URBAN TRANSPORTATION ENERGY IN JAPAN AND RESIDENTIAL LOCATION ASSESSMENT ON WORK TRIP ENERGY

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Abstract

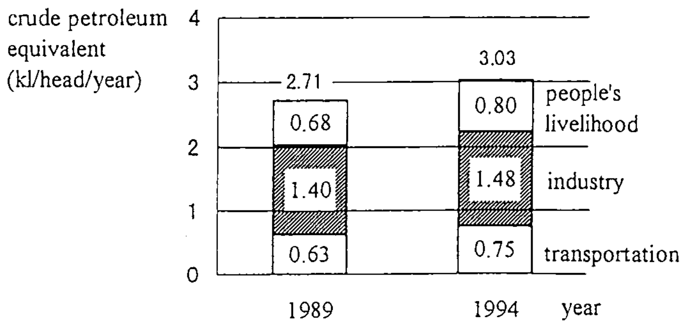
Urban transportation energy use in Japanese cities is dealt with in two aspects ; the relation between urban transportation energy and population and residential location assessment on energy for commuting. Per capita daily energy use by mode (passenger car, commercial vehicle, bus and railway) and the aggregated is shown against population. Passenger car's share in passenger transport is one of the key factors reducing energy use because passenger cars use 49～64% of the daily urban transportation energy. Along reilways, residential decentralization, instead of centralization, is assessed on energy for commuting to the midtown area of a central city. It proved to possibly save commuting energy through cutting down passenger car's share.

INTRODUCTION

Per capita energy use is still increasing in Japan as shown in Fig.1. It shows a 12% increase in the last five years. Per capita transportation energy use shows the largest increasing rate of 19%. The rates of increase in industry and people's livelihood are 6% and 18%, respectively. This is a typical aspect of the recent trend of energy use in Japan.

Firstly, we show how modal energy use for urban transportation in Japan depends on city size (population). Public Transport service is poorer in smaller cities. This is attributed to more intensive motorization. This tendency is shown through investigation of travel and transportation mode and reflected on per capita modal and aggregated energy use. Per capita daily energy use by travel mode is shown against city population. Study modes are passenger car, commercial vehicle, bus and railway. As for passenger car energy use, modal choice, fuel consumption and other criteria are introduced to estimate per capita energy use. Fuel consumption is also used to calculate commercial vehicle and bus energy use. An average energy rate, that is expressed in kilogram calorie per rolling-stock kilometer, is adopted to estimate per capita energy use for urban transport by rail. Per capita daily energy use integrated over the modes is also shown. Some typical results are as follows : a smaller population city tends to have less efficiency in transportation and passenger car energy use, and as a natural consequence, it is the most inefficient in energy use.

Secondly, we report the possibility of reduction in some transportation energy through a simple simulation. The city under study has a 600,000 population and some railway and bus transport. Residential decentralization along railway is simulated to test for improvement in energy use for commuting to midtown of the study city through modal conversion from car to railway. The simulation result shows a certain effectuality of far residential suburbanization though it is opposite to the way shown by, for example, Markovits (1971) or Morimoto *et al* (1985).



(Drawn on the data from General Energy Statistics (1995))

Figure 1 - Per capita yearly energy use in Japan

TRANSPORTATION ENERGY USE

Mode description

Urban transportation under the present study is shared by four modes as reported above. Each is defined as follows.

Passenger car

This dominates larger portion of whole trips which people living in the study city make daily, except for goods transportation. The whole trips are called "person trips" in the paper. Another portion of person trips is borne by some commercial vehicles that are converted for person trips. The ratio of the sum of these two portions to the number of person trips is called passenger car's share in the paper. Hereafter, real passenger cars and some commercial vehicles converted for person trips are called passenger cars collectively in the paper. The car here is defined by that registered in the study city.

Commercial vehicle

This bears the whole goods transport in the city. The whole goods transport is described in the vehicle kilometers produced, except for those vehicles converted for person trips. Data from a person trip survey is available for estimating the portion of the converted ones to the whole commercial vehicles. The commercial vehicle is also defined by that registered in the city.

Bus

This is also expressed by the whole distance produced by buses for passenger transportation in the city.

Railway

Almost all the rolling-stock are used for passenger transportation in average Japanese cities. Railway transport here is expressed by the whole rolling-stock kilometers produced for passenger transportation in the city. As to other modes, taxi is considered as passenger car and motorbike is disregarded for data is not available, especially on driving distance.

Modal energy use

The relation between total daily modal energy use E_m and per capita daily modal energy use e_m is given by

$$E_m = Pe_m, \tag{1}$$

where

P : population (10 thousands),

m : mode.

In the following $e'_m s$ are investigated.

Per capita daily modal energy use

Passenger car

$$e_p = g\frac{r_p}{100}\frac{1}{n}\,l_p f_p, \tag{2}$$

where

e_p : per capita daily energy use for passenger car (kcal/person/day),

g : person trip generating rate (trip/person/day),

r_p : passenger car's share (%),

n : average number of passengers in a car (person/car trip),

l_p : average length of passenger car trip (km/car trip),

f_p : average energy rate of passenger car (kcal/km/car).

Trip generating rate g turned out to be statistically independent on city population and equal to 2.52 on the average through testing on the data from person trip survey that have been made in Japanese cities (Figure 2). The average number n of passengers in a car and average trip length l_p are also statistically independent of population. As defined above, the passenger cars include commercial vehicles in part. But there is no reason that those values of the commercial vehicles included in the passenger cars should be different from those of the real passenger cars because the former are used as passenger cars. Now n =1.31 and l_p =12.34.

The passenger car's share r_p is found to be a linear function of population on the data from person trip survey. That is given by

$$r_p = 59.5 - 9.87 \times 10^{-2} P , \tag{3}$$

where

P : population (10 thousands).

This is shown in Figure 3.

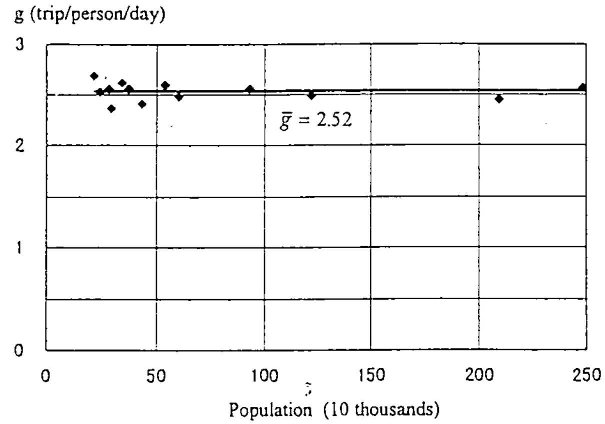


Figure 2 - Person trip generating rate

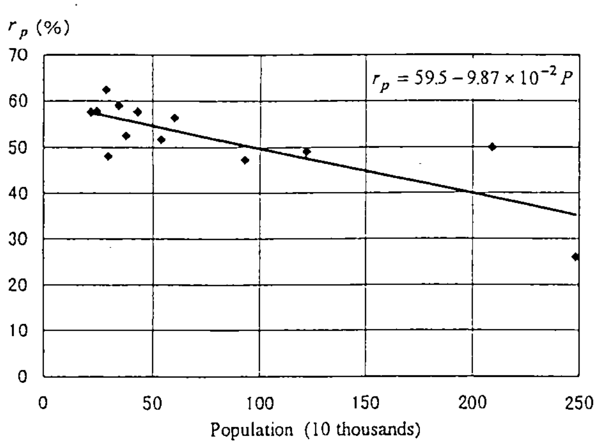


Figure 3 - Passenger car's share

The average energy rate is given by

$$f_p = \alpha_1 f_{p1} + \alpha_2 f_{p2} , \qquad (4)$$

where

f_{p1} : the rate of real passenger car (kcal／km／car),

f_{p2} : the rate of converted commercial vehicle (kcal／km／vehicle),

α_1 and α_2 : weights for averaging.

The rate f_{p1} is also given by a weighted average rate of the real passenger car classes. Energy rate of a real passenger car class is assumed here as some function of average travel speed having a limit at a certain speed as follows :

$$f_{p1}^k = a_{p1}^k v + \frac{b_{p1}^k}{v} , \qquad (5)$$

where

f_{p1}^k : energy rate of a real passenger car class k (kcal／km／car),

v : average travel speed (km／h) ,

a_{p1}^k and b_{p1}^k : constants.

The real passenger cars here are classified by piston displacement as follows : $k \leqq 660$ (cc), $661 \leqq k \leqq 2{,}000$ and $k \geqq 2{,}001$.

Three kinds of authorized travel speed modes for testing fuel consumption are available to estimate the values of a_{p1}^k and b_{p1}^k. That is, the authorized modes give three observed points (f_{p1}^{ki}, v^i) where v^i is the average travel speed corresponding to test mode i , and f_{p1}^{ki} is the corresponding energy rate for class k . The following modes are authorized in Japan : ten-modes, ten-fifteen-modes and a constant speed. Now the rate f_{p1} is given by the average rate of f_{p1}^k weighted by the number of the registered real passenger cars of class k .

It is difficult, however, to know some authorized energy rate f_{p2} in a similar way because no published data on fuel consumption corresponding to some authorized travel speed modes are available to estimate the parameters included in the function. Hence an expedient is adopted for rate f_{p2} as follows :

$$f_{p2} = \gamma_c f_{p1} , \qquad (6)$$

where

γ_c : nationwide general ratio of the average energy rate of commercial vehicles to that of real passenger cars.

The ratio comes to 1.478 on the data from Annual Report (1995 and 1996).

Taking the average of f_{p1} and f_{p2} weighted by α_1 and α_2 , respectively, we have

$$f_p = 3.64v + \frac{1.30 \times 10^4}{v} , \qquad (7)$$

where

α_1 : the ratio of the number of real passenger cars to that of passenger cars including converted commercial vehicles,

α_2 : $1-\alpha_1$.

Nationwide data on passenger and goods transportation by commercial vehicles are available to estimate α_1 and α_2. That is, α_1 =0.806 and α_2 =0.194. An equivalent expression of eqn (7) in fuel consumption rate is $f_p = 4.33\times10^{-4}v+\frac{1.55}{v}$ (l/km/car). In any case, the limit is found at v =60 km/h that is often said to be a reasonable speed.

Consequently, we have

$$e_p = 0.22(3.64v+\frac{1.30\times10^4}{v})\times(59.5-9.87\times10^{-2}P), \tag{8}$$

where

v : average travel speed (km/h),

P : population (10 thousands).

<u>Commercial vehicle</u>

Taking no consideration of modal share in goods transportation, it is written as

$$e_c = r_c(1-\alpha_c)d_c f_c, \tag{9}$$

where

e_c : per capita daily energy use for commercial vehicle (kcal/person/day),

r_c : ownership of commercial vehicle (vehicle/person),

α_c : the ratio of the number of diverted commercial vehicles to that of the whole commercial vehicles,

d_c : average daily transportation by a commercial vehicle (km/day),

f_c : average energy rate of commercial vehicle (kcal/km/vehicle).

Commercial vehicle ownership is found to be given by a function of population as shown in Figure 4. That is expressed by

$$r_c = 0.179-0.264\times10^{-3}P. \tag{10}$$

The ratio α_c is already known in estimating α_1 and α_2 used for taking the average of f_{p1} and f_{p2}, that is, α_c =0.437. This is a general value estimated on nationwide data due to not being available data by city. Average daily transportation d_c is found statistically independent of population and d_c =41.5 km/day. Average energy rate f_c is already known in estimating f_{p2}; that is, $f_c = f_{p2} = \gamma_c f_{p1}$ where γ_c =1.478 as shown before. Finally,

$$e_c = 23.4(4.92v+\frac{1.76\times10^4}{v})\times(0.179-0.264\times10^{-3}P), \tag{11}$$

where

P : population (10 thousands).

<u>Bus</u>

$$e_b = r_b d_b f_b, \tag{12}$$

where

e_b : per capita daily energy use for bus transportation (kcal/person/day),

r_b : bus ownership (bus/person),

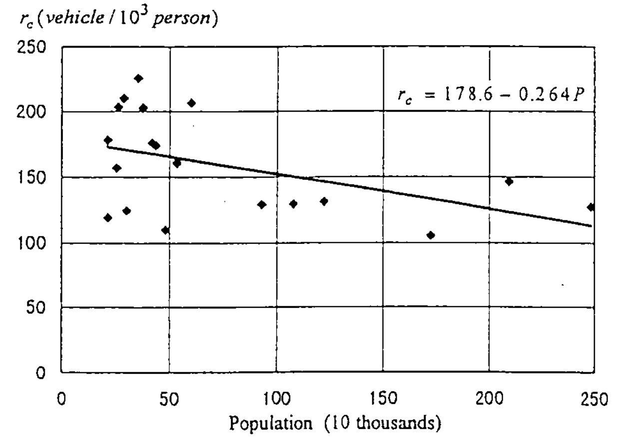


Figure 4 - Ownership of commercial vehicle

d_b : average daily transportation by a bus (km/day),
f_b : average energy rate (kcal/km/bus).

Statistical independence of r_b and d_b of population are found and are equal to $r_b = 2.11 \times 10^{-3}$ (bus/person) and $d_b = 92.54$ (km/day). An expedient is also adopted to estimate f_b due to detailed data not being available on bus fuel consumption. That is, $f_b = \gamma_b f_{p1}$ where γ_b is a nationwide general ratio of the average energy rate of buses to that of real passenger cars. Thus, $\gamma_b = 2.68$ on the data from the preceding annual report.
Finally

$$e_b = 0.44(3.96v + \frac{1.42 \times 10^{-4}}{v}), \tag{13}$$

where population term has disappeared.

Railway

$$e_r = \frac{1}{P} D_r f_r, \tag{14}$$

where

e_r : per capita daily energy use for railway transportation (kcal/person/day),
D_r : average daily rolling-stock kilometers in a city (km/day),
f_r : average energy rate (kcal/km/rolling-stock).

Freight trains and super-express trains are disregarded here since those are not considered urban transport. Average daily rolling-stock kilometers are expressed by

$$D_r = 7.0 \times 10^{-3} P^2. \tag{15}$$

This is shown in Figure 5. A nationwide average energy rate $f_r = 5{,}570$ (kcal/km/rolling-stock); therefore eqn (14) comes to

$$e_r = 39P, \tag{16}$$

where

P : population (10 thousands).

Aggregation
Per capita daily aggregated energy use is given by

$$e = e_p + e_c + e_b + e_r. \quad (17)$$

Average travel speed

The problem here is to test how the average travel speed v is dependent on city population or on other factors. Figure 6 is drawn on the data from Road Traffic Census (1995). That shows the average travel speed observed by test driving in two different city sections, densely inhabited district (D.I.D.) and the rest area during congestion periods. The average speed is about 20 and 30 km/h in each. Little dependence of the speed on population is noted in Figure 6. At present, no data are available to test dependence of speed on population or other factors.

Graphical presentation

Figure 7 and 8 show per capita and total daily energy use by mode, respectively, at an assumed speed v =30 km/h. Figure 9 shows the corresponding distribution, and Figure 10 shows relative effect of travel speed change on an

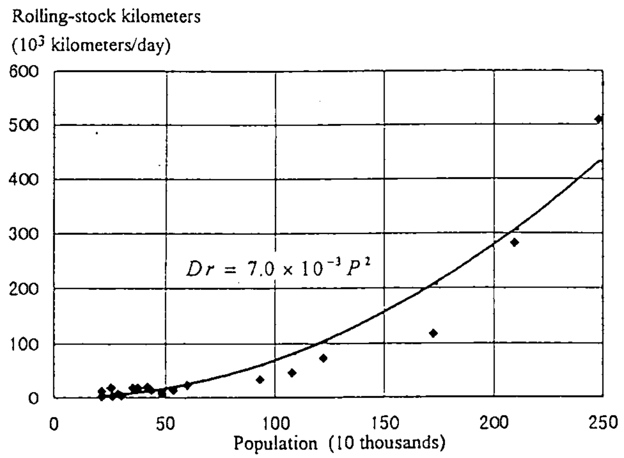


Figure 5 - Rolling-stock kilometer vs. population

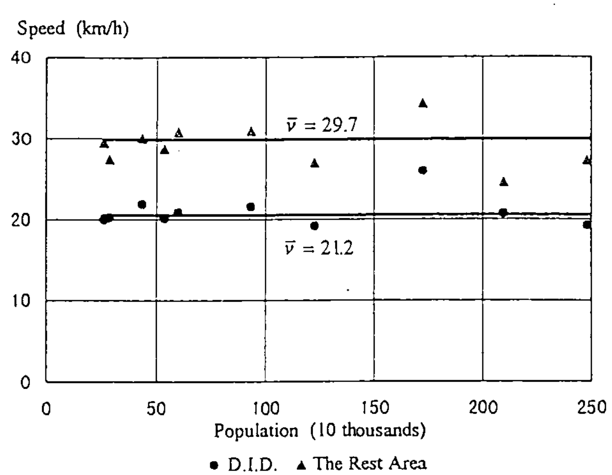


Figure 6 - Average travel speed in two different city sections

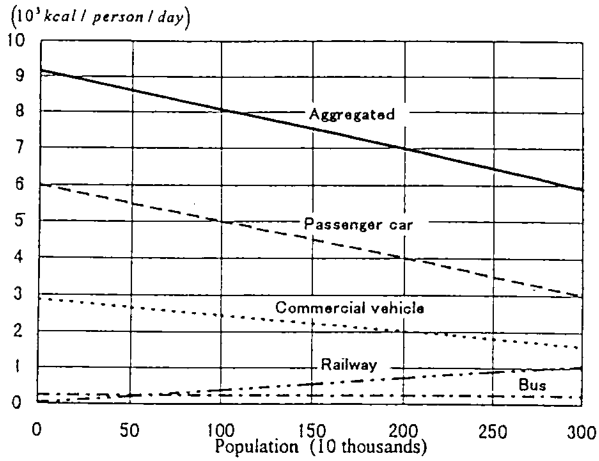


Figure 7 - Per capita daily modal energy use $(v = 35km/h)$

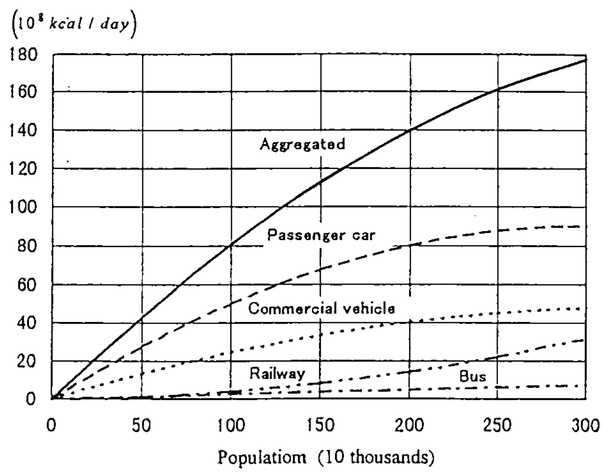


Figure 8 - Daily modal energy use $(v = 35km/h)$

improvement in daily energy use. Those are of course calculated on an assumed independence of travel speed of population.

Examination

Per capita daily energy use for passenger car and commercial vehicle decreases linearly with population. That for railway increases linearly and that for bus is constant. The former two are very large ; therefore, per capita daily aggregated energy use decreases linearly with population. Nevertheless, a smaller population city is less efficient in energy use for urban transportation than a larger city. This is attributed of course to poor public transport in a small city as stated earlier. Passenger car is the largest in percentage of modal energy use to the aggregated use. It amounts to about 49~64% vs. population of below three million, and commercial vehicle is the second largest. About 77~98% of daily energy use is due to the two kinds.
Because of the substantial difference in average travel speed in D.I.D. and the city rest section, travel speed up in D.I.D. will bring more improvement in energy use than that in the rest due to fuel consumption characteristics as

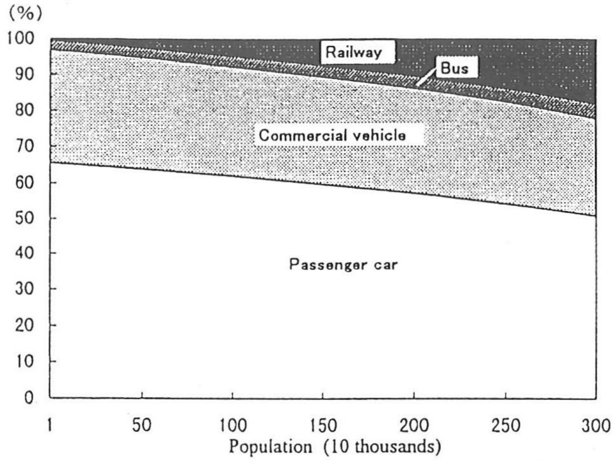


Figure 9 - Distribution of per capita daily modal energy use $(v = 35km/h)$

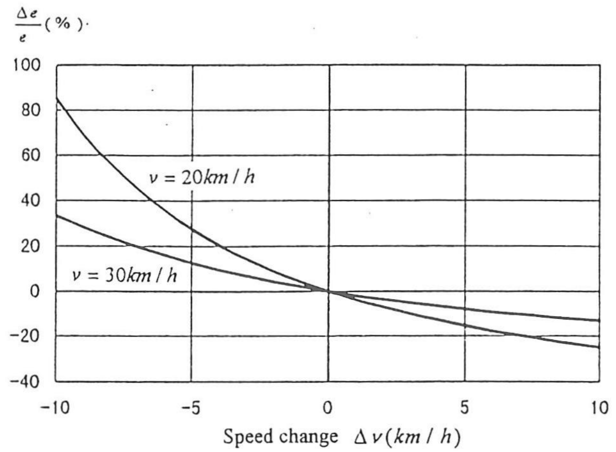


Figure 10 - Relative change in energy vs. travel speed change

shown in Figure 10. Similarly, travel speed up during congestion periods will have a better effect on energy use. In these respects, a specific relation of mode choice and residential location is investigated from the data observed in a Japanese local city having a 600,000 population.

RESIDENTIAL LOCATION ASSESSMENT

Definition

The study is limited to commuting terminated in the central area of Okayama City from other areas by car or railway. The city stands in the western part of Japan. The commuting under study amounts to about 45% of that terminated in the city by car or railway. Myojin *et al* (1994) showed that about 90% of the daily energy use for urban transportation here was due to passenger and commercial cars in 1982.

Residential location and mode choice

The residential locations of the commuters under study and their mode choice are observed on the whole to depend on two parameters : direct distance x from residential location to the terminal railway station in the central area and θ from the residential location to the nearest railway station. Hereafter, these are called commute length and access, respectively.

The residential location and mode choice are described as follows, respectively,

$$f = f(x,\theta), \tag{18}$$

$$r = r(x,\theta), \tag{19}$$

where

f : density of distribution of commute length with access θ,

r : railway's share defined by the ratio of the number of railway choices, irrespective of access mode, to that of commute length x and access θ.

Figure 11 illustrates central area, commute length, access and railway stations.

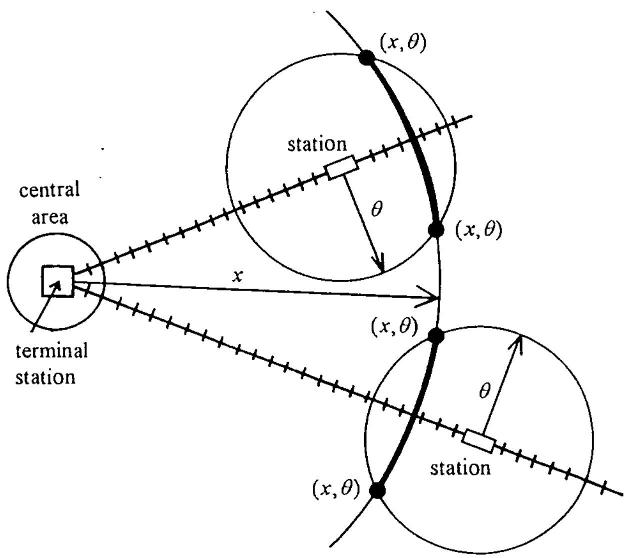


Figure 11 - Illustration of points (x,θ) on a central area-railway station space

Integration of the above by θ gives

$$F(x,\theta) = \int_0^\theta f(x,\eta)d\eta . \tag{20}$$

$$R(x,\theta) = \int_0^\theta r(x,\eta)d\eta . \tag{21}$$

The integration is done of course along heavy lines shown in Figure 11. $F(x,\theta)$ is a probability density of commute length with the access shorter than θ, and $R(x,\theta)$ is railway's share summed over the access likewise.

General forms of the functions $f(x,\theta)$ and $r(x,\theta)$ are difficult to decide. Therefore, $F(x,\theta)$ and $R(x,\theta)$ are estimated directly on the data surveyed so far. After a trial, a certain value of θ is chosen to settle railway's share function. Probability density function $F(x,\theta)$ is also estimated rather subsequently. Incidentally, three or more classes of θ might exist instead of two, that is, we might have $R(x,\theta_{k-1} \leqq \theta < \theta_k) = \int_{\theta_{k-1}}^{\theta_k} r(x,\eta)d\eta, k = 1,2,\cdots,\theta_0 = 0$. But the quantity of data available was not large enough to have many such classes. Figure 12 shows railway's share and the probability density against commute length. The access is

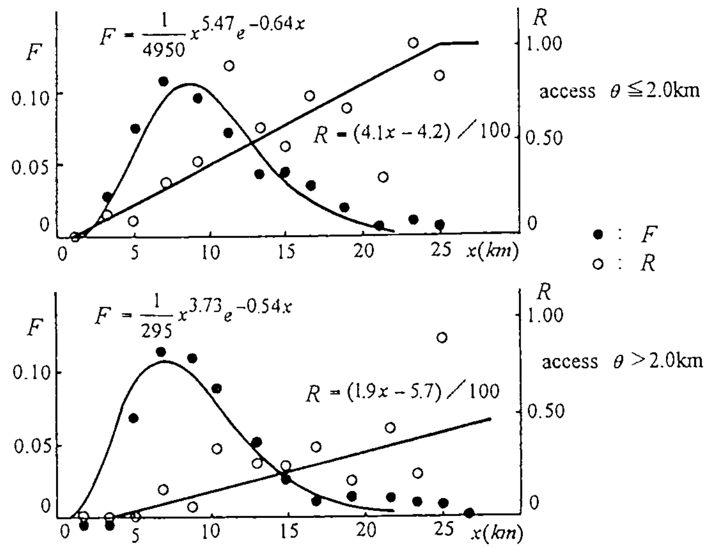


Figure 12 - Railway's share and commute length distribution

classified into two : $\theta \leqq 2.0$km and $\theta > 2.0$km. The railway's share is practically linear with the commute length and is assumed as

$$R(x,\theta) = ax + b \ , \tag{22}$$

where

x : commute length,

a and b : parameters depending on θ.

The following function of probability density is assumed so as to have a peak at a commute length

$$F(x,\theta) = \kappa \ x^{\alpha} e^{-\beta x} \ , \tag{23}$$

where

α, β and κ : parameters likewise.

Those parameters are estimated on the data from person trip survey made previously.

Effect of change in residential location

An imaginary change in residential location is introduced by moving the peak position of the above density function. A new imaginary density function is introduced to measure an effect of the change in residential location by

$$\int_0^{\infty} F_i(x,\theta)\{1 - R(x,\theta)\} x dx \ , \tag{24}$$

where

$F_i(x,\theta)$: new imaginary density function settled by moving the original peak position.

Railway's share $R(x,\theta)$ is assumed invariable despite the peak moving.

Figure 13 shows some relative effects of the changes in residential location on the total travel distance of car commutes to work. The figures in Figure 13 represent an integrated value of (24) divided by the reference that is calculated using the original density function $F(x,\theta)$ for $F_i(x,\theta)$. The figures, therefore, mean a shorter／longer total travel distance of car commutes to work as compared with the reference one if it is below／over 1.00. Figure 13 shows the cases of residential decentralization (peak positions are over the references) instead of centralization. This is mentioned later.

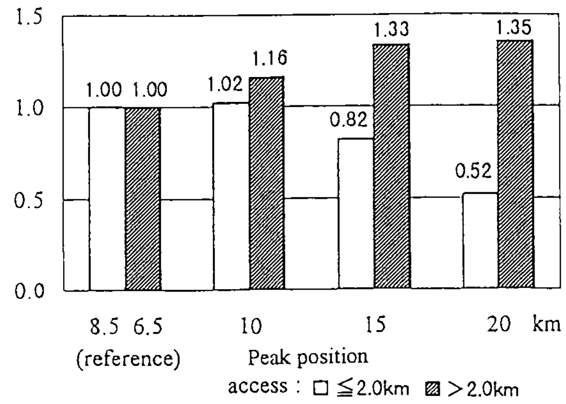


Figure 13 - Effect of residential decentralization

Examination

The relative total travel distance of car commutes to work decreases in case of access below 2.0 km and peak position over 15km, but it increases otherwise, except in the case of peak position below the reference. The car's share is sure to decrease by moving the peak position rightwards to the reference, irrespective of the access classes. Consequently, far residential decentralization along railway can decrease both the total travel distance and the car's share in case of access below 2.0 km. In the contrary, decentralization, in case of access over 2.0 km, brings an increase in the total travel distance of car commutes despite a decrease in car's share. This suggests a certain reduction in transportation energy by far residential decentralization along railway if it is designed within certain access to a railway station.

It is not clear yet whether residential centralization by moving the peak position leftwards to the reference reduces energy for commutes or not, because it increases car commute density through increasing car's share despite a likely reduction in the total travel distance of car commutes. An increase in car commuts density brings a rapid increase in energy use (Figure 10) due to the slowing down. But a reduction in car travel distance saves energy in itself. The problem, therefore, in residential centralization is to find a balance of energy depending on an increase in car's share and a decrease in the total car travel distance, however it is not easy at present. For that reason only rightward moving of the peak position is dealt with in this paper.

CONCLUDING REMARKS

Per capita daily energy for urban transportation is expressed by a nearly linearly decreasing function with respect to population. The function is expressed by the sum of four modal expressions : passenger car, commercial vehicle, bus and railway. The expression for passenger cars, which include some commercial vehicles converted for personal trips, has average travel speed and population as parameters, that for commercial vehicles also includes the same parameters, that for bus travel, speed alone and that for railway, population alone. The first two decrease linearly with population but not linearly with average travel speed. These two include population so as to describe mode choice and commercial vehicle ownership, respectively. Due to data not being available for general relation between average travel speed and population, the figures are drawn for assumed constant travel speed. This presents a problem for further study.

Residential decentralization along railway has some possibility to save energy for commuting to and around the midtown area of the central city through cutting down the passenger car's share. That is like some of the Japanese residential towns which, for merits or demerits, have been developed in some long distance from the central cities. Public transport system of high-level service is provided between these towns and the large central cities but not so in many other cities. Some renewal of existing railway system is one of the prerequisites to residential decentralization in those cities.

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