commuting assignment problem. Its practical utility is demonstrated with reference to data from four cities in Hokkaido, Japan, where we calibrate the travel behavioral functions and conduct sensitivity analyses on different patterns of residential and employment location with the aim to quantify the savings in travel (and implicitly environmental load) in the urban area with a more compact city development. The realism of varying the locations of employment and residences (as represented by the different scenarios) for established cities, as outcomes of planning policy are discussed in the conclusions.

2. LITERATURE

The model builds on a substantial body of previous research, especially on the theory of optimization. We recognize the contribution of Hitchcock (1941) in formulating the classical transportation problem of operations research. However, it was Blunden (1966) who drew attention to transport researchers about the more general literature of linear programming that had previously been classified during the Second World War (As Chief Scientific Advisor to the Australian Military Board, the late Professor Ross Blunden gained access to this classified strategic information, and later lectured on the topic in 1956 at the University of California, Berkeley). The solution to the primal minimization and maximization problem is explained in Blunden and Black (1984). It is especially pertinent, in the context of this paper, to refer to the point that the results obtained from dual solution in the linear programming formulation point to how best to re-arrange homes and workplaces to achieve the greatest travel savings in the system (Black and Blunden, 1977).

It is standard transport modeling practice to embed in a GIS framework (such as TRANSCAD) to use a trip distribution model to estimate the origin-destination flows between all zones and to calculate the associated mean trip length (Easa, 1993). A substantial contribution on these spatial interaction models was made by Sir Alan Wilson who showed that a fully-constrained gravity model based on maximizing entropy gave the most probable distribution of trip flows given the land-use constraints and the observed mean trip length (Wilson, 1970).

However, there are alternative models of trip distribution (Clark and Peters, 1965; Stopher and Meyburg, 1975). One of them is based on an analogy of the Stouffer hypothesis applied to migration (Stouffer, 1940), and re-packaged at the intervening opportunities model first applied in the 1956 Chicago Area Transportation Study (for a review of these developments, see, Cheung and Black, 2008). A conceptual variation of this model that introduced zonal
preference functions by inverting the “l-factor” in the intervening opportunity model of trip distribution (Ruiter, 1969) was first sketched out graphically by Black and Conroy (1977). However, it was much later before a full descriptive model of zonal journey-to-work travel behavior in an urban system was developed (Masuya and Black, 1992; Black, et al, 1993) where research also involved fitting mathematical functions to the shape of the preference functions, including the quadratic function. The latter model has particular advantages because its zonal parameters have been investigated to classify typical patterns of zone-specific travel behavior and trip lengths (Masuya, et al, 2006).

3. FORMULATION OF OPTIMAL COMMUTING ASSIGNMENT PROBLEM

We have formulated a mathematical model to minimize the total amount of travel in distance in the city considering the preference function of journey-to-work travel by applying the optimal commuting assignment problem. The model is formulated as a non-linear mathematical problem that includes the quadratic models of the travel preference functions. The minimization problem is subject to the land-use constraints being satisfied that the number of work trips generated by each residential zone equals the number of resident workers living there, and that the number of work trips attracted to each employment zone equals the number of jobs located there. An additional constraint is that inter-zonal trip flows are non-negative.

The raw zonal preference functions are derived from data for the zonal number of resident workers, the zonal number of job opportunities, the origin-destination pattern of traffic (OD traffic pattern), and the inter-zonal distances. Quadratic functions are then fitted to these zonal preference functions. The variation of job opportunities by re-locating employment makes the ratio of number of jobs ($u_g^{a_i}$). As a result, the ratio of number of journey-to-work trips from zone $i$ to $k$-th zone in zone $i$ is changed from $f^{a_{ik}}$ to $f^{b_{ik}}$ by the change in $u_g^{a_i}$ from $u_g^{b_i}$ as shown in Figure 1.

Traffic generated from residential land uses and traffic attracted to employment zones forms the journey-to-work patterns in urban areas and contributes the most to person kilometers of travel. The journey-to-work trip length depends on the urban structure with its distinctive land-use pattern (spatial distribution of residential and employment zones) and the travel
behavior of these commuters. The mathematical model is formulated to minimize the least possible overall amount of travel in distance in the city considering the preference function of commuters in their journey-to-work travel by applying the optimal commuting assignment problem. This minimization model is formulated as a non-linear mathematical problem that includes the quadratic models of the preference functions (Equations (1) – (17), below).

\[
\sum_{i=1}^{n} F_i^a = T \quad (1)
\]
\[
F_i^a = F_i^b + \Delta F_i \quad (i = 1, \cdots, n) \quad (2)
\]
\[
\Delta F_i : \text{free variable} \quad (i = 1, \cdots, n) \quad (3)
\]
\[
\sum_{i=1}^{n} \Delta F_i = 0 \quad (4)
\]
\[
\Delta F_i^L \leq \Delta F_i \leq \Delta F_i^U \quad (i = 1, \cdots, n) \quad (5)
\]
\[
\sum_{i=1}^{n} G_i^a = T \quad (6)
\]
\[
G_i^a = G_i^b + \Delta G_i \quad (i = 1, \cdots, n) \quad (7)
\]
\[
\Delta G_i : \text{free variable} \quad (i = 1, \cdots, n) \quad (8)
\]
\[
\sum_{i=1}^{n} \Delta G_i = 0 \quad (9)
\]
\[
\Delta G_i^L \leq \Delta G_i \leq \Delta G_i^U \quad (i = 1, \cdots, n) \quad (10)
\]
\[
ug_{ik}^a = G_i^a / T \quad (i = 1, \cdots, n) \quad (11)
\]
\[
\Delta F_i^L , \Delta F_i^U \quad (i = 1, \cdots, n) \quad (12)
\]
\[
\Delta G_i^L , \Delta G_i^U \quad (i = 1, \cdots, n) \quad (13)
\]
\[
\Delta G_i^L , \Delta G_i^U \quad (i = 1, \cdots, n) \quad (14)
\]
\[
\Delta G_i^L , \Delta G_i^U \quad (i = 1, \cdots, n) \quad (15)
\]
\[
\Delta G_i^L , \Delta G_i^U \quad (i = 1, \cdots, n) \quad (16)
\]
\[
\Delta G_i^L , \Delta G_i^U \quad (i = 1, \cdots, n) \quad (17)
\]

Where

- $F_i^b, F_i^a$: number of resident workers living in zone $i$ before and after implementation of re-location of residence respectively
- $\Delta F_i$: variation of number of workers in zone $i$ (free variable)
- $T$: total number of trips
- $\Delta F_i^L, \Delta F_i^U$: lower and upper limit of number of variation of workers in zone $i$ respectively
- $G_i^b, G_i^a$: number of jobs located in zone $i$ before and after implementation of re-location of employment respectively
- $\Delta G_i$: variation of number of jobs in zone $i$ (free variable)
- $\Delta G_i^L, \Delta G_i^U$: lower and upper limit of variation of number of jobs in zone $i$ respectively
Equations (1) and (6) refer to the land-use constraints being satisfied that the sum of the number of resident workers living or jobs located in each zones equals the total number of jobs. Equations (2) and (7) represent the relationships between the number of resident workers living or jobs located in each zones before and after implementation of re-location of employment. Equations (4) and (9) also represent the constraint with respect to the sum of the variations of number of resident workers or jobs in each zone. Equations (11) and (12) refer to the ratio, and cumulative ratio, of the number of jobs after implementation of re-location of employment in each OD pair. Equations (13) - (16) also refer to the number of journey-to-work trips after the implementation of re-location of employment including the quadratic models of the preference functions. The number of jobs and the number of journey-to-work trips can be calculated as a problem of minimizing the total amount of travel in terms of distance in Eqn. (17) under Eqn. (1) - (16) as the constraint equations.

4. EMPIRICAL ANALYSIS

The model can be applied to any city because the necessary data are routinely collected in urban transport planning studies. The study area is divided into discrete zones. Land-use surveys establish the total number of jobs and commuters located in each zone. Person trip surveys (sample) or a census of journey-to-work travel will establish the OD flows. Zonal distances between zone centroids are calculated based on the shortest travel path over the road network. Intra-zonal distance will vary by zone size and can be adjusted to represent the average journey distance within a zone. Future zonal locations for homes and work-places are based on scenario analyses.

The cities were chosen to illustrate the wider application of the model. The choice of four cities in Hokkaido (Figure 2 and Table 1), was governed primarily by the availability of suitable data on person trip surveys collected for the respective city governments. For each city, the numbers of zones defined in these surveys were Sapporo 53, Asahikawa 52, Hakodate 55 and Kushiro 48. Zonal land-use activity was assumed to be concentrated at one point at the geometric center of each zone. The shaded zones in each city locate the main employment center. The percentage of jobs in these centers are: 19.5 % for zone 1 in Sapporo; 10.2 % for zone 4 and 8.5 % for zone 2 in Asahikawa, 9.1 % for zone 14 and 9.1 % for zone 9 in Hakodate; and 11.6 % for zone 2 in Kushiro.
Table 1. Case study cities: area, total number of jobs and mean trip length

<table>
<thead>
<tr>
<th>Study city</th>
<th>Survey Year</th>
<th>Area (km²)</th>
<th>Number of zones</th>
<th>Total number of trips</th>
<th>Mean trip length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapporo</td>
<td>1994</td>
<td>1121.1</td>
<td>53</td>
<td>606116</td>
<td>5.97</td>
</tr>
<tr>
<td>Asahikawa</td>
<td>2002</td>
<td>747.6</td>
<td>52</td>
<td>168038</td>
<td>4.33</td>
</tr>
<tr>
<td>Hakodate</td>
<td>1999</td>
<td>346.8</td>
<td>55</td>
<td>116274</td>
<td>4.29</td>
</tr>
<tr>
<td>Kushiro</td>
<td>1999</td>
<td>221.6</td>
<td>48</td>
<td>93417</td>
<td>4.05</td>
</tr>
</tbody>
</table>

Figure 2. Four cities in Hokkaido, the city center and zone system specified for each city

4.1 Journey-to-work Preference Function

The raw preference function shown in Figure 3 is the inverse of Stouffer's intervening opportunities model (Stouffer, 1940) that relates the proportion of migrants (travelers) continuing given reaching various proportions of opportunities reached. Previously, we have examined curve fitting by considering the characteristic shapes of the preference functions, the correlation coefficient from some statistical models and the numerical difference between the observed values and the estimated values. This process confirmed that the quadratic function (Equation 18) is superior to the logarithm function or power function.

\[ Y = a X^2 + bX + c \]  

Y = cumulative proportion of total metropolitan jobs taken from an origin zone;  
X = cumulative proportion of zonal jobs reached from each origin zone;  
a, b: regression coefficients; and  
c: regression constant.
Raw preference functions were drawn for four cities using the origin-destination data for the journey to work for each city. The shapes of raw preference functions illustrated in Figure 3 are convex. These curves pass through the coordinate value (1.0, 1.0), and the vertex of these curves has a coordinate value (1.0, 1.0) with the shape of function. The raw preference function is transformed into the quadratic function (Equation 18). Table 2 shows the regression coefficients, regression constants and correlation coefficients for the four cities illustrated in Figure 3. Table 3 shows the goodness of fit values (correlation coefficient) summarized for four cities based on the curve fitting by a quadratic function.

![Graph showing cumulative proportion of study area jobs reached vs cumulative proportion of zonal trips for four cities.](image)

Table 2. Regression coefficient, constant and correlation coefficient

<table>
<thead>
<tr>
<th>Zone number</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapporo-02</td>
<td>-0.3997</td>
<td>0.8097</td>
<td>0.5843</td>
<td>0.9759</td>
</tr>
<tr>
<td>Asahikawa-50</td>
<td>-0.0823</td>
<td>0.4673</td>
<td>0.5983</td>
<td>0.9873</td>
</tr>
<tr>
<td>Hakodate-19</td>
<td>-0.5253</td>
<td>1.5231</td>
<td>0.0255</td>
<td>0.9936</td>
</tr>
<tr>
<td>Kushiro-11</td>
<td>-0.7121</td>
<td>1.5300</td>
<td>0.1693</td>
<td>0.9896</td>
</tr>
</tbody>
</table>

Table 3. Average, minimum and maximum of correlation coefficient

<table>
<thead>
<tr>
<th>Study city</th>
<th>Average</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapporo</td>
<td>0.9913</td>
<td>0.9672</td>
<td>0.9987</td>
</tr>
<tr>
<td>Asahikawa</td>
<td>0.9711</td>
<td>0.6248</td>
<td>0.9991</td>
</tr>
<tr>
<td>Hakodate</td>
<td>0.9674</td>
<td>0.6567</td>
<td>0.9992</td>
</tr>
<tr>
<td>Kushiro</td>
<td>0.9612</td>
<td>0.6963</td>
<td>0.9978</td>
</tr>
</tbody>
</table>

4.2 Modeling Residential and Employment Relocation and Trip Lengths

The mean trip length under the same upper limit and the same lower limit for variation of the number of jobs in each zone are also estimated for 27 theoretical scenarios. The upper limits for variation of the possible number of zonal workers or jobs are set at 1000, 2000 and 3000, and the compensatory decrease rate (lower limit) for the variation of number of workers or jobs are set at -0.1 (-10%), -0.2 (-20%) and -0.3 (-30%), as shown in Table 4 and Figures 4 and 5. Table 4 shows the mean trip length for 27 scenarios for four cities after residential and employment relocation. The mean trip length decreases when accompanied by an increase in
the variation of the possible number of workers or jobs.

The mean trip length decreases with the expansion of the range of the upper and lower limit for variation of the possible number of workers or jobs. As for the range from 0 to 1000 of the possible number of workers or jobs, the effect of a decrease in the mean trip length is especially large as shown in Figure 4. Figure 5 depicts the decrease extent of the mean trip length based on the decrease rate for variation of possible number of workers or jobs. The decrease of the mean trip length is 3.4% (from 5.80 to 5.60 km) in Sapporo, and 6.2% (from 4.23 to 3.97 km) in Hakodate toward 1000 trips for the upper limit and -10% for the lower limit. The scenario of 3000 trips for an upper limit and -30% for lower limit is the largest decrease in all 27 scenarios - 10.5% (0.61 km) in Sapporo, and 18.8% (0.80 km) in Hakodate.

Table 4. Mean trip length for 27 scenarios in four cities

<table>
<thead>
<tr>
<th>Decrease rate of number of workers and jobs</th>
<th>Possible number of workers located</th>
<th>Possible number of jobs located</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1000</td>
<td>5.598</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>5.550</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>5.519</td>
</tr>
<tr>
<td>0.2</td>
<td>1000</td>
<td>5.511</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>5.415</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>5.358</td>
</tr>
<tr>
<td>0.3</td>
<td>1000</td>
<td>5.461</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>5.326</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>5.240</td>
</tr>
</tbody>
</table>

Figure 4. Mean trip length for 27 scenarios in Sapporo (a) and Hakodate (b)
5. TOTAL NUMBER OF TRIPS BY THE MOVE AND TRIP LENGTH

The mean trip length is decreased by the movement in the urban system of the number of workers and jobs. In this section, the relationship between the total amount of trips (the sum of the number of workers and jobs) by the move and the mean trip length are investigated. Table 5 shows the number of workers and jobs by the move for 27 scenarios for four cities after residential and employment relocation. Figure 6 shows the relationship between the total number of trips by the move and the mean trip length based on Tables 4 and 5.

The total number of trips to be moved needed to decrease the mean trip length is different depending on the urban size. Results for Sapporo Asahikawa, Hakodate and Kushiro are shown in Figure 6(a). Figure 6(b) shows the relationship between the move rate of the number of trips (= the total number of trips by the move divided by the total number of trips generated and attracted) and the decrease rate of the mean trip length. The decrease rate of the mean trip length on the Y-axis is a ratio of the mean trip length by the move and the actual mean trip length. The increase of the move rate of the number of trips decreases the same decrease rate of the mean trip length regardless of the urban size. The linear regression equation shown in Equation (19) is the relationship between the move rate of number of trips (x) and the decrease rate of the mean trip length (Y). The change in the mean trip length by the residential and employment relocation can be generalized by equation (19).

\[ Y = -0.4331x + 1.0048 \] (correlation coefficient: -0.99) \hspace{1cm} (19)

The number of workers and jobs in each zone can be readily changed by residential and employment relocation. As a result, there are increasing zones and decreasing zones compared with the observed land-use pattern in each city. Figure 7 depicts the increasing zones and decreasing zones for 27 scenarios for the four cities after residential and employment relocation. The increasing zones (dark blue shade in Figure 7) are the zones where workers or jobs were increased in all of the 27 scenarios. On the other hand, the decreasing zones (light shade of blue in Figure 7) are the zones where the workers or jobs are
decreased in all of the 27 scenarios. The zones that increased or decreased with the scenario are shown with a white background in Figure 7. The overall tendency in the four cities is for the increasing zones to be located surrounding the CBD, and the decreasing zones to be located in the suburban areas. These results confirm quantitatively the proposition that a compact city, with a better spatial distribution of homes and workplaces, can achieve a more sustainable city from the viewpoint of commuter travel and its implicit reduced environmental load.

Table 5 Total number of trips by move for 27 scenarios in four cities

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Sapporo</th>
<th>Asahikawa</th>
<th>Hakodate</th>
<th>Kushiro</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>0.2</td>
<td>2000</td>
<td>2000</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>0.3</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
</tr>
</tbody>
</table>

Figure 6 Relationship between total number of trips by the move and the mean trip length (6a) and the decrease rate of the mean trip length and the move rate (6b)
Figure 7 Locations for employment and residential relocation to achieve a compact city in Sapporo (a), Asahikawa (b), Hakodate (c) and Kushiro (d)
6. CONCLUSIONS

This paper has proposed a mathematical optimization model with a behavioral commuting component (preference function) embedded in it that can be applied in land-use and transport planning practice to determine the mean trip lengths of different scenarios for the spatial distribution of homes and jobs. This model and its equations are described in Section 3. Zonal preference functions (Stouffer hypothesis) to represent journey to work travel have been calibrated. The preference functions found to best fit statistically the zonal data for the four case study cities - Sapporo, Asahikawa, Hakodate and Kushiro - were quadratic functions. The application presented in this paper of the optimal commuting assignment problem has been restricted to small and medium-sized cities of Japan, but can be calibrated for any city where data are available.

Policy formulation requires evidence as to the costs and benefits associated with each plan or policy and this is certainly the case when proposing the compact city as a solution to achieving more sustainable cities. Planners and policy makers have intuitively realized that a compact city is more sustainable by encouraging shorter trip lengths and providing a better potential market for commuting by public transportation. Scenario-based planning using the optimal commuting assignment problem with behavioral travel parameters in the model allows the most effective development strategy to be selected based on the minimization of trip lengths. Different hypothetical scenarios were generated to redistribute the location of residences and employment in these cities of Hokkaido. The key finding in Section 5 is that the mean trip length decreases by increasing the number of jobs in zones around CBD and by decreasing the number of jobs in zones far from the CBD. The linear regression equation shown in Equation (19) is the relationship between the move rate of number of trips ($x$) and the decrease rate of the mean trip length ($Y$) which is a useful relationship when estimating, for example, greenhouse gas reductions in the urban transport sector.

When cities are growing in population and employment they must either grow upwards at increasing density or outwards in the green-field, peri-urban regions. Historically, most cities have expanded outwards at ever-lower urban densities because land is usually cheaper at the metropolitan fringe for housing, yet jobs lag behind. This pattern of urban development has predominated and the journey-to-work trip lengths have increased in an unsustainable way. Furthermore, the majority of these work trips are made by private transportation. The reductions in mean trip lengths reported for the spatial restructuring scenarios (re-locating homes and workplaces) described in this paper are hypothetical, but the same model could be applied to test the trip length implications of realistic, long-term metropolitan strategic plans, such as those described for a range of Australasian cities by Alpkokin (et al., 2007). Of course, there are social, economic and environmental considerations that policy makers must also include (see for example, Black and Doust, 2008) but the arrangement of homes and workplaces, trip lengths and associated environmental loads are important components of the long-term sustainability.

Whilst the optimal commuting assignment model has considerable practical utility in the evaluation of alternative urban forms aimed at achieving greater transport sustainability it is a completely different matter as to whether more efficient development outcomes will occur in practice. The processes of urban development are complex and involve many agents of which
the planning authority is but one stakeholder. It is only in cities with very strong planning controls that integrated land-use and transport planning is possible to guide the location of employment. In Australia, the national capital, Canberra, with its leasehold land tenure system, is one successful example. However, in cities where development is market-driven the prospect of government plans with radically different locations of homes and work-places, for example, being implemented is bleak. In his book *The Metropolitan Revolution: The Rise of Post-Urban America* (Teaford, 2006) explains how the central city has declined and describes the boom in suburban business districts sprouting from previously undeveloped green-field sites around thriving shopping malls. However, far less is known about the role of urban policy in this decentralization process, and further research is required to assess the long-term success or otherwise of government plans to locate metropolitan employment.

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