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IDENTIFYING MOST CARBON-EFFICIENT TRANSPORT SYSTEMS FOR CONURBATIONS IN ASIAN DEVELOPING COUNTRIES

I ITO, NAGOYA UNIVERSITY, K.ITO@URBAN.ENV.NAGOYA-U.AC.JP
KAZUKI NAKAMURA, NAGOYA UNIVERSITY, K.NAKA@URBAN.ENV.NAGOYA-U.AC.JP
HIROKAZU KATO, NAGOYA UNIVERSITY, KATO@GENV.NAGOYA-U.AC.JP
YOSHITSUGU HAYASHI, NAGOYA UNIVERSITY, YHAYASHI@GENV.NAGOYA-U.AC.JP

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Kei ITO, Nagoya University, k.ito@urban.env.nagoya-u.ac.jp

Kazuki NAKAMURA, Nagoya University, k.naka@urban.env.nagoya-u.ac.jp

Hirokazu KATO, Nagoya University, kato@genv.nagoya-u.ac.jp

Yoshitsugu HAYASHI, Nagoya University, yhayashi@genv.nagoya-u.ac.jp

ABSTRACT

To effectively develop low-carbon passenger transport systems in developing Asian countries' cities, we derive a scale of transport systems for individual urban areas applicable to their own targets to eliminate CO_2 emission, using the back-casting approach. To define differences in transport demand for mass transit systems due to regional feature differences, we analyze relationships between population density and demand for passenger railways. The effects of introduction of traffic infrastructure on population density underpinned the estimation of the demand for public transport systems. Chronological traffic data during Japan's motorization period formed the basis of parameter estimation, on the assumption that passenger transport in developing Asian countries will follow a similar course to Japan's. Models applied to various cities in Thailand produced applicable transport systems and their sizes on the basis of the 2050 CO_2 emission target.

Keywords: low-carbon transport, back-casting approach, mass transit, Asian developing countries

INTRODUCTION

The International Energy Association (IEA) (2011) reports that by 2050 it will become increasingly difficult to halve CO_2 emissions and maintain the average temperature increase below two degrees centigrade because of increasing global energy consumption. Among other issues, as the increase of energy consumption in developing Asian countries is predicted to occupy more than 50% of the world's total increase of energy consumption, emission control in these countries is becoming increasingly urgent. In developing Asian countries, in particular, the rapid rise of CO_2 emissions resulting from the increase in passenger cars and urban traffic jams are serious concerns.

As developing Asian countries must reduce CO_2 emissions drastically over an extended period, a forecasting approach cannot realistically predict the future by extending the current trend to identify counter-measures that will achieve the CO_2 emission target. Therefore, we use the back-casting approach that first establishes the future CO_2 emission target and then identifies several countermeasures necessary to achieve the target.

For a low-carbon passenger transport system in urban areas, it is considered effective to reduce the use of automobiles by guiding passengers to a mass transit system, which emits lesser CO_2. At present, developing Asian countries have treated symptoms rather than causes by constructing new roads to resolve urban area traffic jams, which in the long term will encourage the use of passenger cars, thus increasing CO_2 emissions, while mass transit infrastructure and service levels remain low. This situation suggests that introducing a mass transit system as trunk lines of a traffic network by forecasting the long-range future would be the framework for designing low-carbon transport systems in urban areas of developing Asian countries.

The transport systems introduced will include a highly detailed mass-transit railway system, bus rapid transit (BRT) designed to offer higher level of services on bus routes, and light rail transit (LRT). Therefore, predicting optimal future transport systems may be helpful in designing developing Asian countries' urban transport systems.

Ito et al. (2010) propose a method for selecting a low-carbon urban passenger transport system, using life cycle assessment (LCA). The present study presents a back-casting method for selecting an urban trunk line transport system and for determining the scale of the transport systems in developing Asian countries.

PROCESS OF ANALYSIS

First, to predict the scale of transport systems by the back-casting approach, we estimate the amount of CO_2 emissions from passenger transport. The 2050 emission target is set at 30% of 2005 emissions, and we determine the difference between the target and the predicted value by modeling CO_2 emissions from passenger cars, existing railways, and proposed transport systems. In predicting future CO_2 emissions, we predetermine a scenario of technological advancement for vehicles and a precondition of fuel consumption ratio. As the developing Asian countries are now in the process of motorization, predicting the post-motorization transit demand and CO_2 emissions based on these countries' statistics is equivalent to extrapolating a model. Thus, we construct a model using Japan's chronological motorization data.

By relating regional features to passenger demand, we find the optimal (least CO_2 emission per passenger-km) proposed transport. The mass transit infrastructure and vehicles are constructed at the time of new-line introduction, and the equipment will be used thereafter for a long period. On the basis of these assumptions, we compare the total amount of CO_2 emissions for the life-cycle of a transit system, including construction and maintenance of the infrastructure, construction of vehicles, and the stages of operation, which we call "System Life Cycle CO_2, <SyLC-CO_2>," to select the optimal transportation system using the previous studies' method. This study examines elevated railroads, LRT, and BRT that have recently been planned and studied in several developing Asian countries' cities, as the cities' main transport system. After comparing the four transit systems' (three mass transit systems' AND passenger cars') CO_2 emissions, we identify the transport system with the least CO_2 emission. FIGURE 1 depicts a flowchart for deriving a transport system's desirable scale.

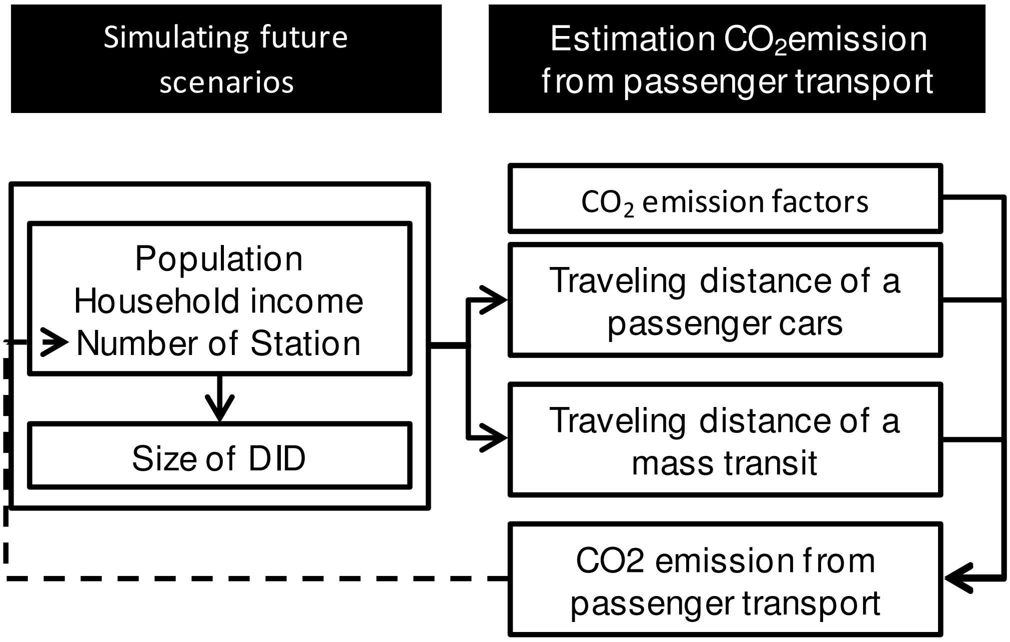

FIGURE 1 - Analytical framework

MODEL DEVELOPMENT TO OBTAIN THE SCALE OF A PROPOSED TRANSPORT SYSTEM

This study predicts CO_2 emissions from passenger vehicles, two-wheeled vehicles, and mass transit estimation models established by macro indices. We also establish models to describe the phenomenon that introducing mass transit systems suppresses expansion of both the city area and car usage.

Prediction Model for Passenger Car CO_2 Emissions

We obtain the value of passenger car CO_2 emissions by multiplying the number of privately owned passenger cars by the average yearly traveling distance of passenger cars and by a CO_2 emission factor. (See Formula (1))

$$E_c = N_c \cdot l \cdot e_c \qquad (1)$$

E_c: CO_2 emissions from passenger cars [t-CO_2/year],
N_c: Number of privately owned passenger cars [car],
l: passenger car's average yearly traveling distance [km/year],
e_c: CO_2 emission factor [t-CO_2/km]

The number of passenger cars in developing countries is affected by the predicted rising average income. In addition, to predict the number of passenger cars in urban areas, we consider changing urban composition factors, such as inhabitable area and transport network, as indices. Therefore, we use the Nakamura et al. (2011) model formula (See Formulae (2) and (3)) to predict the number of passenger cars in Asian urban areas. Densely Inhabited Districts (DID), where population density is over or equal to 4,000 person/km^2, are used as the data of urbanized areas for Japanese cities.

$$C = \frac{K}{1 + 10.5 \cdot \exp(-0.791 \cdot I)} \qquad (2)$$

$$K = 1.99 \times 10^4 \cdot r^{0.299} \cdot D_{DID}{}^{-0.487} \qquad (3)$$

C: Car ownership rate [Number of passenger cars/1000],
I: Income required purchasing a passenger car as a standard of living [Average income/lowest price of a passenger car],
K: parameter
r: Length of extension of paved road per person [meters/man],
D_{DID}: Density in Densely Inhabited Districts (DID).

In Formula (2), car ownership rate is represented by a logistic curve with a variable for the annual income standardized by car prices. K represents the rate of car ownership with no restriction on income levels. K is estimated by DID population density and road length. The scenario includes the average yearly traveling distance of a passenger car [km/year] and the basic unit of CO_2 emission [t-CO_2/km].

Prediction Model for Two-wheeled Vehicles' CO_2 Emissions

Two-wheeled vehicles contribute to a large portion of traffic in developing Asian countries. In this study, the proportion of CO_2 emissions from two-wheeled vehicles is estimated by multiplying ownership rate by average travel distance and an emission factor (See Formula (4)).

$$E_w = N_w \cdot l \cdot e_w \qquad (4)$$

E_w: CO_2 emissions from two-wheeled vehicles [t-CO_2/year],
N_w: Number of privately owned two-wheeled vehicles [vehicle],
l: Average yearly traveling distance [km/year],
e_w: CO_2 emission factor [t-CO_2/km]

Two-wheeled vehicles are less expensive than passenger cars; therefore, income level has relatively lesser influence on the two-wheeled vehicle ownership rate. Further, two-wheeled vehicle users are likely to trade up to passenger cars when their income rises. This study estimates the two-wheeled vehicle ownership rate by a multiple regression analysis using prediction data by J. Pongthanaisawan et al. (2007).

Prediction Model for Mass Transit CO_2 Emissions

CO_2 emissions originating from mass transit vehicles are calculated by multiplying each vehicle's total running distance by the basic unit of its CO_2 emissions.

$$E_s = n \cdot L \cdot e_s \qquad (5)$$

E_s: Total mass transit CO_2 yearly emission [t-CO_2/year],
n: Number of vehicles operated per year [car/year],
L: Total extension of the lines operated [km],
e_s: CO_2 emission factor [t-CO_2/car-km]

Number of vehicles operated per year is calculated by the daily passenger using the methods by Ito et al.(2012).

Prediction Model for Urban Area Expansion

We establish a model to describe the phenomenon that the introduction of mass transit systems causes urban construction. Nakamura et al. (2011) predict that expansion of the urban area would be limited to areas with highly concentrated railroad construction, and formulated a model using panel data including income level, number of stations, extended length of paved road and streets, density of population, and ratio of passenger car owners during Japan's motorization (Formula (6)). This study illustrates the relationship of mass transit implementation with future DID and daily passenger, by applying Formula (6).

$$\Delta_{DID} = 0.463 \cdot \Delta_{pop} + 0.0636 \cdot \Delta_i + 0.0246 \cdot sta + 0.207 \quad (6)$$

Δ_{DID}: Rate of change of the DID area
Δ_{POP}: Rate of population change
Δi: Rate of income change required to purchase a passenger car as a standard of living

sta: Density of stations per inhabitable area (number of stations/km_2)

Model for Identifying Low-Carbon Transport System for Urban Areas

The transport system with the least SyLC-CO_2 per transit passenger-km is identified as the city's optimal low-carbon transport system. To identify an optimal system, we develop a model to determine CO_2 emissions on the basis of passenger demand for mass transit, as determined by DID population density.

FIGURE 2 illustrates the relationship of daily passenger of inner city railroad services such as subways, streetcars, mono-rails, and automated guide way transit (AGT) in Japan with DID population density in the cities along the railroads. As the daily passenger of subways and those of medium-sized transit systems are widely different even within a city having a single DID population density, we separate designed models for various conditions. Based on the preceding analysis, TABLE 1 identifies the transit system with the least SyLC-CO_2 in each condition.

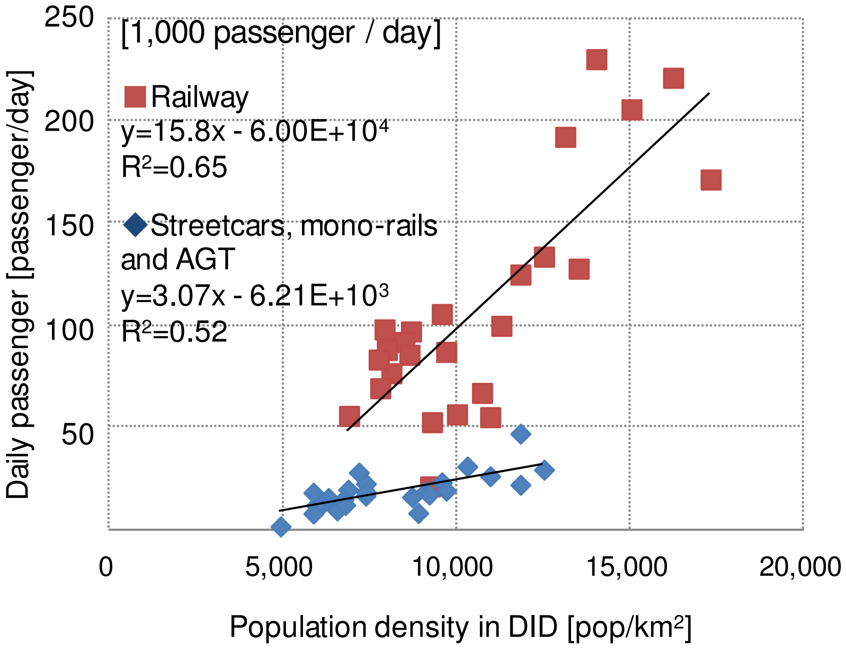

FIGURE 2 – Relationship between Population density in DID and Daily passenger

TABLE 1 – Daily passenger and Least Sylc-CO_2 Transit Mode

Transport mode	2000 [pop/km^2]	2050 [pop/km^2]
Railway	> 7000	> 7000
LRT	6,400 – 7,000	5,900 – 7,000
BRT	3,100 – 6,400	4,200 – 5,900
Passenger car	3,100 <	4,200 <

APPLICATION OF THE MODEL TO CITIES IN THAILAND

Cities to Be Discussed

We identify the optimal low-carbon passenger transport system in Thailand, for which statistical data necessary for this study is readily available.

Our method for selecting a mass transit system uses DID population density to identify features of urban areas. As the concept of DID is unique to Japan and cannot be directly applied to other countries, we select Thailand's *thesaban nakhon* as a district equivalent to Japan's DID and use its population density as an alternative index to DID. A *thesaban* is an administrative unit defining an urban area in Thailand, and a *thesaban nakhon* is a city district with a population density larger than a pre-determined figure in a *thesaban*. Thus, a *thesaban nakhon* is a city district with a population of more than 50,000 and population density of more than 3,000 [pop/km2], which is similar to the definition of the DID. TABLE 2 shows the population, city area and population density in *thesaban* of a number of *thesaban nakhons*, along with Bangkok's and Pattaya's, which do not fall under the definition of *thesaban nakhon*, but have a city district of population density similar to the *thesaban nakhon*. Bangkok has a population of roughly 5.7 million, an overwhelmingly large population among major cities in Thailand, and has a municipal railroad network, the only one in Thailand, with an extension of more than 77.3 km at the end of 2010.

TABLE 2 - Population, Area, and Population Density of Cities in Thailand

City	Population [pop]	City area [km^2]	*Thesaban* area [km^2]
Bangkok	5,701,394	1,568.7	431
Nonthaburi	261,474	38.9	38.9
Pakkret	178,907	36.0	36.0
Hat Yai	158,122	21.0	21.0
Nakhon Ratchasima	141,714	37.5	37.5
Chaing Mai	141,361	40.2	40.2
Udon Thani	137,948	47.7	47.7
Surat Thani	125,730	69.0	69.0
Khon Kaen	113,754	46.0	46.0
NakhonSi Thammarat	108,907	22.6	22.6
Pattaya	107,944	20.8	20.8
Nakhon Sawan	89,682	27.9	27.9
Ubon Ratchathani	83,173	29.0	29.0
Nakhon Pathom	81,204	19.9	19.9
Rangsit	77,969	20.8	20.8
Phuket	75,720	12.0	12.0
Phitsanulok	74,848	18.3	18.3
Song Khla	71,272	9.27	9.27
Laem Chabang	70,770	10.9	10.9
Chaing Rai	70,040	60.9	60.9
Yala	64,370	19.0	19.0

Trang	61,019	14.8	14.8
Rayong	60,332	19.4	19.4
Lampang	57,558	22.2	22.2
Phra Nakhon Si Ayutthaya	54,190	14.8	14.8
Samut Sakhon	54,090	10.3	10.3
Samut Prakan	53,759	19.1	19.1
Om Noi	52,314	30.4	30.4
Mae Sot	35,365	27.2	27.2

Establishing a Future Framework

Scenario for population and inhabitable area

The WHO (2012) has predicted the future rate of population growth for Thailand as a whole. Thus, on the assumption that each city's population growth will occur at the predicted national rate, we predict each city's 2050 population on the basis of the 2005 figures for areas considered as inhabitable.

Scenario for vehicle technology development and power generation

The average present fuel efficiency of passenger cars and CO_2 emission factors are calculated by each city based on the fuel efficiency calculations by J. Pongthanaisawan et al. (2007). They estimate present fuel efficiency by fuel type, according to the proportion of various fuels used in Thailand. As vehicles' fuel efficiency rate of improvement is considered to be the same as in Japan, we assume that the average yearly rate of fuel efficiency improvement is 2.16% referring to the Report by Japan Automobile Manufacturers Association (2011).

In the scenario for the number of passenger cars by model, we assume that hybrid cars (hereafter "HV") will be widely used in the future, and all passenger cars will be HVs by 2050, according to the estimate by Yamamoto et al. (2010).

As railways and LRT run on electricity, we calculate CO_2 emission by the primary energy consumption during generation of the CO_2 emissions for each electricity fueled transport. Although electricity is consumed as heat energy during voltage alteration or during transmission, we do not consider the loss in this study. We calculate the 2005 CO_2 emission factor for electricity generation by multiplying the total electricity generated in Thailand by the rate of the primary energy consumed for generation. We assume the 2050 emission factor of electricity generation to be the same as that of the primary energy usage, and the efficiency of thermal generation to be improved to the same level as that of Japan in 2005.

RESULTS CHOSEN AS THE OPTIMAL TRANSPORT SYSTEM IN THAILAND'S URBAN AREAS

Bangkok

FIGURE 3 depicts changes in population density and railway station density in Bangkok, both of which are estimated using the analysis flow according to (a) the present railway construction program and (b) the proposed construction plan to achieve the 2050 CO_2 emissions target.

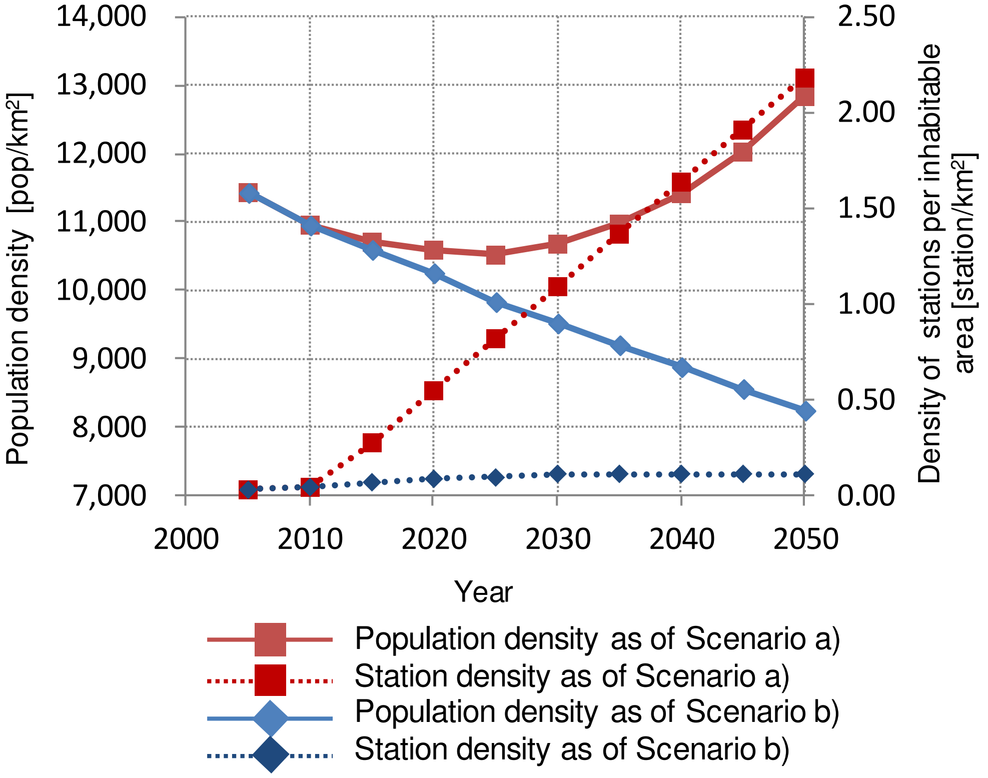

FIGURE 3 - Transition of Population Density and Number of Mass Transit Stations in Bangkok

Although railway construction will continue until 2029 according to the present railway construction program (a), population density will show a significant decrease until that period. This suggests that passenger car usage will increase because the present-day construction program will not satisfy the transportation demand increase caused by economic growth. On the contrary, when Thailand enhances its railway construction program, the population density will increase up to 13,000 [people/km^2] in 2050 after a temporary decrease. However, because railway construction must increase 23 times more than that of the present program, large-scale policies and programs must be undertaken. For the optimal SyLC-CO_2 transit system to be constructed, railways can be selected at any point in the future because the present population density is so high.

FIGURE 4 depicts the variations in CO_2 emissions along with changes in car ownership numbers. As the rate of passenger car CO_2 emissions is quite high, the rate will be 90 times that of mass transit when railroad construction is enhanced according to plan (b).

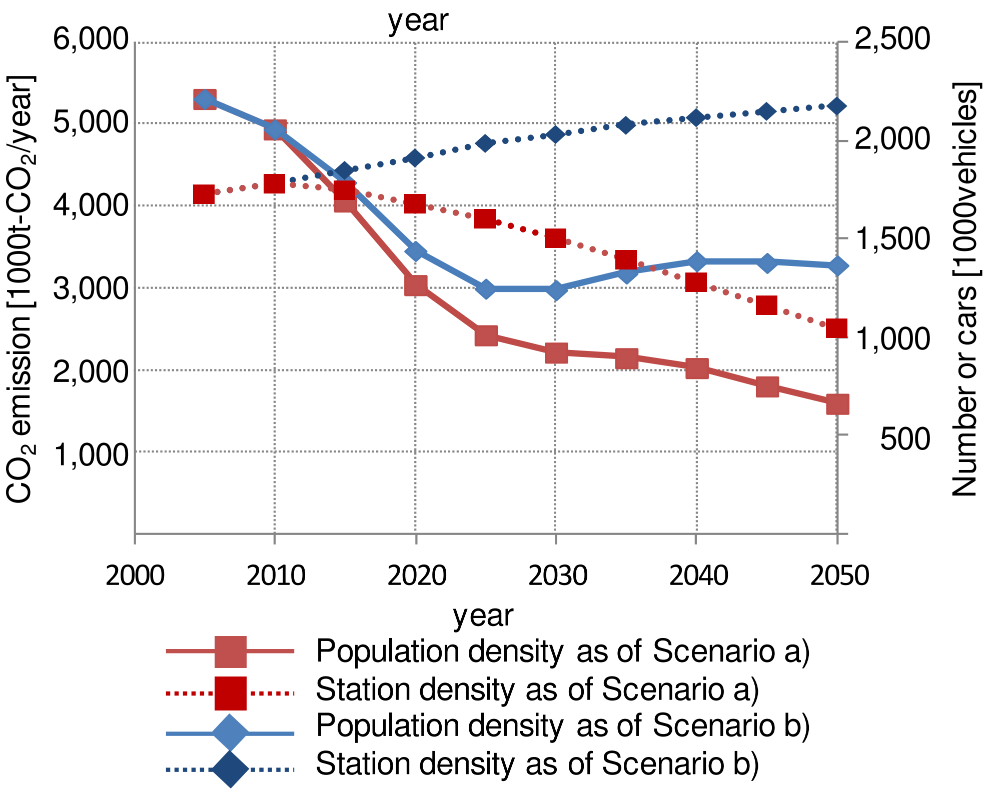

FIGURE 4 - Transition of Number of Passenger Cars and CO_2 Emissions in Bangkok

In construction program (a), although car ownership in 2050 will have increased by 26% over that of 2005, CO_2 emitted will have decreased to 58% of 2005's emissions. This decrease results from high fuel efficiency of HVs replacing passenger cars, and the basic unit of CO_2 at the time of electricity usage reflecting the result of technology innovation. Plan (b), which enhances railroad construction, will markedly decrease car ownership and halve the present program's projected CO_2 emissions.

Results Chosen As Optimal (Least CO_2 Emission) in Other Cities

TABLE 3 shows the optimal transport systems chosen for each of the cities. In many cities, the central area population density exceeds 7,000 people per km^2. Elevated railroads are the optimal mass transit system in ten cities. In seven cities, however, passenger cars will be optimal; suggesting that a mass transit system will not reduce emissions.

FIGURE 5 depicts the relationship between CO_2 emission in 2050 with no construction of mass transit systems and with construction of sufficient stations to achieve the CO_2 emission target. This figure demonstrates that cities that emit more CO_2 will need larger construction programs.

TABLE 3 - Number of *Thesaban Nakhon* Regions Arranged by Optimal (Least Sylc-CO_2) Passenger Transport

Least SyLC-CO_2 Transport mode	Cities
Railway	10 cities (Bngkok, Nonthaburi, Hat Yai, Nakhon Ratchasima, Nakhon Sawan, Nakhon Pathom, Phuket, Song Khla, Rayong, Samut Sakhon)
LRT	-
BRT	12 cities (Pakkret, Pattaya, Chang Mai, Udon Than, Khon Kaen, Nakhon Si Thammarat, Ubon Ratchathani,Rangsit, Phitsanulok, Trang, Phra Nakhon Si Ayutthaya, Samut Prakan)
Passenger car	7 cities (Surat Thani, Laem Chabang, Chaing Rai, Yala, Lampang, Om Noi, Mae Sot)

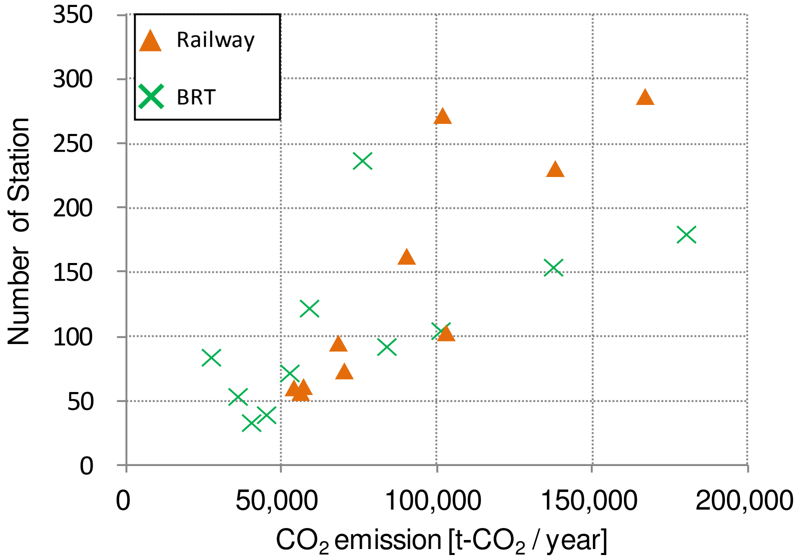

FIGURE 5 - CO_2 Emissions and Number of Stations

CONCLUSION

The present study examined methods for determining the scale of transit systems in cities of developing Asian countries. The method is introduced in Thailand and for selecting transit systems to be introduced to achieve the 2050 CO_2 emission target by surveying the cases of *thesaban nakhon*, Bangkok, and Pattaya. The results revealed the following.

(1) In Asian megacities like Bangkok, implementing only the existing railroad construction program will cause continually decreasing population density. Therefore, the city must initiate mass transit construction as early as possible to achieve the CO_2 emission target in 2050.

(2) If mass transit system is not constructed, when the fuel efficiency of passenger cars improves to that of present-day Japan's HVs, CO_2 emissions originating from

passenger transport may decrease by 40%. Considering the possibility of HV technological innovation and a broad use of electric vehicles, improvement in fuel efficiency will probably decrease the rate of CO_2 emissions.
(3) *Thesaban nakhon* can be divided into two groups: a group with high population density where railroads become the lowest carbon transit system and the other with lower population density where construction of a mass transit system may not reduce CO_2 emissions. In these areas, the policy direction to be chosen for a low-carbon transit system will differ widely.

Introduction of a large-scale mass transit system is a key policy for changing major cities' rate of traffic sharing. To achieve a low-carbon transit system, cities must consider upgrading land use along with the mass transit system, provision of various services at terminals, and other methods. This study's method can determine a city's mass transit system's type and size using macro data, and decide the direction of traffic policy.

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