Estimating Additional Mass Transit Needed to Reduce Carbon Dioxide Emissions from Regional Passenger Transport in Japan

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This study aims to estimate the necessary scale of additional mass transit on trunk lines to reduce carbon dioxide (CO_2) emissions from regional passenger transport in Japan. First, a local transport region is defined as an area within which most daily transport is conducted. In each region, the target of CO_2 emissions from local passenger transport activities in 2050 is set to 20% of those emissions in 2000. The amount of CO_2 exhaust from local passenger transport can be estimated on the basis of technological innovation; thus, the amount of reduction needed to achieve the target can be calculated. Second, changes in CO_2 emissions from the introduction of a mass transit system are evaluated, considering their reduction from replacing private vehicles and the emissions from constructing and operating the mass transit system. For this purpose, life-cycle assessment is applied. The total amount of CO_2 emissions from infrastructure construction, vehicle production, and operation from mass transit is calculated. The transport density of each route is estimated with population density in a densely inhabited district of each local transport region. The transit system that emits the least CO_2 per passenger kilometer is selected. The extent of new services needed to achieve the CO_2 reduction target is calculated. A series of calculations provides the lengths of additional mass transit routes required to reduce traffic volumes sufficiently to achieve the CO_2 reduction target for local passenger transport by 2050.

The Intergovernmental Panel on Climate Change states that carbon dioxide (CO_2) emissions must be reduced 50% by 2050 relative to 1990 levels to avoid the impact of climate change on ecosystems (*1*). 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 emissions by more than 50%.

During the late 1990s, the Environmentally Sustainable Transport (EST) project of the Organisation for Economic Co-operation and Development (*2*) recommended transport system revision, because the burden on developed countries of reducing emissions in the transport sector to the target level could not be achieved by technical innovation alone. The EST project began in Japan in 2004, but the reduction policy for 2050 is not defined as it targets only the goals of the Kyoto Protocol. However, the EST project has established its value, as demonstrated by the fact that setting long-term reduction targets became an important policy issue after the Hokkaido Toyako Summit. After the discussion at the G8 summit in Toyako, Hokkaido, Japan, creation of a low-carbon society aiming at long-term CO_2 reduction became an important policy issue. In this context, EST can play an important role.

The Ministry of the Environment in Japan established the vision of reducing greenhouse gas emissions by 80% by 2050. To achieve this target, it is necessary to reduce CO_2 emissions, which make up more than 90% of greenhouse gas emissions. This paper calculates the extent of changes in transport policies in each region needed to reduce CO_2 by 80% of the 2000 level by 2050. In the transport sector, use of private vehicles, which emit considerable CO_2 per passenger kilometer, must be reduced. The most efficient measure for reducing CO_2 emissions per capita is expected to be mass transit systems, such as railways and bus systems, as each vehicle carries more passengers than private vehicles. This study proposes a method for estimating the requisite level of mass transit. In addition, the life-cycle assessment method is applied to include CO_2 emissions from infrastructure construction for the newly developed mass transit.

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 transport demand is small, the emissions per passenger could be higher than for passenger vehicles. Mass transit requires a high 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.

The relationship between indices that reflect the characteristics of every region of Japan and the transport density from data for existing railways was analyzed (*3*). The relationship between transport

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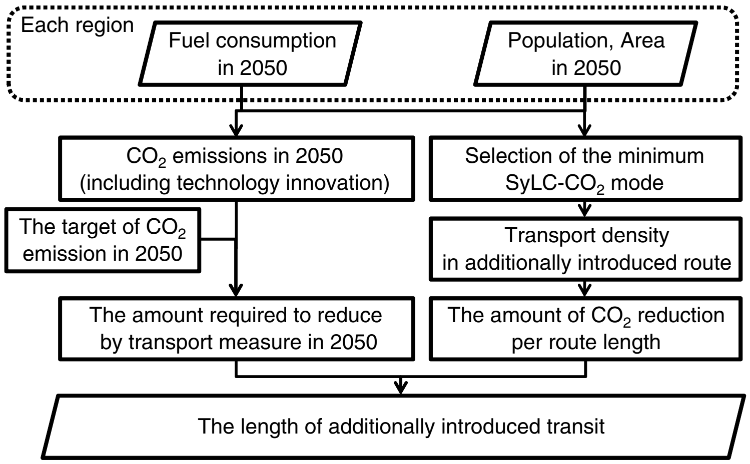

FIGURE 1 Analytical framework.

and population densities in the densely inhabited district (DID) is most significant. In addition, a method was developed 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, taking profitability and maximum transport capacity into consideration. This study develops and applies that 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.

Definition of Local Transport Region as the Spatial Unit of Analysis

The structure of regional transport systems is larger than the municipal scale. This study uses the definition of Kawashima et al., which focused on commuting trips, to classify all the municipalities of Japan, which are defined as local transport regions (*4*). They are composed of core cities and edge cities, as defined in Table 1. Eighty-five regions are set throughout Japan. This study excludes rural areas, which do not belong to any local transport region, as the introduction of mass transit has only a small effect.

TABLE 1 Basis of Local Transport Regions

Core city	Municipal population greater than 100,000, and ratio of daytime population to nighttime population ≥ 1.00 Or municipality within 20 km of core city
Edge city	Municipality where there are more than 500 commuters to core city Or municipality where (commuter to core city)/(resident commuter) > 0.05 Or municipality belongs to urban area from which the core city attracts the most commuters
Rural area	Area with no core cities and no edge cities

CALCULATION OF CO_2 REDUCTION REQUIRED FROM PASSENGER TRANSPORT

Method of Estimating Amount of CO_2 Emissions in 2000

First, the amount of CO_2 emissions in 2000 is estimated to set the target for 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 from the travel distance of each type of vehicle multiplied by the CO_2 emission factor (Equation 1):

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

where

E = amount of CO_2 emissions,
L_k = travel distance,
e_k = CO_2 emission factor, and
k = vehicle type.

This study counts travel distances of private vehicles in the municipalities where the vehicles are registered. Origin and destination data from road traffic censuses in Japan are used for counting. The survey was not conducted in 2000, so data from a 1999 survey are used for this estimation. The data for travel distance of private vehicles in the survey are counted separately for weekdays and holidays.

Matsuhashi et al. calculated the emission factor for each type of vehicle by multiplying the fuel consumption by an emission factor weighted by the fuel composition (*5*). The study mentions that minivans emit 219 g of CO_2 per vehicle kilometer, passenger cars emit 292 g of CO_2 per vehicle kilometer, and buses emit 756 g of CO_2 per

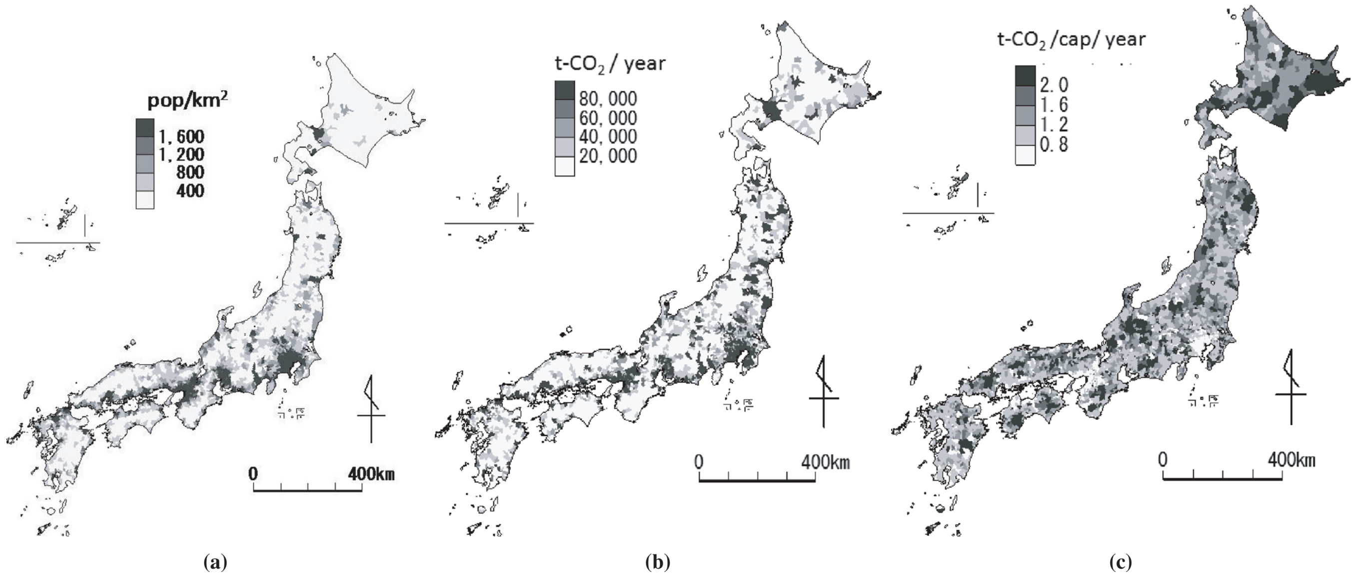

FIGURE 2 CO_2 emissions from each municipality in 2000: (*a*) population density, (*b*) total emissions, and (*c*) emissions per capita.

vehicle kilometer. This study applies those values for the emission factors.

Railways

Emissions from railway services are estimated by using the annual statistics of the Japanese Railway Company in 2000 (*6*). The amount of electricity and fuel consumed by each company is distributed to each route according to passenger kilometers transported. Next, the distributed electricity and fuel consumption for the routes is multiplied by the CO_2 emission factor for each energy type (*7*). The amount of CO_2 emissions estimated for each route is distributed to municipalities according to the number of stations in 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.

Municipally aggregated CO_2 emissions are high in major cities such as Tokyo and Osaka, Japan, although emissions would be high in the countryside when aggregated in per capita units because 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 emissions in 2050.

Model of Ownership of Private Vehicle

The model for a core city is expressed as a Cobb and Douglass function, as shown in Equation 2:

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

where

i = local transport region,
C = core city,
y = number of private vehicles per household,
D_d = population density in DID,
A = number of people 15 to 64 years old,
R = road length per capita,
d_s = dummy variable of railway station, and
α_0, α_1, α_2, α_3, and α_4 = parameters.

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

The number of private vehicles in an edge city 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:

$$y_{s_i} = y_{s_i}\ g \qquad (3)$$

TABLE 2 Results of Regression Analysis in Equation 2

Variable	α	t
Constant	1.71	6.97
d_{dC_i}	–0.230	–6.67
A_{C_i}	1.01	92.2
R_{C_i}	0.0805	4.10
d_s	0.0605	2.19

NOTE: α = Partial regression coefficient; t = T-value; R^2: adjusted R square = .987; n-sample number = 265.

TABLE 3 Results of Regression Analysis in Equation 4

Variable	β	t
Constant	–3.87	–14.4
d_r	–0.0722	10.3
R/R_{c_i}	0.144	18.9
A_{c_i}	0.807	11.1

NOTE: $R^2 = .586$; $n = 1{,}827$.

TABLE 4 Results of Regression Analysis in Equation 5

Variable	γ	t
Constant	10.6	33.0
d_r	–0.198	–6.03
S_t	0.068	2.33

NOTE: $R^2 = .622$; $n = 47$.

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

where

D_r = population density in inhabitable area,
R_{c_i} = road length per capita in core city, and
β_0, β_1, β_2, and β_3 = parameters.

The parameters of Equation 4, estimated by municipality data in 2000, are shown in Table 3.

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

Model of Travel Distance

The model is expressed as a Cobb and Douglass function, like the model estimating the number of private vehicles. The model is shown in Equation 5:

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

where S_t is the number of stations per inhabitable area and γ_0, γ_1, and γ_2 are 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 4.

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, as it becomes the subject of later analysis.

CO_2 Emission Estimation in 2050

The 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 remains unchanged with decreasing population. Road length is set to be proportional to the inhabitable area. This calculation is obtained as a baseline for CO_2 emissions, and scenarios about technological innovation are applied to estimate CO_2 emissions in 2050. In the baseline, the types of fuels and vehicles in 2050 are the same as in 2000. Improvements in vehicles and fuel technologies and diffusion of low-emission vehicles are considered in the technology scenario, and emission factors of the transit mode are set. On the basis of the long-term energy vision for 2100, this study assumes that hybrid vehicles and electric vehicles will be widely used (*8*). The CO_2 emissions from each type of vehicle are divided into the CO_2 emissions resulting from the production and supply of fuel and energy for the vehicle (well to tank) and the CO_2 emissions resulting from operation (tank to wheel). The rate of efficiency improvement is set for both well-to-tank and tank-to-wheel processes. Improving the efficiency of well-to-tank processes also influences the CO_2 emissions from railway operations (which use electrical power). CO_2 emissions from vehicle production and construction of

TABLE 5 Setting of Diffusion Rate and CO_2 Emission Factor in Technology Scenario (*9–12*)

	Energy and Vehicle Type	In 2000	In 2050	Increase Rate (2050/2000)
Efficiency through well-to-tank process	Petroleum	88%	88%	1.0
	Electrical power	—	—	2.0
Efficiency through tank-to-wheel process	Gasoline cars Hybrid cars	16%	26%	1.6
	Electric cars	70%	95%	1.4
	Electric railway	84%	97%	1.2
Emission factors [g CO_2/vehicle km]	Minivan	2.2×10^2	1.4×10^2	1.6
	Passenger car	2.9×10^2	1.8×10^2	1.6
	Hybrid cars	1.1×10^2	7.0×10	1.6
	Electric cars	7.9×10	2.9×10	2.7
	Bus	1.1×10^3	6.9×10^2	1.6
	Electric railway	1.4×10^3	6.0×10^2	2.3

NOTE: — = no diffusion rate set.

TABLE 6 Results of Travel Distance by Passenger Vehicles and Amount of CO_2 Emissions from Passenger Transport

	2000	2050 Baseline	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 (metric tons-CO_2/year)	1.33×10^8	1.06×10^8	0.433×10^8
CO_2 emission from passenger transport per capita (metric tons-CO_2/capita/year)	1.05	1.07	0.436

infrastructure remain constant at 2000 values. Table 5 lists the value of energy efficiency in both processes in 2000 and 2050 and the emission factor of each vehicle (*9–12*). 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. Hybrid vehicles and electric vehicles emit less CO_2 during congestion; thus, the problems arising from this assumption are minimized. The amount of emissions is shown in Table 6.

In the baseline, the number of private vehicles would decrease in accordance with the decline in total population (21.8%). Travel distance per vehicle would increase, as population density would drop. The amount of CO_2 emissions becomes 9% lower than that in 2000 in Japan. Emissions per capita increase by about 16% from 2000 levels. In the improved scenario, the amount decreases by about 65% from that in 2000. On a per capita basis, it decreases by about 56% from 2000 levels. The scenario shows a larger reduction rate than the fixed scenario. It is necessary to implement transport measures, because 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 will be emitted. Thus, the total amount of CO_2 emissions from infrastructure construction, vehicle production, and operation—called system lifecycle 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.

An earlier study showed the relationship between the amount of SyLC-CO_2 per passenger kilometer of a medium-sized transit mode and the associated transport demand (*13*). 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 transport 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 transport density and the SyLC-CO_2 of each transit mode in 2000 and in 2050. The emission factor for each transit mode is shown in Table 5.

When transport density increases, the amount of SyLC-CO_2 emission decreases, as the CO_2 emissions allocated to passenger kilometers other than vehicular travel decrease. 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 emissions 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 emissions from operation is small. In 2000, the transit mode that emitted the lowest SyLC-CO_2 was private vehicles when transport density was less than 590 passengers per day; BRT when density was between 590 and 4,600 passengers per day; and LRT at more than 5,500 passengers per day. In 2050, private vehicles have the lowest SyLC-CO_2 when transport density is less than 2,400 passengers per day; BRT has the lowest SyLC-CO_2 when density is between 2,400 and 4,800 passengers per day; and LRT has the lowest SyLC-CO_2 when density exceeds 4,800 passengers per day, because improvement in the emission factor associated with operation is considered.

This study does not model the mechanism to change regional transport systems by introducing mass transit; it is assumed that passengers switch their transit mode from private vehicles to mass transit. Thus, the amount of switching of travel distance by private vehicles takes the value of transport density multiplied by the length of the mass transit routes. Equation 6 shows this relationship:

$$\Delta L = D \quad l \tag{6}$$

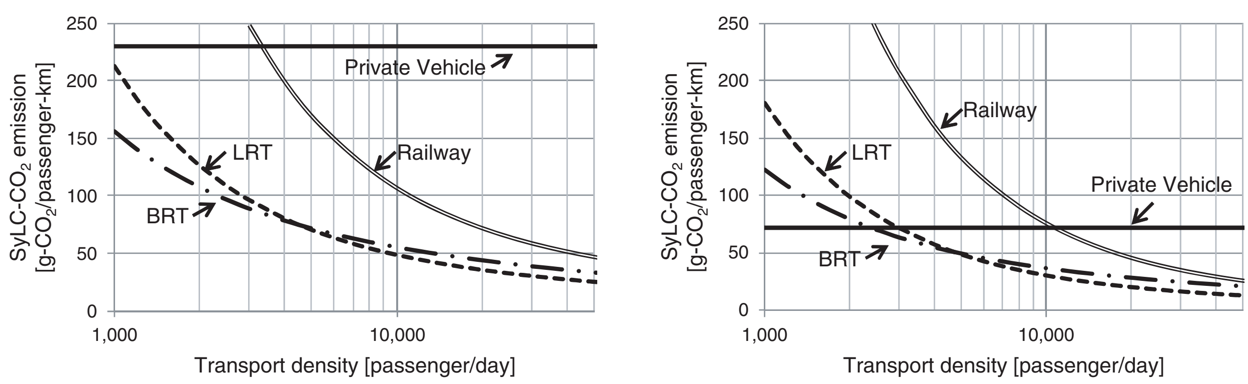

FIGURE 3 Transport density and SyLC-CO_2 of each transit mode in (*a*) 2000 and (*b*) 2050.

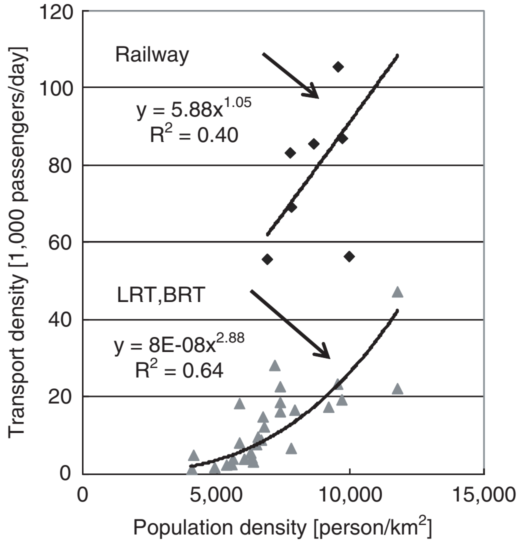

FIGURE 4 Population density and transport density.

where

ΔL = amount of travel distance switching from private vehicle to mass transit,
D = transport density (passengers per day), and
l = length of mass transit routes.

A previous study 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 (*3*). The results showed a strong correlation with 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.

The relationship between DID population density in core cities and SyLC-CO_2 from newly introduced transit modes is determined by using the relationship between SyLC-CO_2 and transport density from each transit mode shown in Figure 3.

Figure 5 shows that SyLC-CO_2 emissions per passenger kilometer from railways decrease more than those from LRT and BRT because the transport 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 transport density was less than 2,700 persons/km^2; BRT was lowest with density between 2,700 and 5,500 persons/km^2; LRT was lowest with density between 5,500 and 7,000 persons/km^2; and railway was lowest with density above 7,000 persons/km^2. In 2050, private vehicles have the lowest SyLC-CO_2 when transport density is less than 4,400 person/km^2; BRT is lowest with density between 4,400 and 5,600 persons/km^2; LRT is lowest with density between 5,600 and 7,000 persons/km^2; and railway is lowest with density above 7,000 persons/km^2, because improvement in the emission factor associated with operation is considered.

This information 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 electric vehicles.

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 number of regions where private cars are selected as the lowest SyLC-CO_2 emissions mode increases in 2050, because the estimated population makes the amount of SyLC-CO_2 emissions from mass transit much higher.

The introduction of mass transit cannot reduce CO_2 levels in regions where private vehicles are selected. Therefore, if traffic demand does not change, improvement will rely solely on technological innovation. In other words, without limiting local transport activities, target reductions 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.

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 kilometer (Equation 7):

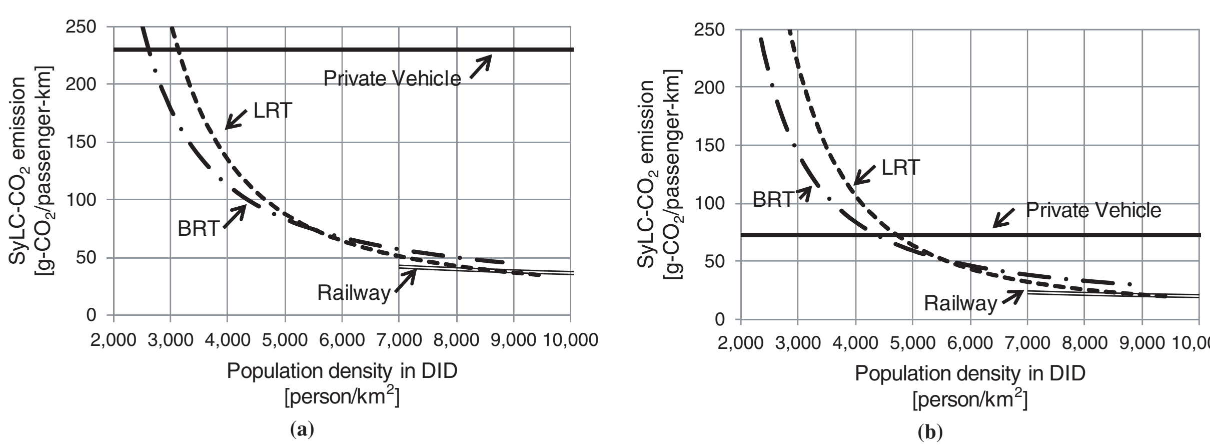

FIGURE 5 Relationship between population density and SyLC-CO_2 for each transit mode in (*a*) 2000 and (*b*) 2050.

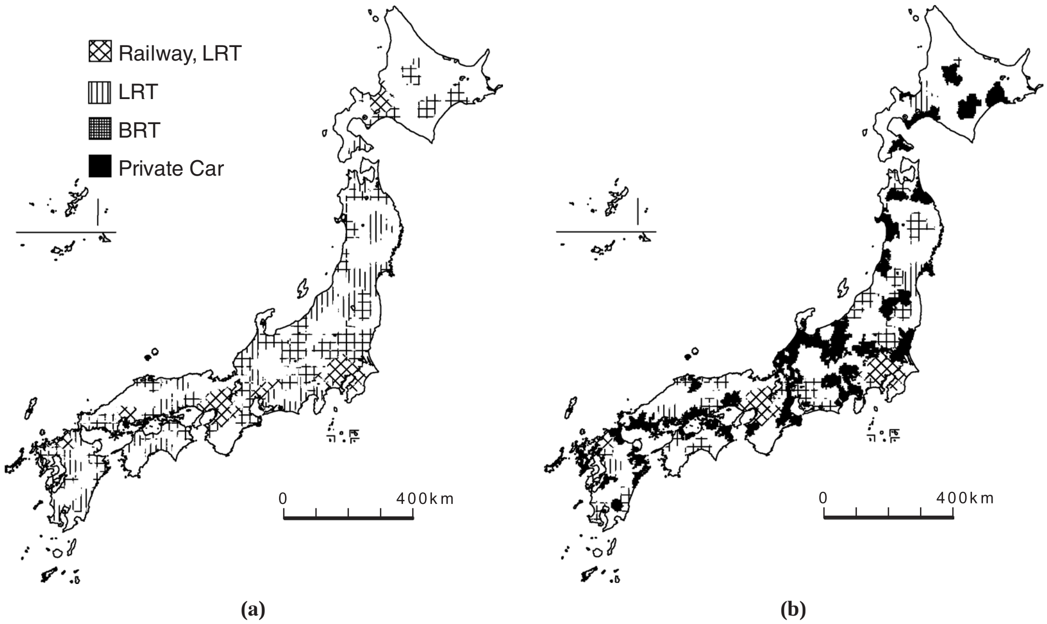

FIGURE 6 Minimum SyLC-CO_2 transit modes in local transport regions in (*a*) 2000 and (*b*) 2050.

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

where

e = CO_2 emissions per passenger kilometer,
PV = private vehicle, and
MT = mass transit.

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

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

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 route length 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.

CONCLUSIONS

In this study, a method for determining the required length of newly introduced mass transit routes for each local transport region is established to reduce CO_2 emissions by 80% of the 2000 level by 2050. The method is used to determine suitable mass transit modes and their lengths. The main results of this paper are as follows:

1. Total CO_2 emissions in Japan will decrease by 30% from 2000 to 2050 because of population decline and technological innovations related to vehicles and fuels. In some regions, the target reduction can be achieved only with technological innovations.

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, the target of an 80% reduction in CO_2 emission is imposed uniformly in every local transport region. It is not clear whether the target is fair, because the rate of population decline is not uniform in each region.

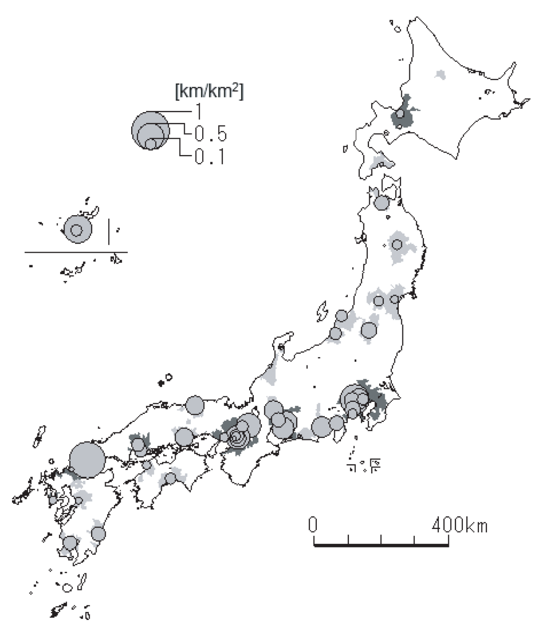

FIGURE 7 Length of introduced routes for each region per inhabitable area.

2. This study assumes a constant rate of future private vehicle ownership in rural areas and does not consider the possibility of increases due to an increase in the number of elderly people.

3. A backcasting approach evaluates a number of combined measures needed to achieve the reduction targets. (A backcasting approach draws up a target image and investigates for a roadmap or pathways satisfied to achieve it.) Transport measures other than the introduction of mass transit should be considered as options.

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