ESTIMATING THE AMOUNT OF ADDITIONAL MASS TRANSIT NEEDED TO REDUCE CO$_2$ EMISSIONS FROM REGIONAL PASSENGER TRANSPORT IN JAPAN

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ABSTRACT

The study assumes the introduction of low CO_2 emission transit such as on trunk lines to reduce CO_2 emissions from regional passenger transport and aims to estimate the required scale.

First, a local transport region in Japan is defined as the unit of analysis in which most common transport is completed. In each region, the target of CO_2 emissions from local passenger transport in 2050 is set to 20% of that in 2000. The amount of CO_2 exhausted from local passenger transport could be estimated on the basis of technological innovations; thus, the amount of reduction needed to achieve the target can be estimated.

Second, the change in CO_2 emissions resulting from the introduction of a mass transit system is evaluated, including reduction by replacing private vehicles and the emissions arising from construction and operation of the mass transit system. For this purpose, life cycle assessment is applied. The transit density of each route is estimated from the population density in the densely inhabited district of each local transport region, allowing the transit system that emits the least CO_2 per passenger-km to be selected. In addition, the extent of new service and the associated CO_2 emission reduction are calculated.

A series of calculations yields the lengths of additional mass transit routes required to reduce traffic volume sufficiently to achieve the CO_2 reduction target for local passenger transport by 2050.

Keywords: environmentally sustainable transport (EST), backcasting, life cycle assessment, low-carbon transport system

INTRODUCTION

According to the IPCC[1], carbon dioxide emissions must be reduced to half by 2050 relative to 1990 levels to avoid the impact of climate change on ecosystems. Developed countries have already emitted considerable CO_2; therefore, they are forced to reduce by more than half. To avoid disrupting economic development in developing countries, high-emitting developed countries have a duty to reduce CO_2 emission by more than 50%.

During the late 1990s, the environmentally sustainable transport (EST) project of the OECD[2] recommended transport system revision, since the burden on developed countries of reducing emissions in the transport sector to the target level could not be achieved only by technical innovation. The EST project began in Japan[3] in 2004, focusing on the transport system and a subsidized progressive approach adopted by the local government. However, the reduction policy for 2050 is not defined, since it targets only the Kyoto Protocol goals. However, the EST project has established its value, as demonstrated by the fact that long-term reduction targets became an important policy issue after the Hokkaido Toyako Summit. After the discussion of the G8 summit in Toyako, Hokkaido, the creation of low-carbon society aiming at long-term CO_2 reduction became an important policy issue. In this context, EST can play important role.

In this paper, we calculate the extent of change in transport policies in each region that needs to reduce CO_2 by 80% of the 2000 level by 2050. In the transport sector, use of private vehicles that emit considerable CO_2 per passenger-km must be reduced. The most efficient measure is expected to be the introduction of mass transit systems, such as railways or bus systems, since CO_2 emission per capita can be reduced when each vehicle has multiple passengers. As described above, this study suggests a method for estimating the requisite level of mass transit. In addition, the LCA method is applied to include CO_2 emission due to infrastructure construction for the newly developed mass transit.

PERSPECTIVE OF THIS STUDY AND PREVIOUS RESEARCH

To shape the measures needed to realize EST, it is necessary to forecast future CO_2 emissions and understand the effect of measures to reduce them. To forecast CO_2 emissions, this study employs estimation models using macro indices, since the subject of analysis is local transport regions all over Japan. Some existing studies have analyzed CO_2 emissions by passenger transport in Japan using this approach as follows.

From road traffic census data, Matsuhashi et al.[4] estimated the amount of passenger vehicle travel in terms of CO_2 emissions. They showed that a large-scale difference in estimated value appeared, depending on the methodology used to estimate and aggregate the amount of CO_2 emissions. Kudo et al.[5] built upon this study and proposed an advanced methodology for describing the amount of CO_2 emitted by passenger rail travel for each municipality. Morita et al.[6] represented the number of private vehicles and average mileage per vehicle by models using macro indices in each municipality and calculated the amount of CO_2 emissions.

Nakamura et al.[7] estimated the amount of CO_2 emissions from the transport sector in each municipality and revealed the extent of measures needed to achieve the CO_2 reduction target using a backcasting approach. They demonstrated the difficulty of achieving the target by a single measure and the need to combine measures. Kuriyama et al.[8] analyzed the factor disturbing approaches for realizing EST and showed that a comprehensive approach is needed, since measures are interrelated. Matsuhashi et al.[9] demonstrated the role of urban planning in achieving a low-carbon society and However, the scale of measures for realizing EST has not yet been determined.

FRAMEWORK FOR ANALYSIS

Procedure for studying EST measures

Measures to realize EST can be divided into two categories: improving technology to reduce CO_2 emissions from vehicular travel and changing transport activities.

This study focuses on regional passenger transport and estimates the extent of measures needed for each region to achieve the CO_2 reduction target. Technological measures are given as an exogenous scenario.

The centerpiece of such transport measures is the introduction of mass transit with lower emissions in each region's trunk lines to shift the transport mode from private vehicles to mass transit. The reason is that track-based mass transit generally emits less CO_2 per passenger than personal vehicles. However, when the transport demand is small, the emissions per passenger could be higher than that of passenger vehicles. In fact, mass transit requires high transport density to retain the advantage of CO_2 emission reduction. To meet this condition, high population density and a large concentration of population along the railway is necessary.

We[10] analyzed the relationship between indices that reflect the characteristics of every region of Japan and the transport density from data for existing railways. The relationship between transport and population densities in the densely inhabited district (DID) is most significant. In addition, we developed a method for estimating the reduction in CO_2 emissions caused by the introduction of additional mass transit. The transit mode that emits the least CO_2 is selected considering profitability and maximum transport capacity. This study develops and applies the method.

First, the amount of CO_2 emissions from passenger transport in 2050 is estimated, including predicted improvements in vehicle and fuel technologies. The emission target in 2050 is set as 20% of that in 2000, and the difference between the target and the predicted value is determined. Second, the feasible transit mode and extent of installation that emits the least CO_2 is selected for trunk lines in each region to achieve the reduction target. The analytical framework is shown in Figure 1.
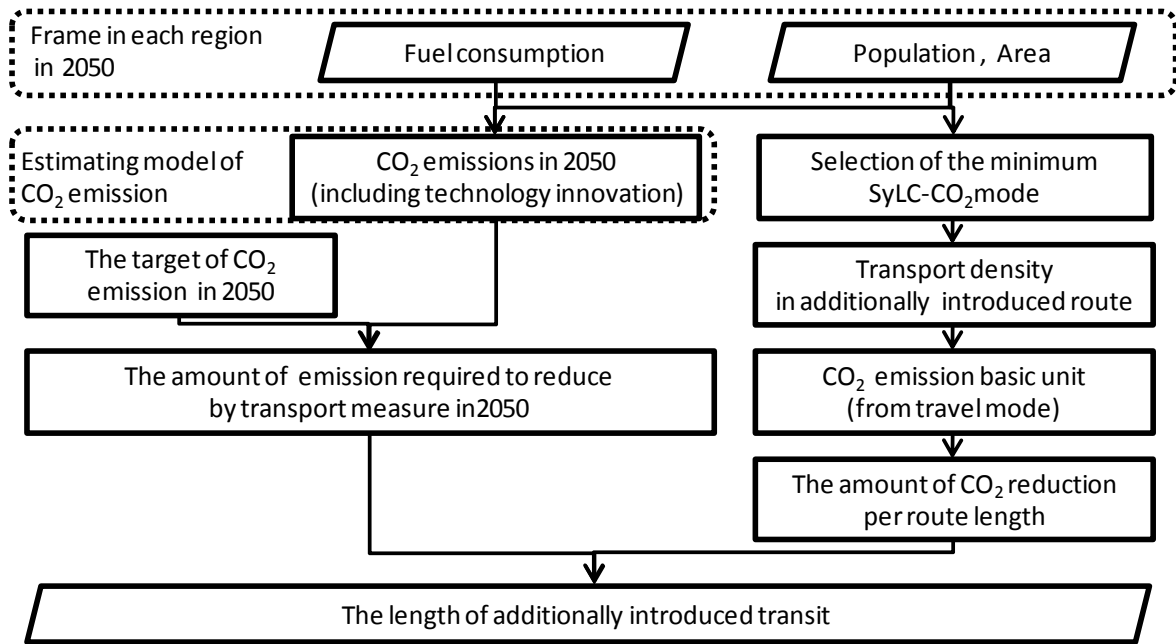
Figure 1 – Analytical framework

Definition of the local transport region as the special unit of analysis

The structure of regional transport systems is larger than the municipal scale. This study uses the definition of Kawashima[11], which focused on commuting trips, to classify all the municipalities of Japan, which are defined as local transport regions. They are composed of core cities and edge cities, as defined in Table 1. Eighty-five regions are set throughout Japan. Rural areas do not belong to any local transport region. This study excludes these areas, since the introduction of mass transit has only a small effect.

Table1 – Basis of local transport regions

Core city (C)	a) Over hundred thousand and daytime population/night-time population $\geq$ municipality of 1.00 b) Municipality within 20 km bring together
Edge city (E)	a) Municipality of commuter to core city over five hundred b) Municipality to core city (commuter)/(resident commuter) > 0.05 c) Municipality involved in urban area over 2 comprehend larger urban area of commuter to core city
Rural area (R)	City that contain no core city and edge city

CALCULATION OF CO$_2$ REDUCTION REQUIRED FROM PASSENGER TRANSPORT

Method of estimating the amount of CO$_2$ emission in 2000

First, the amount of CO$_2$ emission in 2000 is estimated to set the target in 2050. Private vehicles, buses, and railways are included in the estimation as regional passenger transport. The amount of CO$_2$ emissions is estimated at the municipality level in 2000 and aggregated in the local traffic regions. The method of estimation for each transit mode is described below.

Private Vehicles and Buses

Passenger cars and minivans are treated as private vehicles. The amount of CO$_2$ emissions is derived by the travel distance of each type of vehicle multiplied by the CO$_2$ emission factor (eq.1).

$$E = \left(\sum_k L_k^{weekday} + \sum_k L_k^{holiday} \right) \cdot e_k \quad (1)$$

E: Amount of CO$_2$ emission, L_k: travel distance, e_k: CO$_2$ emission factor, k: vehicle type

This study aggregates origin and destination data from road traffic censuses as distance data for the municipality where a vehicle is registered. No survey was conducted in 2000, so data from a 1999 survey are used for this estimation. Matsuhashi et al.[4] calculated the emission factor for each type of vehicle by multiplying the fuel consumption by an emission factor weighted by the fuel composition. The result is listed in Table 2. This study applies these values of the emission factor.

Table 2 – CO$_2$ emission factors

Vehicle type	CO$_2$ emission factor [g-CO$_2$/vehicle-km]
Minivan	219
Passenger car	292
Bus	756

Railways

The emission from railway services is estimated using the annual statistics of the Japanese Railway Company in 2000[12]. The amount of electricity and fuel consumed by each company is distributed to each route by the passenger-km transported. Next, the distributed electricity and fuel consumption for the routes is multiplied by the CO$_2$ emission factor for

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each energy type[13]. The amount of CO_2 emissions estimated for each route is distributed to municipalities according to the number of stations within the municipality.

The total amount of CO_2 emissions estimated by the above methods is defined as the amount of CO_2 emissions from passenger transport and is shown in Figure 2.

(1) Total emission   (2) Emission per capita
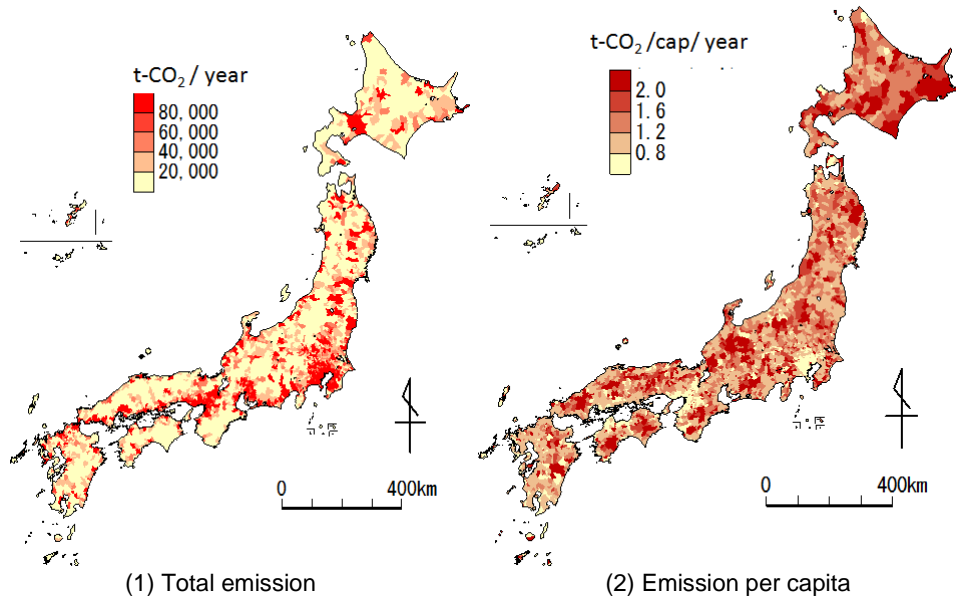
Figure 2 – CO_2 emission from each municipality in 2000

Municipally aggregated CO_2 emissions are high in major cities such as Tokyo or Osaka, although it would be high in the countryside when aggregated in per capita units. The main reason for this is that passenger transport depends mainly on public transport in metropolitan areas and on private vehicles in the countryside.

Establishment of future CO_2 emission estimation model

Private vehicles

Models are established to estimate the number of vehicles and the travel distance per vehicle, because private vehicles affect CO_2 emissions considerably. These models are applied to estimate the amount of CO_2 emission in 2050.
<Private vehicle ownership model>

1. Core city (C)

The model is expressed as a Cobb and Douglass function, as shown in eq.2.

$$y_{c_i} = \exp(\alpha_0) \cdot D_{dC_i}{}^{\alpha_1} \cdot A_{C_i}{}^{\alpha_2} \cdot R_{C_i}{}^{\alpha_3} \cdot \exp(\alpha_4 \cdot d_s) \tag{2}$$

i: Local transport region, C: core city, y: number of private vehicles per household, D_d: population density in DID, A: number of people from 15 to 64 years old, R: road length per capita, d_s: dummy variable of railway station, $\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4$: parameters

The parameters of eq.2, estimated from municipality data in 2000, are shown in Table 3.

Table 3 – Results of regression analysis in eq.2

Variables	α	t	R^2	n
Const.	1.71	6.97		
D_{dci}	−0.230	−6.67		
A_{ci}	1.01	92.2	0.987	265
R_{ci}	0.0805	4.10		
D_s	0.0605	2.19		

α : Partial regression coefficient, t: t value, R^2: adjusted R square, n: sample number

2. Edge city (E)

In an edge city, the number of private vehicles is estimated as the number of private vehicles in the core city multiplied by an adjusting function g to include the influence of the core city.

$$y_{S_i} = y_{S_i} \cdot g \tag{3}$$

$$g = \exp(\beta_0) \cdot D_r{}^{\beta_1} \cdot \left(\frac{R}{R_{C_i}}\right)^{\beta_2} \cdot A^{\beta_3} \tag{4}$$

g: Adjusting function, D_r: population density in inhabitable area, R: road length per capita, R_{ci}: road length per capita in core city, $\beta_0, \beta_1, \beta_2, \beta_3$: parameters

The parameters of eq.4, estimated by municipality data in 2000, are shown in Table 4.

Table 4 – Results of regression analysis in eq.4

Variables	β	t	R^2	n
Const.	−3.87	−14.4		
D_r	0.0722	10.3		
R / R_{ci}	0.144	18.9	0.586	1,827
A_{ci}	0.807	11.1		

β : Partial regression coefficient, t: t value, R^2: adjusted R square, n: sample number

3. Rural area (R)

Vehicle ownership is fixed at the value in 2000, since ownership is saturated.

<Travel distance model>
The model is expressed as a Cobb and Douglass function, like the model estimating the number of private vehicles. The model is shown in eq.5.

$$L = \gamma_0 \cdot D_r^{\gamma_1} \cdot S_t^{\gamma_2} \tag{5}$$

S_t: Number of stations per inhabitable area, $\gamma_0, \gamma_1, \gamma_2$: parameters

Travel distance per vehicle estimated from data at the municipality level has no clear trend. This study uses the model established from the data at the prefecture level. The parameters of travel distance are shown in Table 5.

Table 5 – Results of regression analysis in eq.5

Variables	γ	t	R^2	n
Const.	10.6	33.0		
D_r	−0.198	−6.03	0.622	47
S_t	0.068	2.33		

γ: Partial regression coefficient, t: t value, R^2: adjusted R square,
n: sample number

Buses and Railways

The relationship between operation distance and passenger demand is not proportional. In addition, the service level in 2000 is assumed to be maintained, and the model is not assumed, since it becomes the subject of later analysis.

Vehicle and fuel technology scenario

Constant and improved scenarios for vehicle and fuel technologies are considered. The emission factors of the transit mode are set for both scenarios.

Constant scenario

The types of fuels and vehicles in 2050 are the same as in 2000.

Improved scenario

Diffusion of low-emission vehicles is assumed. Based on "Long Term Energy Vision 2100,"[14)] this study assumes that hybrid vehicles (HVs) and electric vehicles (EVs) are widely

used. The CO_2 emissions from each type of vehicle is divided into the CO_2 emissions resulting from production and supply of fuel and energy for the vehicle (well-to-tank, WtT) and the CO_2 emissions resulting from operation (tank-to-wheel, TtW). The rate of efficiency improvement is set for both the WtT and TtW processes.

Improving the efficiency of WtT processes also influences the CO_2 emissions from railway operation (which uses electrical power). CO_2 emissions from vehicle production and construction of infrastructure remain constant at 2000 values. Table 6 lists the value of energy efficiency in both processes in 2000 and 2050. The CO_2 emission factor is assumed to be constant, although it would worsen in high-DID population areas because of traffic congestion and operational conditions. HVs and EVs emit less CO_2 during congestion, thus the problems arising from this assumption is minimized.

Table 6 – Setting of diffusion rate and CO_2 emission factor in improved scenario [15)-17)]

	Vehicle type/Section	CO_2 emission factor from vehicle travel [g-CO_2/vehicle-km]	Diffusion rate	Fuel reduction rate from 2000
Private vehicle	Hybrid vehicle	114	60%	33.2%
	Electric vehicle	55.5	40%	70.6%
Bus	Hybrid vehicle	647	100%	14.3%
Railway	Electrified section	-	-	10%
	Non-electrified section	-	-	30%

CO_2 emissions estimation in 2050

Population in each municipality in 2050 is estimated by a cohort model that assumes that birth rate, survival rate, and net migration rate will be constant at present conditions. The size of the inhabitable area increases proportionally with increasing population and would remain unchanged with decreasing population. Road length is set to be proportional to the inhabitable area. The amount of emissions with the above assumptions is shown in Table 7.

Table 7 – Results of travel distance by passenger vehicles and
the amount of CO_2 emissions from passenger transport

	2000	2050 a) Constant scenario	2050 b) Improved scenario
Total travel distance by private vehicle [km]	3.84×10^{11}	2.83×10^{11}	2.83×10^{11}
Travel distance per private vehicle [km/vehicle]	7,260	7,760	7,760
CO_2 emission from passenger transport [Mt-CO_2/year]	1.33×10^8	1.06×10^8	0.433×10^8
CO_2 emission from passenger transport per capita [t-CO_2/capita/year]	1.05	1.07	0.436

Constant scenario

The number of private vehicles would decrease in accordance with the decline in total population (21.8%). At the same time, travel distance per vehicle would increase, since population density would drop. The amount of CO_2 emission becomes 9% lower than that in 2000 in Japan. The emission per capita increases by about 16% from that of 2000.

Improved scenario

The amount decreases by about 65% from that of 2000. On a per capita basis, it decreases by about 56% from 2000. The scenario shows a larger reduction rate than the fixed scenario. It is necessary to implement transport measures, since the target value is not achieved.

SELECTION OF MASS TRANSIT AND ESTIMATION OF INSTALLATION SCALE

Selection of mass transit mode

When mass transit is introduced, additional CO_2 would be emitted. Thus, the total amount of CO_2 emissions from infrastructure construction and vehicle production and operation, called system life cycle CO_2 (SyLC-CO_2) in this study, is calculated. If mass transit has a low passenger density with dedicated infrastructure, the emissions due to construction could become larger than those from vehicular travel.

In an earlier study, we[18] showed the relationship between the amount of SyLC-CO_2 per passenger-km of a medium-sized transit mode and the associated transport demand. The study showed that the transit mode that emits the least SyLC-CO_2 changes from bus rapid transit (BRT) to light rail transit (LRT) and heavy rail with increasing transit density. In this study, the mass transit systems noted above are compared with private vehicles, and the
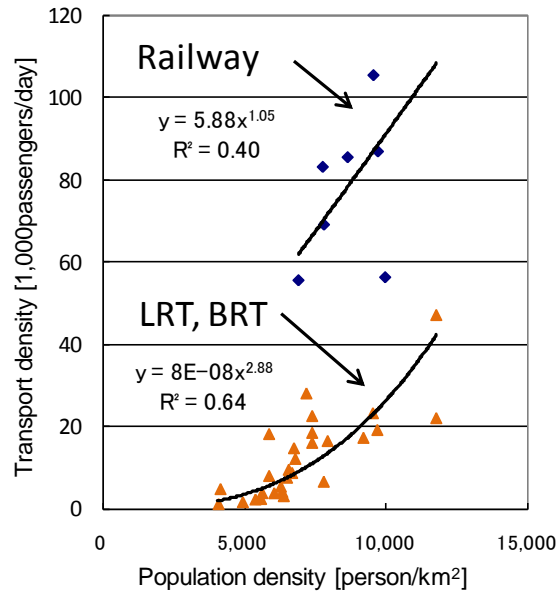
lowest SyLC-CO_2 emission mode is chosen. Figure 3 shows the relationship between transit density and the SyLC-CO_2 of each transit mode in 2000 and in 2050.

When transport density increases, the amount of SyLC-CO_2 emission decreases, since the CO_2 emission allocated to passenger-km other than vehicular travel decreases.

For transport density up to 5,500 passengers per day, BRT emits the smallest amount of SyLC-CO_2 because the amount of CO_2 emission from infrastructure construction is smallest of all the modes. For greater transport density, LRT becomes a minimal SyLC-CO_2 mode, because the amount of CO_2 emission from operation is small.

(1) In 2000   (2) In 2050

Figure 3 – Transport density and SyLC-CO_2 of each transit mode

The effect on reducing CO_2 emissions of changing regional transport systems by introducing mass transit must be considered. Although in this study, we do not model the mechanism, it is supposed that passengers simply change their transit mode from private vehicles to mass transit. Thus, the amount of CO_2 reduction from private vehicles takes the value of transport density multiplied by the length of the mass transit routes. Eq.6 shows this relationship.

$$\Delta L = D \cdot l \qquad (6)$$

D: transport density [person/day], *l*: length of mass transit routes

Our previous study[10] on public transit (subway, LRT, automated guideway transit, and monorail) analyzed the relationship between actual values such as scheduled speed, transport density, and regional characteristics. The result showed a strong correlation with the transport density and population density in the DID in the core city of the region.

Figure 4 shows the relationship between DID population density and the density of existing transit routes (railway, LRT, BRT). This relationship is applied to core cities in local transport regions and indicates a feasible transit mode with the lowest SyLC-CO_2 emissions.

Figure 4 – Population density and transport density

The relationship between DID population density in core cities and SyLC-CO$_2$ from newly introduced transit modes is determined using the relationship between SyLC-CO$_2$ and transit density from each transit mode shown in Figure 3.

Figure 5 shows that SyLC-CO$_2$ emission per passenger-km from railways decreases more than that from LRT or BRT because the transit density of each mode is estimated by a different relational expression, as shown in Figure 4.

In 2000, the transit mode that emitted the lowest SyLC-CO$_2$ was private vehicles when the transit density is less than 2,700 passengers per day, BRT between 2,700 and 5,500, LRT above 5,500, and railway above 7,000. In 2050, private vehicles are the lowest when the transit density is less than 4,400 passengers per day, BRT between 4,400 and 5,600, LRT above 5,600, and railway above 7,000, because improvement in the emission factor associated with operation is considered.

This indicates that in 2050, private vehicles become the lowest SyLC-CO$_2$-emission mode at higher transit densities because of the large-scale diffusion of EVs.
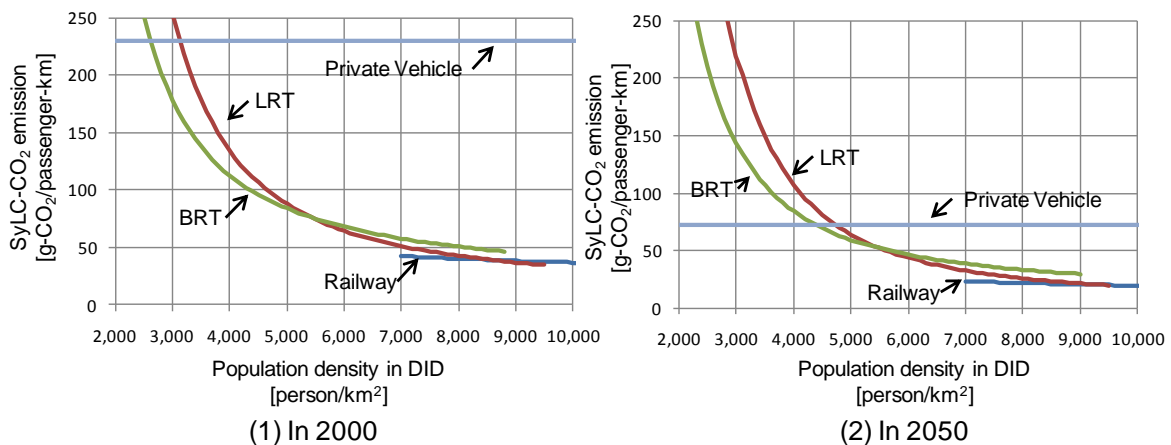

(1) In 2000   (2) In 2050

Figure 5 – Relationship between population density and SyLC-CO$_2$ for each transit mode

Following the above analysis, Figure 6 shows the transit modes selected as having the lowest SyLC-CO_2 emissions for each local transport region in Japan.

The introduction of mass transit cannot reduce CO_2 in regions where private vehicles are selected. Therefore, if the traffic demand does not change, improvement will rely solely on technological innovation. In other words, without limiting local transport activities, reduction targets cannot be achieved by technical measures alone. To prevent this situation, it is necessary to increase population density sufficiently to allow mass transit systems to reduce CO_2 emission.
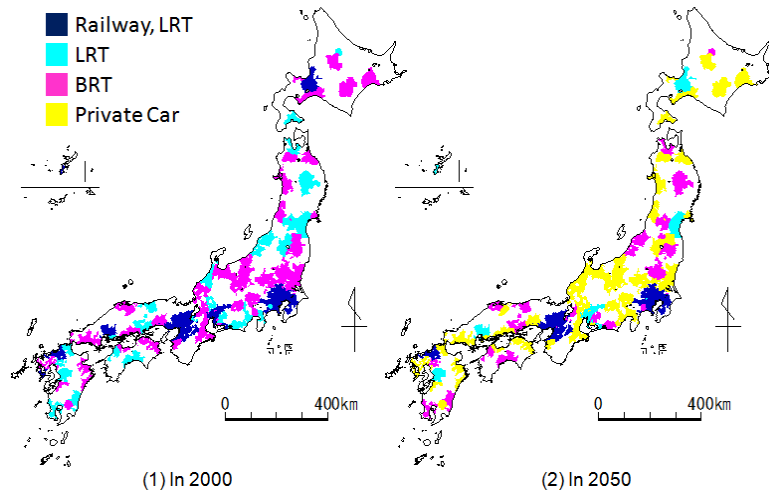
Figure 6 – Minimum SyLC-CO_2 transit modes in local transport regions in 2050

Determining the length of introduced mass transit routes

The amount of CO_2 reduction resulting from users switching from private vehicles to mass transit is calculated as the number of passengers multiplied by the amount of CO_2 reduction per passenger-km (eq.7).

$$\Delta E = \left(e_{PV} - e_{MT} \right) \cdot \Delta L \tag{7}$$

e_{PV}: CO_2 emissions per passenger-km (private vehicle), e_{MT}: CO_2 emissions per passenger-km (mass transit)

The length of newly constructed routes required to achieve the reduction target is calculated from eqs.6 and 7.

$$I = \frac{\Delta E}{D \cdot \left(e_{PV} - e_{MT} \right)} \tag{8}$$

Figure 7 shows the estimated route length in the region where an LRT system is selected. Route length in each local transport region has no typical trend because it is influenced by the amount of CO_2 emission reduction required or by population density in the region. However, many transport regions are located in metropolitan areas, which suggests that the introduction of mass transit should be emphasized in these areas.
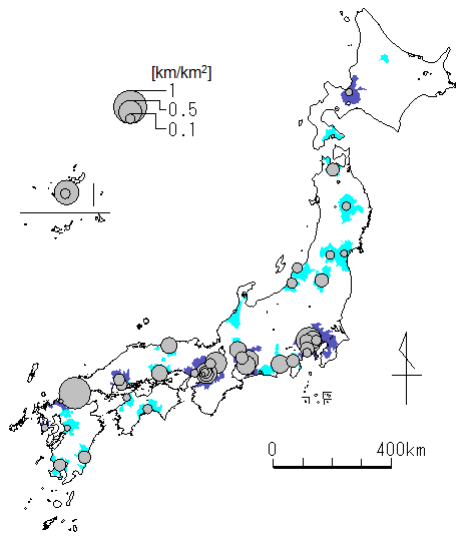
Figure 7 – Length of introduced routes for each region per inhabitable area

CONCLUSIONS

In this study, a method for determining the length of newly introduced mass transit routes for each local transport region is established, assuming the goal of reducing CO_2 emissions by 80% of the 2000 level by 2050. The suitable mass transit mode and route length are determined using the method. The main results of this paper are as follows.

1) The total CO_2 emissions in Japan will decrease by 30% compared with 2000 by 2050, because of population decline and technological innovations related to vehicles and fuels. In some regions, the target reduction could be achieved only by technological innovation.

2) In 2050, private vehicles are selected as the transit mode that emits the lowest SyLC-CO_2 in some transport regions. In these regions, it is impossible to reduce CO_2 emissions from passenger transport by introducing mass transit.

The following problems remain to be addressed.

1) In this study, a target of an 80% reduction in CO_2 emissions is imposed uniformly in every local transport region. It is not clear whether the target is fair, since the rate of population decline is not uniform in each region.

2) This study assumes a constant future private vehicle ownership rate in rural area and does not consider the possibility of future ownership rate increases in the elderly.

3) A backcasting approach evaluates the number of combined measures needed to achieve reduction targets. Transport measures other than the introduction of mass transit should be considered as options.

ACKNOWLEDGEMENT

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