Simplified land use assessment on car commuting energy

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Abstract

The model has three submodels: land use, road and railway network, and commuter trips. The first includes two parameters, residential and workplace with locational densities over the circularized study area. Three kinds of simplified density distributions and the variations are introduced to each resident and workplace, named conic, reverse conic, level and railway-oriented locations, respectively. In the road and railway submodel, the road is defined by traffic lane density distribution, and several simple railway networks are provided. Major parts of the commuter trips submodel are commuter trip distribution, which delivers commuters from residences to workplaces, railway choice and car commuting speed on traffic lane. Energy for car commuting is calculated using energy rate function.

The results are (1) The case without railway; energy is minimized at the combination of conic resident and workplace locations, (2) The case with railway; the effects of railway network and railway oriented relocation on car commuting energy are shown against the combinations of the simplified density distributions. Railway oriented location has characteristic energy use tendency but some details remain to be confirmed.
1 Introduction

The paper is on the line of the authors’ interest in assessing energy for urban transportation (Myojin, et al., 1999, 1999). A model for assessing resident and job locations provided with road with/without railway networks on car commuting energy is dealt with in the present paper. The study area is assumed to be in a circle. Car commuting energy is calculated for those combinations of simplified resident-workplace locations and the variations provided with road with/without railway networks. The results included are some spatial distributions of car commute density over the study area and comparative energy uses resulting from those locational combinations and some railway oriented relocations of the original simplified locations.

2 Modeling

2.1 Definition

The model is outlined in Figure 1. Major parts of the model are resident-workplace location, spatial distribution of commute trip density, commute density distribution on traffic lane, car commuting speed and energy. Assessment is made on energy for car commuting.

![Flow diagram for model description](image)

Figure 1: Flow diagram for model description

2.2 Resident-workplace location

Three kinds of simplified density distributions are introduced to each resident and workplace; decreasing, increasing linearly outwards and flat, named conic, reverse conic,
level location, respectively. These are called the original simplified locations hereafter in the paper. Every possible set of original simplified locations is alphabetized in Table 1.

A variation is added to the original ones: railway-oriented location. The railway-oriented location finds its local peak density along railway and decreases monotonously off railway line. This will be shown later in further details.

Table 1: Combinations of original simplified locations

<table>
<thead>
<tr>
<th>Workplace density</th>
<th>Residential density</th>
<th>Density</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>H</td>
</tr>
</tbody>
</table>

2.3 Commute trip distribution

The probability \( p(P_iP_j) \) of a commute trip from origin \( P_i \) to destination \( P_j \) is assumed as

\[
p(P_iP_j) = \kappa \cdot u(P_i)v(P_j)f(l)
\]  

(1)

where \( u(P_i) \) = normalized potential function for commute trip generating that is defined by some parameters at \( P_i \), \( v(P_j) \) = normalized potential function for commute trip attracting that is also described by some parameters at \( P_j \), \( f(l) \) = commute length distribution in which \( l \) = commute length defined by \( P_i \) and \( P_j \), and \( \kappa \) = constant. Integration of the probability \( p(P_iP_j) \) by \( P_j \) over the study area, keeping \( P_i \) fixed, must be equal to \( u(P_i) \), from which \( \kappa = 1/A(P_i) \). So we have

\[
p(P_iP_j) = u(P_i)v(P_j)f(l)/A(P_i)
\]  

(2)

where \( A(P_i) = \int P_j v(P_j)f(l)dP_j \) (integration of \( v(P_j)f(l) \) over the whole possible points \( P_j \) keeping \( P_i \) fixed, where \( P_i, P_j \) and \( l \) are illustrated in Figure 2 with other notations to appear).
2.4 Spatial distribution of car commute density

This is defined by the number of car commutes passing through an infinitely small area. We define a probability \( p(r, \theta) \) of a commute trip passing through an arbitrary point \( P_0 \) in Figure 2. A brief explanation for the probability \( p(r, \theta) \) is as follows:

1. Integrate \( P_0 \) by \( P_i \) along the line from \( P_i \) to \( Q_i \) after integrating the function by \( P_i \) along the line from \( P_i \) to \( Q_i \) (Fig.2), where \( r(P_i, P_0; P) = \) car choice ratio of a commute trip from \( P_i \) to \( P_0 \), when railway service is available, \( P = \) population and \( Q_i \) and \( Q_0 \) = intersections of the extended line \( P_0 P_i \) and the periphery, and

2. Do the sum of the similar integration by turning the line in 360-degrees round \( P_i \).

Obviously the spatial distribution \( p(r, \theta) \) thus obtained is homogeneous on concentric circle only for the original simplified locations without railway network but not so for the otherwise.

2.5 Road and railway network

2.5.1 Road network

Road network in the paper is represented by traffic lane density distribution over the study area. Traffic lane density here is defined by traffic lane length over an infinitely small area. Based on the data from some Japanese local cities having population from 600,000 to 1,000,000, this is assumed by a negative exponential function

\[
n_i = \eta e^{-\xi r}
\]

where \( r \) is distance from the center, \( \eta \) and \( \xi \) are constants that may or may not depend on population. This will be made clear later. Eqn.(3) is based on another assumption that the density is homogenous over concentric circle.
2.5.2 Railway network

Typical but simple railway networks are drawn: one ring and/or four radial lines of equal length meeting at right angles at the center of study area. In the paper, three network patterns are tested, as shown in Figure 3; one varying ring, four radial lines of equal varying length and one varying ring on four radial lines of full length.

![Figure 3: Railway network (heavy line)](image)

2.6 Car commuting speed

This means traffic speed on lane through the hours (peak hours in the morning, because just commute to work is regarded). This is calculated using so called speed-density relation in which background car trip density is also regarded on the data from traffic census in Japan.

2.7 Energy for car commute

Car commuting energy is calculated by

\[ E = \int_0^\theta \int_0^d (r, \theta; P) e(r, \theta) r d\theta dr \] (4)

where \( e(r, \theta) \) = energy rate (kcal/car trip-km) converted from fuel-speed function identified for Japanese passenger cars on the data from the late Ministry of Transport.

3 Calculation

3.1 Preparation

3.1.1 Railway-oriented locations

Figure 4 illustrates railway-oriented location. Railway-oriented location is given by a conditional relocation of the original simplified location. That is made in the way that, for example by the radial railway line, the locational density is conserved on every concentric
circle throughout the relocation, conversely, no local centralization and/or decentralization of the original density should take place through the modification. The density conservation in the case of four radial railway lines is illustrated in detail in Figure 4, where the figures $ABCD$, $A'B'CD$ and $A''B'C$ are equal in area each other and of course the area of $ABCD$ is defined by the original simplified locational density, that is uniform over a circle, and the $A'B'CD$ and $A''B'C$ by the relocated ones. The height $DA$ or $DA'$ is the density at $D$ lying on a line dividing the area contained between adjacent radial lines into two equal territories. Another modified density is drawn symmetrically on the other side of the radial line.

A measure is introduced to define the extent to which the relocated density is inclined to railway line. For example, the relocated density $A''B'C$ is more inclined to the line than the $A'B'CD$, while no inclination is found in the original density $ABCD$. Thus the density subtracted the original one $(CB)$ from the relocated one $(CB'$ or $CB''$ etc.) at point $C$ that lies on railway line, divided by the original one, may be most preferable as the measure because it, being defined simply and commonly throughout railway line and of physical meaning, can meet the requirements as above. It is easy to see that it ranges from zero to infinity.

![Figure 4: Illustrative railway-oriented locations](image)

### 3.1.2 Commute length distribution

Following function is introduced

$$f(l) = \gamma l^\alpha e^{-\beta l}.$$  \hspace{1cm} (5)

where $\alpha$, $\beta$ and $\gamma$ are constants. The function finds its peak at $l = l_p = \alpha / \beta$. The peak position is estimated, for example, at $l_p = 1.8$ kilometers ($\alpha = 0.735$ and $\beta = 0.407$) based on the data from trip survey in Okayama where the authors live and work. In the present paper, however, $l_p = 2.0$ is assumed. Normalization factor $\gamma$ is evaluated in due result.
3.1.3 Railway choice

Railway choice ratio, instead of car choice one, is assumed as a linear function:

\[ r_c(l, l_a, l_e) = a + bl + cl_a + dl_e \]

where \( l = \) commute length, \( l_a(l_e) = \) access to (egress from) the nearest railway, and \( a, b, c \) and \( d = \) constants. Based on the data from trip survey in some Japanese local cities of 600,000-1,000,000 population, the constants were estimated at \( a = 0.0981, b = 0.00269 \) and \( c = d = -0.0103 \). Car choice ratio \( r_c \) is given by

\[ r_c = r_c(P_1, P_2; P) = 1 - r_c(l, l_a, l_e) = 1 - \left\{0.0981 + 0.00269l + 0.0103(l_a + l_e)\right\} \]

where 600,000 \( \leq P \leq 1,000,000 \), and \( l, l_a, \) and \( l_e \) depend, of course, on \( P_1 \) and \( P_2 \). The ratio is applied to the cases with railway network.

3.1.4 Total commute trips

The percentage of the total number of trips to work to the city population proved nearly constant ranging from 35.8 to 38.1\% despite of population. So the total peak hour trips to work is assumed here as

\[ T_{am} = 0.37P \]

3.1.5 Spatial distribution of traffic lane density

Through testing based on road network data from some Japanese local cities, the constants in eqn. (3) were estimated at \( \eta = 7.283 + 0.07P \) and \( \varsigma = 0.325 \), which means traffic lane density is distributed in proportion to population.

3.1.6 Other factors

These are estimated on the data from traffic census and trip survey in Japanese cities: \( g = 29.5 \), \( h = -1.20 \) and \( e = 1.37 \) in eqns (4) and (6), respectively. No statistical significance was found of correlation of \( e \) with population.

3.2 Results

The following is some typical results obtained so far;

3.2.1 Spatial distribution of car commute density

Figure 5 shows spatial distributions of car commute trip density resulting from the original simplified locations (without railway) A, B, C and L. Car commute trip density is divided by the corresponding traffic lane density to get spatial distribution of car commute density on traffic lane.
3.2.2 Mixed effects

Original simplified location with railway

Figure 6 shows comparative energy use from the original simplified locations provided with railway networks, one ring on four radial lines of full length, in which $R = 9.7$ km is given to the relative radius of ring line $R_r$. Relative radius $R = 0$, for example, means original simplified location provided only with four radial lines of full length.

Figure 7 shows the marginal effects of ring line in terms of the percentage of energy reduction by ring line to the energy use resulting from the original simplified locations provided with the four radial lines of full length.

Railway-oriented location

Figure 8 shows energy use resulting from relocation of the original simplified locations A, B, C and I provided with full length radial lines. Horizontal axis is named railway-oriented gradation, the measure for railway-orientedness of the relocated density. By definition, each corresponds to that from the original simplified location only when the gradation $= 0$. 
Spatial distributions of car commute density resulting from the original simplified locations without railway are, as a matter of course, grouped into three patterns; bell, plate and plateau (Figure 5). Most of these spatial distributions, divided by the traffic lane density distribution given, are transformed to a certain distribution of car commute density on traffic lane, having a bottom at the center and a concentric peak density moving outwardly in alphabetical order of the locations. This comes mostly from an exponentially decreasing tendency of traffic lane density distribution used.

Energy use from the original simplified locations without railway has a clear tendency to increase toward south-east corner of locations in Table 1. Location A is the most centralized while I is the most decentralized. It is noteworthy that, with the conditions attached in the paper, energy use from I is round 1.8 times as much as that from A.

The maximum percentage of incremental energy reduction by varying ring line, set on full length radial lines provided for the original simplified locations, to the energy use form those without ring line falls within 2.5 and 7.0%, corresponding to locations A and I, respectively. The ring lines to give peak reduction grow up roughly in alphabetical order.
respectively. The ring lines to give peak reduction grow up roughly in alphabetical order.

The results from the railway-oriented locations are partly true to our expectations but partly not so. As is expected, car commuting energy decreases slowly with the railway-oriented gradation but it is, unexpectedly, reversed slowly and rapidly after that. This unexpected behaviors of A, B and C is characterized by the existence of minimum energy use where two conflicting effects of energy use of growing car trip density in the area along railway, are balanced. The former surpasses the latter to the left of the balancing section but is surpassed by the latter to the right where sharp increase in energy use is caused by higher traffic density. Remarks on an uncertain behavior of relocation of I will be made at the end of the following section.

4 Conclusions

Energy use for car commuting is minimized by given by the location A given by a combination of conic resident and workplace locations, while maximized by I given by a combination of the reverse conic locations. This is attributed to the fact that the location A is most centralized among resident-workplace locations given but I most decentralized. Level locations of resident and / or workplace give of course moderate energy use for car commuting.

On the whole the effect of railway line, provided on the original simplified location, on reducing energy for car commute is larger in reverse conic location than in the conic. This may be attributed to the nature of reverse conic location likelier to generate long commute which is likely to make railway choice. On the other hand, however, reverse conic location is most energy consumptive for car commuting.

The railway-oriented location is defined by a conditional relocation of the original simplified location. The results from the relocations are to and at the same time against our expectations. A certain result so far is that car commute energy decreases slowly with the railway-oriented gradation so long as it is not higher.

The model might have been successful in the sense that we could get general understanding of energy use for car commute generated from several typical simplified locations of resident and workplace. Several problems, however, are left for examination for further improvement of the model. These are related to; (1) traffic speed function, (2) trip length distribution and traffic lane density distribution and (3) railway choice model. The following are remarks for model improvement: (1) Traffic speed function assumed in the paper is so called speed-flow relationship estimated for existing traffic lane. We applied it to calculate traffic speed at an arbitrary point by substituting the flow at an infinitely small area including the point. But the relationship for lane might not necessarily give traffic speed at point. This will be improved by calibrating the estimated speed-flow relationship.
so that special distribution of calculated speed may fit good to the observed which is easy to find using traffic census data. (2) The distributions used were estimated for existing Japanese local cities where resident and workplace are located nearly conicly, that is, these might be specialized to location A for example, but not to location I for example. Widely useful distributions for various locations are needed. Firstly for traffic lane density distribution, one of the promising ways will be found by introducing new function of resident and workplace density together with some other variables if useful. One of these functions will be expressed by linear combination of those variables. It is of course identified on existing data. Secondly for trip length distribution, the problem, if any, may be related not to the function itself but to the values of constants included because the function has been accepted widely for its flexibility coming from the two key constants \( \alpha \) and \( \beta \). Fluctuation analysis of \( \alpha, \beta \) and \( \alpha/\beta \) for various existing cities may suggest need/no need for revised values for reverse-conic locations. (3) Railway choice model will be polished by introducing service frequency, fare and capacity parameters. This may be achieved by analyzing commuters’ mode choice in various cities. Data from person trip survey are available for the analysis. Finally for an uncertain behavior of energy use for relocation of I, our attention for improvement will be focused on calculation program for processing projecting high density of car trip on lane that might cause sharp special fluctuations in traffic speed leading to missing calculation of energy use.

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References
