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MEASURING EMISSION REDUCTION IMPACTS OF MASS RAPID TRANSIT IN BANGKOK: THE EFFECT OF A FULL NETWORK

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ABSTRACT

Mass rapid transit (MRT) is a highly energy efficient transport compared with other road transport. The introduction of MRT is an essential policy measure not only for alleviating traffic congestion but also in reducing energy consumption and environmental burden of the city. MRT development has a good influence in the reduction of carbon dioxide (CO2), especially in developing cities where transportation demand has increased considerably. However, existing approaches to reduce CO2 emission are difficult to apply to urban transport projects due to data constraints. In addition, some authorities in Asian developing countries cannot adequately measure the impact of CO2 emissions from transport projects and they face the difficulties of estimating emissions. In this study, the transportation demand forecasting model is employed in response to this difficulty using models that has been developed over many years based on logical frameworks such as the user equilibrium theory. Moreover, this model is widely used when estimating the impact of traffic demand due to MRT network development in many developed countries. Therefore, the estimation of CO2 emissions based on this method could be appropriate. This study shows the method of estimating CO2 emissions reduction on a full MRT network in Bangkok and its impacts, e.g. co-benefits, measured by employing an existing transportation demand forecasting model.

Keywords: CO2 emission, Co-benefit approach, Mass Rapid Transit, Bangkok

1. INTRODUCTION

Carbon dioxide (CO2) has been recognized as one of the global-warming culprits. In general, the average CO2 emission generated by the transport sector is around a quarter of the total CO2 emissions. Those transport-related CO2 emissions are mainly from road transport. As it is known today in both developed and developing countries, private cars generally produce CO2 emissions per passenger-kilometer much higher than other public transport modes. One major difference between developed and developing countries is the quantity of urban public transport development. Santos et al. (2010) noted that 'public transport can play a role in reducing problems related to several transport externalities: in general, accidents and traffic congestion decrease with higher use of public transport'. In fact, rail-based mass rapid transit has become a world interest as a low carbon transport mode. One reason is that road transport is the biggest producer of greenhouse gases in the transport sector, although the motor car is not solely responsible for all emissions (Chapman, 2007).

Therefore, transport-related CO2 emissions should strongly take into account not only along the rail-based mass rapid transit line(s) but also along the roads in the vicinity of the target area. A single urban transportation system project might realize a small amount of CO2 reduction comparing with what is expected. However, the Clean Development Mechanism (CDM) methodology is quite difficult to apply in order to estimate the amount of emission reduction for the whole network. Existing CDM methodology firstly estimate the amount of emission reduction for each route and then summate it for the whole network but consequently it has some limitations. In addition, few methodologies have been approved. Since traffic congestion reduction effect cannot be counted on existing CDM methodology, measurement of traffic congestion reduction effect is not addressed in accordance with CDM. Thus, it is necessary to explain the feasibility of measurement.

For this reason, an estimation of CO2 reduction from the whole network is strongly necessitated from the viewpoint of measuring against global warming. Thus, a method to estimate CO2 emission should be developed in full-development of the urban transportation system network. However, some authorities in Asian developing countries cannot adequately measure CO2 emissions impact of transport projects and they face the difficulties of estimating emissions. Schipper et al. (2009) mentioned that "Measuring carbon in transport cannot be carried out well in the majority of Asian countries because of the profound lack of data on vehicles, transportation activity, and fuel use by vehicle type". And they suggested CO2 measuring methodology that the activity-structure-intensity-fuel (ASIF) type model as bottom-up approach against the top-down approach of the IPCC. However, this approach needs statistical data of the target area.

But in the present study, the approach to estimate future traffic demand based on demand forecasting model was employed. Data which is required to estimate traffic demand has been properly developed in many cities. Thus, in the present study, ideal conditions were presented with the idea of applying in other developing city in which data have never been

developed properly. Through the present study, it would be easy to identify the necessary conditions present to apply the method to other cities.

This study aims to show the method of estimation of CO2 emissions reduction in the full MRT network in Bangkok and its impacts, e.g. co-benefits, measured by employing existing transportation demand forecast model. The present study uses the results from the model to estimate further on emission reductions. To illustrate the merit of this paper, MRT network development projects in Bangkok, including the existing lines and future extensions, is used to determine the reduction of CO2 emissions and show some co-benefits from the MRT development projects.

The remainder of the paper is outlined as follows. Section 2 describes the methodology used in this paper. Some important results are highlighted in Section 3. Finally, Section 4 concludes the paper and discusses future research issues.

2. METHODOLOGY

In this study, to estimate future traffic demand and CO2 emissions from road transport, we employed the demand forecasting model. We expect to reduce CO2 emission from road transport by introducing MRT in the existing network based on the following conditions.

- **Modal-Shift Effect**: CO2 emissions can be reduced because a passenger will shift from conventional transport modes (e.g., bus, passenger car), in which energy consumption and CO2 emissions of these modes are relatively high compared to a more efficient mode (i.e., MRT);
- **Traffic Congestion Mitigation Effect**: The traffic congestion around the MRT routes can be mitigated by MRT network development (i.e., future line extensions). Consequently, average travel speed of passenger cars can be improved and CO2 emissions on the whole road network can be lessened. In other words, the more MRT network extensions, the more increases in average travel speed of passenger cars. However, consequences of an increase in total vehicle kilometers of travel need to be carefully considered. Therefore, it is necessary to figure out whether these consequences cause more CO2 emission reduction. A framework of the study is shown in Figure 1.

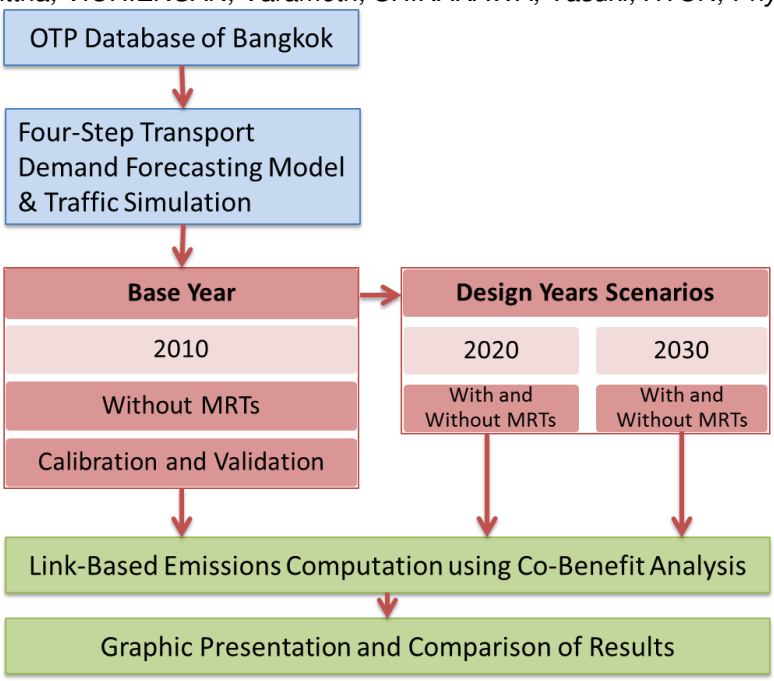

Figure 1 – Flowchart of the Study

As shown in Figure 1, in order to estimate travel demand, the four-step transportation demand forecasting model is adopted in this paper and explained in Section 2.1. Then, Section 2.2 explains the methodology for CO2 emission estimation. Section 2.3 presents a method to evaluate co-benefits from CO2 emission reduction. Finally, Section 2.4 describes scenario setting for the evaluation of CO2 emission.

2.1 Development of Transportation Demand Forecasting Model

In order to evaluate the changes in traffic volume due to the shift from private cars to MRT route, a traditional four-stage model is developed on VISUM platform for highway traffic assignment modelling whereas a micro-traffic simulation model is then executed on VISSIM platform.
The road and MRT network in the Bangkok Metropolitan Area (BMA) and the origin-destination (OD) matrix were developed based on M-MAP project (OTP, 2010).

Model Description

The network model in the base year 2010 consists of 244 zones, 59,536 OD pairs and 4,704 road links. For public transportation, 276 public transport services serving within the BMA area were included in the model. Among these 276 services, two of which are BTS (sky train) lines, one for MRT (subway) line and the others are bus lines. This 2010 network is developed based on M-MAP model to represent the development of road network and public transportation services in the BMA area and the network traffic condition setting is shown in Table 1. Moreover, future networks (2020, 2030) were also created based on M-MAP project. Figure 2 represents the 2010 network developed on VISUM platform and the details of the

network statistics are presented in Table 2. Following M-MAP project, Figure 3, Figure 4 and Figure 5 show the development of public transport services in 2010, 2020, and 2030, respectively.

Following the study of Sittha et al. (2009), a transportation demand forecasting model of BMA area can be developed. The details are explained in the next section.

Table 1 – Network Traffic Condition Setting

Item	Content	Remarks
Object	Road Public transport route (bus, railway, subway)	The network data of the model used within the M-MAP and public transport line data are used.
Link conditions	Route distance Road capacity Free flow speed Link performance function Toll on the toll road Direction regulation Operation frequency	The link conditions set up within the M-MAP is used.

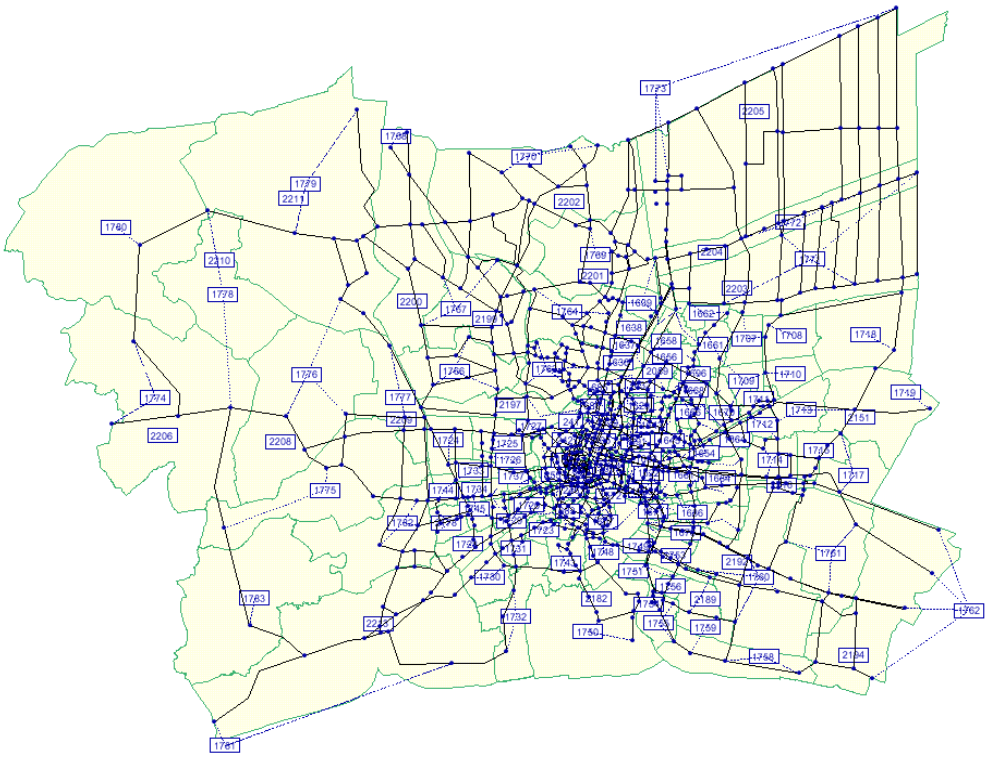

Figure 2 – Bangkok Metropolitan Area Network in 2010

Table 2 – Network Statistics

	Base and Design Years		
	2010	2020	2030
OD pairs	59,536		
Number of zones	244		
Modes of transport	Automobile traffic (private car), Public transport (bus, MRT, BTS)		
Number of public transport routes	276	284	288
Number of railway lines	3	11	15
Number of railway stations	43	237	312
Total length of railway (km)	45.7	391	509

Traffic Generation, Attraction, and Distribution

OD matrices for 2020 and 2030 scenarios were estimated based on the OD matrix in 2010. By assuming that the trips will increase continuously following the growth rate of the population, the OD matrices can be estimated by multiplying the current 2010 OD data with the population growth rates, i.e., 19.6% for 2020 and 49.6% for 2030 (United Nations, 2007). The effect of modal shift by improving MRT is estimated based on the following utility function derived from generalized cost between OD and the amount of travel demand for future scenario in 2020 and 2030 are also estimated.

Utility Function of Private Transport:

$$U_d^{PrT} = -ASC_d - \left(\gamma_{travel} \times u_d^{PrT}\right) - FC_d \tag{1}$$

Here, ASC_d : alternative specific constant for OD pair *d*, γ_{travel} : value of travel time (1.27 baht/min), u_d^{PrT} : private transport travel time between OD pair d (min), FC_d : fuel cost for OD pair *d* (3 baht/km).

Utility Function of Public Transport:

$$U_d^{PuT} = -\left(\gamma_{travel} \times u_d^{PuT}\right) - F_d - \left(\gamma_{wait} \times w_d\right) \tag{2}$$

Here, γ_{travel} : value of travel time (1.27 baht/min), u_d^{PuT} : public transport travel time between OD pair *d* (min), γ_{wait} : value of waiting time (1.46 baht/min), W_d : total waiting time spend in taking public transport to travel between OD pair *d*.

Based on the above utility functions, the respective shares of the demand of private transport and public transport for OD pair d are defined by using a logit model as follows.

$$Q_d^{PrT} = Q_d^{travel} \frac{\exp\left(U_d^{PrT}\right)}{\exp\left(U_d^{PrT}\right) + \exp\left(U_d^{PuT}\right)} \tag{3}$$

$$Q_d^{PuT} = Q_d^{travel} \frac{\exp\left(U_d^{PuT}\right)}{\exp\left(U_d^{PrT}\right) + \exp\left(U_d^{PuT}\right)} \tag{4}$$

Here, Q_d^{travel} : total demand for OD pair *d*, Q_d^{PrT} : private transport demand for OD pair *d*, Q_d^{PuT} : public transport demand for OD pair *d*.

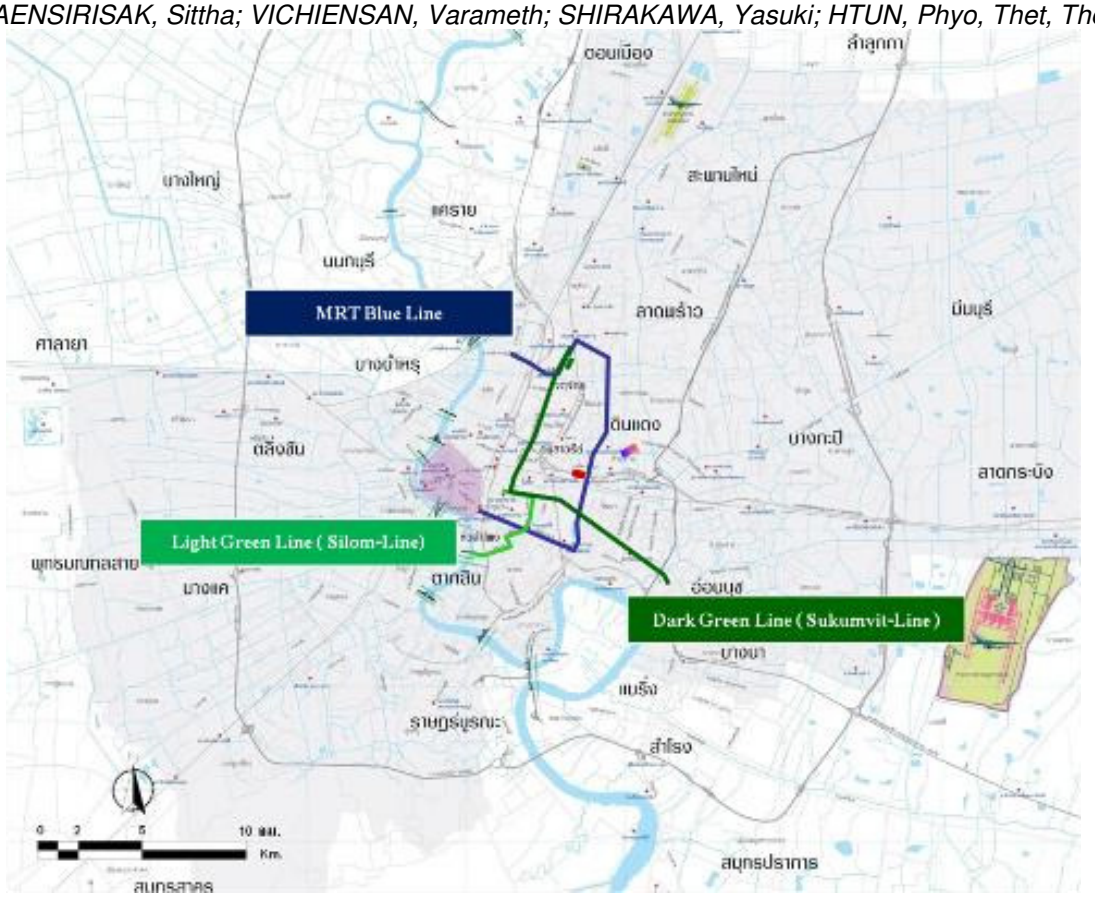

Figure 3 — Base year（2010）of railway network(Office of Transport and Traffic Policy and Planning, 2010)

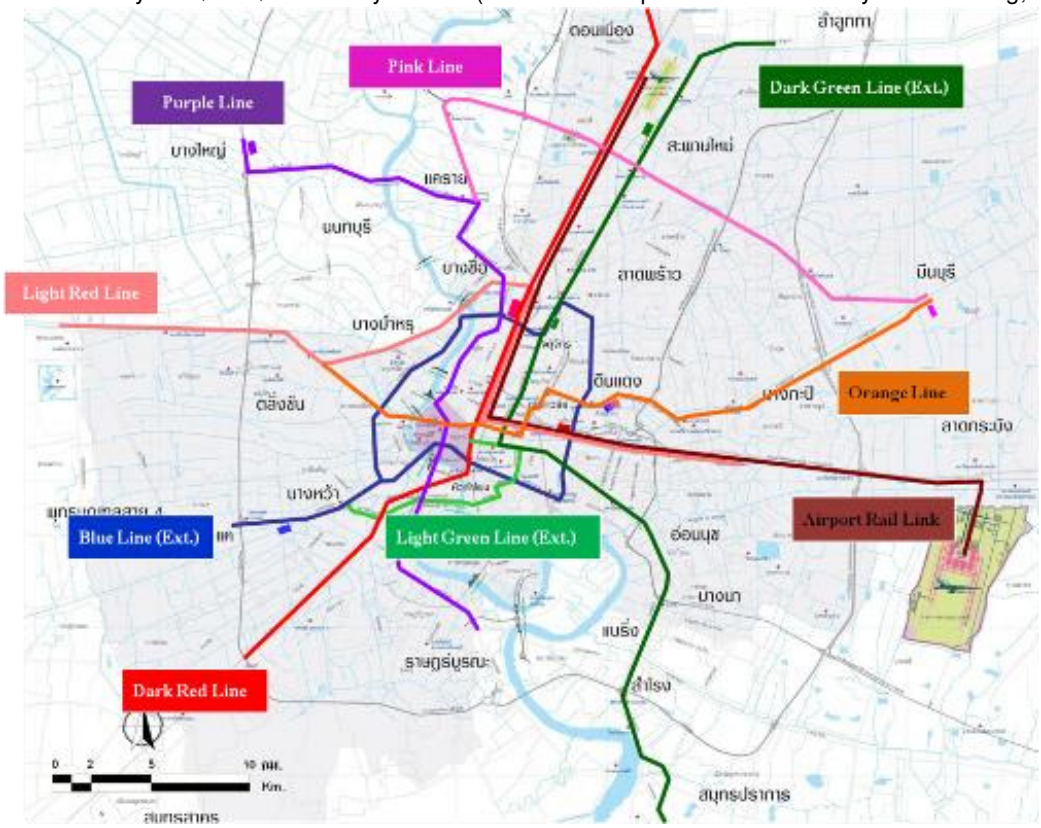

Figure 4 — Map of Network under First 10-year Plan (within 2020)
(Office of Transport and Traffic Policy and Planning, 2010)

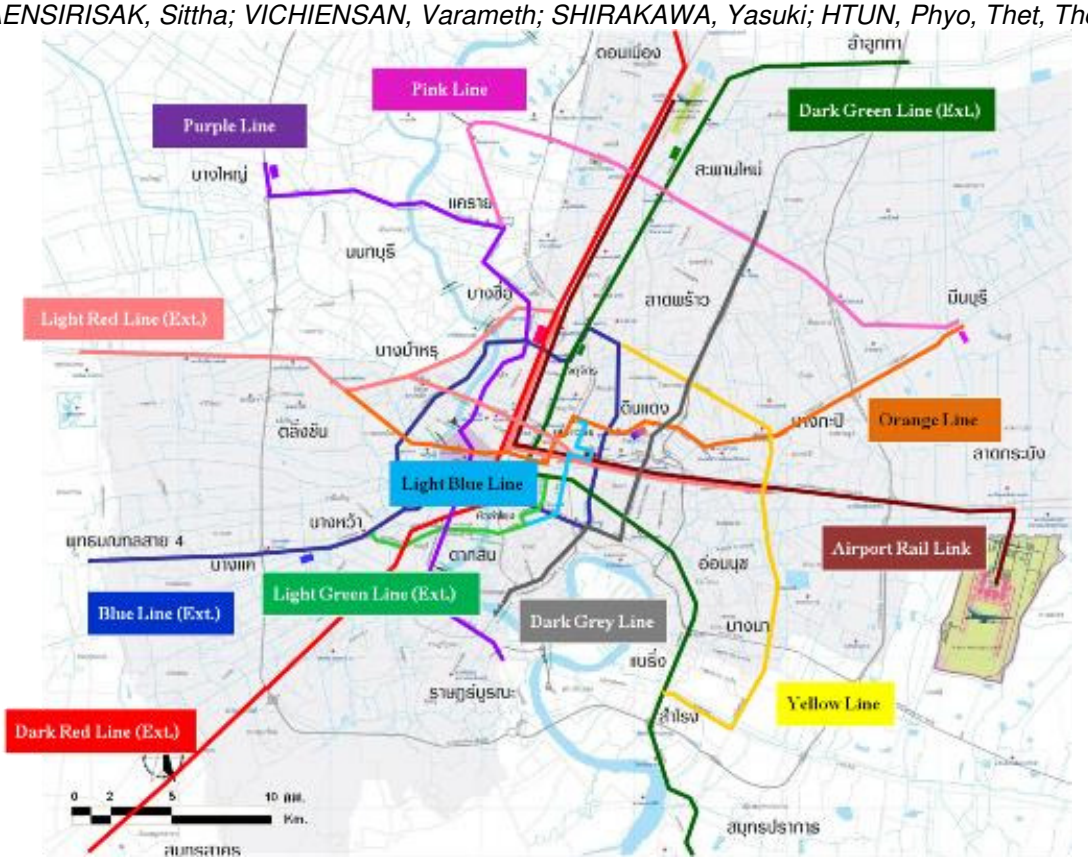

Figure 5 — Map of Network under First 10-year Plan (within 2030)
(Office of Transport and Traffic Policy and Planning, 2010)

Traffic Assignment

Based on the OD tables obtained from the previous section, a logit model is then applied for the mode choice distribution of the total demand matrix, following Sittha et al. (2009).
The link performance function was estimated by using the following formula.
Automobile traffic:

$$t_{cur}^{auto} = t_a^0 \left(1 + 0.73 \left(\frac{V_a^{auto}}{C_a} \right)^3 \right) + \frac{\tau_a}{\gamma_{travel}} \tag{5}$$

Public transport (bus):

$$t_a^{bus} = 1.1 t_a^0 \left(1 + 0.73 \left(\frac{V_a^{auto}}{C_a} \right)^3 \right) \tag{6}$$

Here, t_a^0: free flow travel time of link a (min), V_a: hourly volume of link a (vehicles), C_a : capacity of link a (veh./hr), τ_a : toll fee (baht), γ_{travel} : value of travel time (1.27 baht/min).

The present study, in traffic assignment phase, is calculated by static user equilibrium assignment. The modal shift effected by the MRT network extensions was estimated from the utility functions derived from the generalized cost between OD while the volume of travel demands for future scenarios in 2020 and 2030 were also estimated.

2.2 Methodology for Estimating CO2 Emission Reduction

Outline of CO2 emission estimation

To estimate the CO2 emission, we first calculate the average travel speed and average daily traffic volume of each link. Afterwards, the CO2 emissions of each link for both with- and without-MRT extension cases can be calculated by the average daily traffic volume on each link multiplied by the emission factor which depends on the average travel speed on that link. Emission estimation flow is shown in Figure 6.

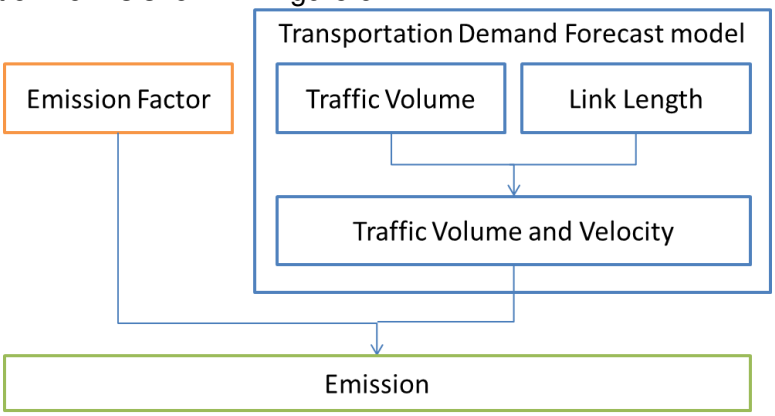

Figure 6 – Emission estimation flow

Finally, the difference in total CO2 emission reduction is compared between with- and without cases. Note that the urban development along MRT extension lines is not taken into consideration in this paper.

The modal shift effect was taken into consideration in the process of modal split classified by modes of transportation, and the traffic congestion mitigation effect was taken into consideration in the stage of the traffic assignment. However, from the viewpoint of considering the route changes due to congestion mitigation around the MRT route, it was necessary to use user equilibrium state while calculating for the traffic assignment.

Estimating CO2 Emissions Reduction

The amount of CO_2 emission reduction is estimated by using the results of the transportation demand forecasting model and its applicability is demonstrated in this study. The outline of the analysis using also the estimation results of the transportation demand forecasting model and its methodology is presented. When using the results of the transportation demand forecasting model, the emission reduction calculation should take into consideration an appropriate rebound effect and local traffic conditions, i.e. egress transportation. Furthermore, the effect of road congestion mitigation should be measured and refined by the simulation method as well as verified by the traffic surveys. But in this study, we analysed the simulation method for emission reduction calculation.

Calculation Formulas of Greenhouse Gas Emission and Its Reduction

Emission calculation formulas are described as follows. The amount of emissions reduction for the whole MRT network in Bangkok as well as for the whole country can be estimated by applying the following formulas for each project.

In Bangkok, para-transit service is operating as a feeder system to connect the main trunk road with Soi (local-branch) streets. Although it has a certain amount of CO_2 emissions, it is not taken into consideration in the transportation demand forecasting model. Since para-transit service is registered with the Department of Land Transport under the Ministry of Transport, the amount of emission based on these registered vehicle numbers can be estimated. The following section shows the estimation of the emissions of each scenario.

Reference Scenario Emissions

(a) Emissions from Road Users

It computes the amount of emission of the target road section which is determined in advance. It is assumed that the daily traffic volume is being used. However, if hourly traffic volume is available, it can also be used for calculation.

$$BE_{road,y} = \sum_i \sum_j \left(D_i \times TVb_{i,j} \times EF(v)_{KM,i,j} \times 10^{-6} \right) \times 365 \quad (7)$$

Where,

$BE_{road,y}$: Baseline emissions from whole road network in year *y* (tCO_2/year)

D_i : Length of route *i* (km)

$TVb_{i,j}$: Baseline traffic volume of vehicle j in route interval *i* (vehicle/day)

$EF(v)_{KM,i,j}$: Emission factor for baseline travel speed $Vb_{i,j}$ of vehicle *j* in route interval *i* (gCO_2/km)

365: A constant, the number of days in a year and as similarly used in the succeeding formulas

Project Emissions

(a) Emissions from MRT Operation

The amount of emissions from MRT operation is calculated.

$$PE_{MRT,y} = EC_{MRT,y} \times EF_{grid} \quad (8)$$

Where,

$PE_{MRT,y}$: Project emissions from MRT operation in year *y* (tCO_2/year)

$EC_{MRT,y}$: Power consumption by MRT operation in year *y* (MWh/year)

EF_{grid} : CO_2 emission factor for electric power system (tCO_2/MWh)

(b) Emissions from Road Users

It computes the amount of emission of the target road section which is determined in advance.

$$PE_{road,y} = \sum_i \sum_j \left(D_i \times TVp_{i,j} \times EF(v)_{KM,i,j} \times 10^{-6} \right) \times 365 \quad (9)$$

Where,

$PE_{road,y}$: Project emissions from road network in year *y* (tCO_2/year)

Di : Length of route *i* (km)

$TVp_{i,j}$: Project daily traffic volume of vehicle j in route interval *i* (vehicle/day)

$EF(v)_{KM,j}$: Emission factor for project travel speed $Vp_{h,i,j}$ of vehicle *j* in route *i* (gCO_2/km)

Emissions Reduction

Emissions reduction is calculated by the following formula.

$$\begin{aligned} ER_y &= BE_y - PE_y \\ &= \left(BE_{MRT,y} + BE_{road,y}\right) - \left(PE_{MRT,y} + PE_{road,y}\right) \end{aligned} \tag{10}$$

Where,

ERy : The amount of Greenhouse gas emissions reduction in year *y* (tCO2/year)

BEy : The amount of reference scenario emissions in year *y* (tCO2/year)

PEy : The amount of project emissions in year *y* (tCO2/year)

The rest of the variables are as previously defined.

2.3 Reference Scenario and Study Area Boundary

Setting Reference Scenario

According to "Law-Carbon Society Vision 2030 Thailand" (November, 2010), estimation is performed in the Business as Usual (BaU) scenario and Counter Mitigation measures (CM) scenario with year 2030 as the target year for Bangkok in the future. This project applies to this future estimation, promotion of the modal shift of the passenger transport in CM scenario. Therefore, in order to be consistent with the existing future estimation in Thailand, the reference scenario is set up as follows.

Reference scenario: BaU scenario (the MRT project does not exist)

Project scenario: CM scenario (state which undertook the MRT project in the BaU scenario)

Setting the Boundary

Various measures in the transport sector are planned in Thailand and Bangkok metropolitan area as mentioned above. It is desirable to set up the boundary based on preliminary investigation and the influence on these measures among others. However, in this project, the boundary was set up focusing on the modal shift effect due to MRT network development. That is, because the MRT line to be targeted by this project are spread across one capital and five neighbouring provinces of Bangkok metropolitan area, the boundary was set and composed of the capital and five neighbouring provinces of Bangkok metropolitan area where traffic conditions are mostly affected.

2.4 Analysis of Co-Benefits

In this study, additional co-benefit evaluation is performed based on the result of transportation demand forecasting model as mentioned above. Since the transportation demand forecasting model estimated the traffic volumes for passenger car and bus for the base year (2010) and the future years (2020 and 2030), the pollutant emission reduction effect is also calculated based on these years. The details are explained as follows:

Items to be evaluated

Items to be evaluated are four types of air pollution emissions including Nitrogen oxide (NOx), Carbon monoxide (CO), Particulate matter (PM), and Tetrahydrocannabinol (THC).

Baseline / Project Scenario

A baseline scenario is the scenario in which the MRT network in Bangkok is not improved and emissions continue to increase by the conventional means of transportation (passenger car and bus). On the other hand, a project scenario is the scenario in which modal shift and traffic congestion mitigation are brought by the MRT network development and consequently emissions are decreased.

Baseline Evaluation Method

Emissions of air pollution in the baseline scenario are calculated by integrating the amount of emissions of the target road section with the following equation. Emission factors used are the most recent value at the time of evaluation and the other parameters are estimated by using the results of the transportation demand forecasting model.

$$BE_k = \sum_i \sum_j \left(D_i \times TVb_{i,j} \times EF(v)_{k,i,j} \times 10^{-6} \right) \times 365 \qquad (11)$$

Where,

BE_k : Emissions of air pollution in the baseline scenario (t/year)

D_i : Length of route *i* (km)

$TVb_{i,j}$: Baseline traffic volume of vehicle type *j*, interval *i* (vehicle/day)

$EF(v)_{k,i,j}$: Emission factor for air pollution for running speed $Vp_{i,j,y}$ of vehicle type *j*, route *i* (g/km)

Calculation Process and Result of Trial Calculation (Quantification) before Project Implementation

Similarly, emissions of air pollutants in the project scenario are calculated as follows.

$$PE_k = \sum_i \sum_j \left(D_i \times TVp_{i,j} \times EF(v)_{k,i,j} \times 10^{-6} \right) \times 365 \qquad (12)$$

Where,

PE_k : Emissions of air pollution in the project scenario (t/year)

$TVp_{i,j}$: Project traffic volume of vehicle type *j*, interval *i* (vehicle/day)

Based on the above calculation, the emission reduction effect of the air pollution is calculated as follows.

$$ER_k = BE_k - PE_k \tag{13}$$

Where,

ER_k : Amount of emission reduction of air pollution (t/year)

3. RESULTS

3.1 Validation of Assignment Result of the Base Year Model

The assignment result of the base year model was validated by traffic volume count on 899 links (about 16% of all links) and its determination coefficient R^2 is 0.568. The result can be shown in Figure 7.

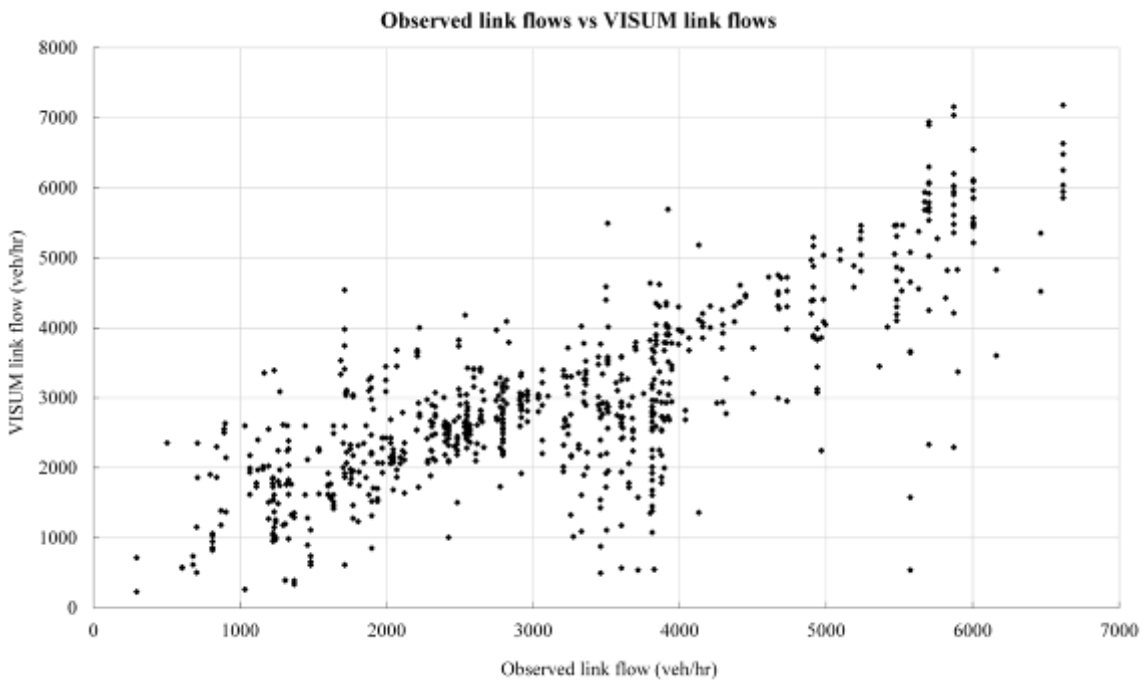

Figure 7 – Observed link flows vs VISUM link flow

Transportation Demand Forecast Modelling Results

Traffic assignment results for current condition 2010, 2020 without the MRT project (reference scenario) and 2030 without the MRT project (reference scenario) are illustrated in Figure 8, Figure 9 and Figure 10, respectively. Project scenarios for 2020 and 2030 are shown in Figure 11 and Figure 12, respectively. These figures give the results that the high

link volumes occur around the downtown area of Bangkok and low link volumes occur in the surrounding areas. For the links on the western area of the network, the link volumes are relatively high despite their locations at the suburban area. It is because all the demand in the western area of BMA is only served by those few links On the other hand, the links located at the north-east area of BMA seems to be relatively low link volumes. This is mainly due to the aggregated definitions of zones and centroid connectors in those areas causing the demand not flowed to some of the links. In Figure11 and 12, it could be seen that the majority of the link around the MRT lines have reduce traffic volume compared to reference scenario of each year (Figure 9 and 10).

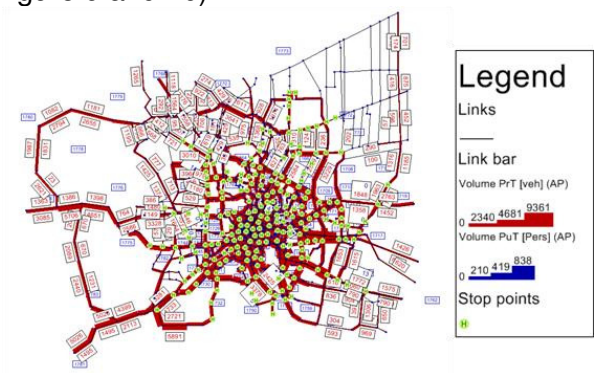

Figure 8 – Traffic Assignment Results in 2010

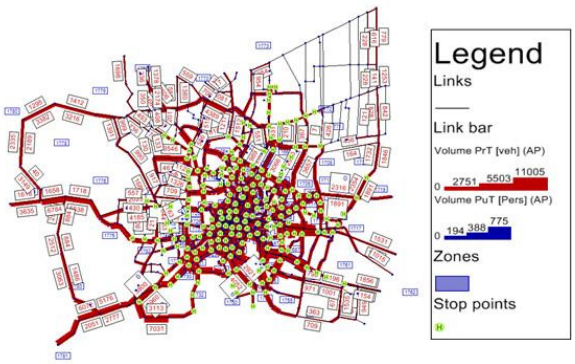

Figure 9 – 2020 without MRT Project (Reference Scenario)

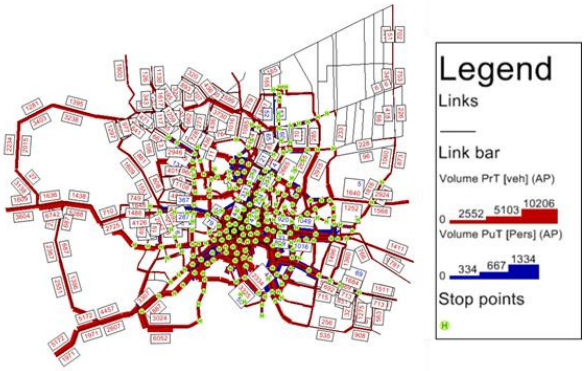

Figure 11 – 2020 with MRT Project (Project Scenario)

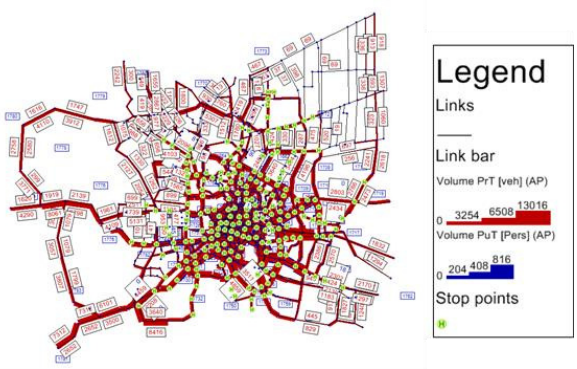

Figure 10 – 2030 without MRT Project (Reference Scenario)

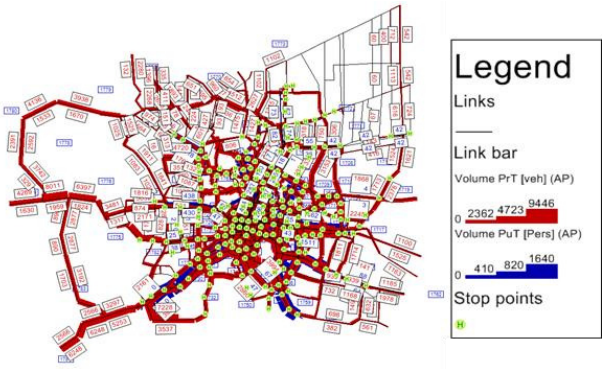

Figure 12 – 2030 with MRT Project (Project Scenario)

3.2 CO2 Emission Estimation Result

Baseline emission from road users for the current condition (2010), reference scenario emissions (BE_{road}) and project scenario emissions (PE_{road}) for the year 2020 and 2030 are calculated by using transportation demand forecasting results mentioned above. These emission amounts are shown in Table 3.

Table 3 – The amount of annual CO2 emissions by road users (Unit: t-CO2/year)

Present condition	Year 2020 Estimation		Year 2030 Estimation	
BE_{road}	BE_{road}	PE_{road}	BE_{road}	PE_{road}
13,317,246	18,251,177	12,736,649	25,279,356	17,453,825

Additionally, the amount of CO2 emissions in Bangkok and the whole Thailand was estimated based on "Thailand Energy Statistics 2010" by Department of Alternative Energy Development and Efficiency (DEDE) and the statistics are as follows.
The whole Thailand : 58,843,664 t-CO2/year
BMA : 13,212,094 t-CO2/year

3.3 Results of Co-Benefit Analysis

The calculation results of air pollution matter are shown in Table 4. Additionally, the amount of emissions here represents only the contribution from passenger car and bus and it does not include the contribution by freight cars such as trucks. Furthermore, it is necessary to keep in mind that there is a possibility that the emission values are overestimated compared to actual emissions since transportation demand forecasting is carried out only for peak hours. Figure 13 to Figure 20 show the annual mean concentration of NOx, CO, PM and THC in present condition year 2010 and target year 2030 where the reduction effects are emphasized. Those figures shows that NOx, CO and THC have relatively highly reduction effects not only along the MRT lines but also the entire network, especially pronounced in the densely urbanized area in the eastern part the city. Since PM is concerned with buses, its reduction is expectedly observed along the bus routes.

Table 4 - Amount of Emissions and Reduction for Air Pollution from Passenger Car and Bus (Unit: t/year)

	Present condition	**Year 2020Estimation**			**Year 2030Estimation**		
	BE_k	**BE_k**	**PE_k**	**ER_k**	**BE_k**	**PE_k**	**ER_k**
NOx	105,193	132,927	100,766	32,161	166,370	128,424	37,946
CO	298,730	413,480	284,301	129,179	569,244	395,955	173,288
PM	787	820	744	76	839	780	59
THC	87,824	138,581	82,118	56,463	213,668	130,232	83,436

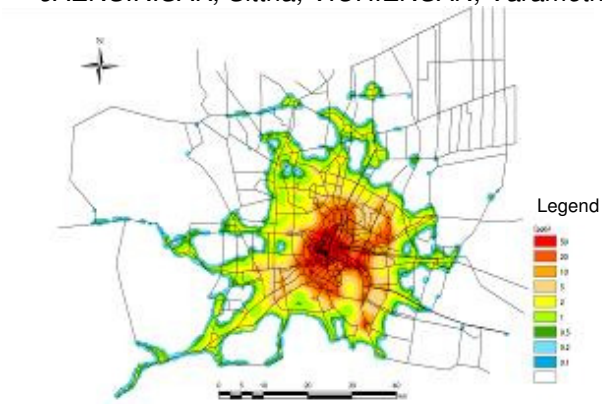

Figure13 Annual mean concentration of NOx in 2010 (Only from buses and passenger cars)

Figure14 NOx reduction effects of the development of MRT network in 2030

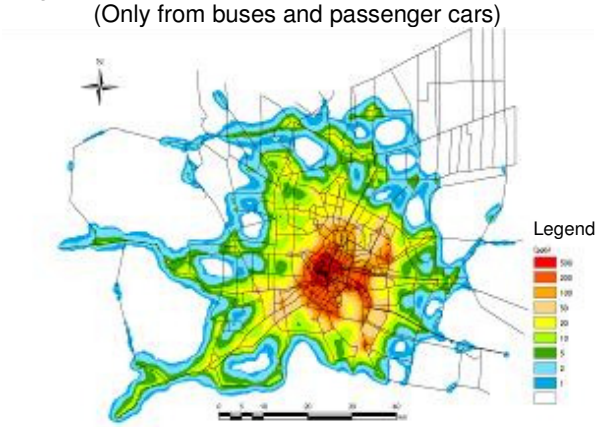

Figure15 Annual mean concentration of CO in 2010 (Only from buses and passenger cars)

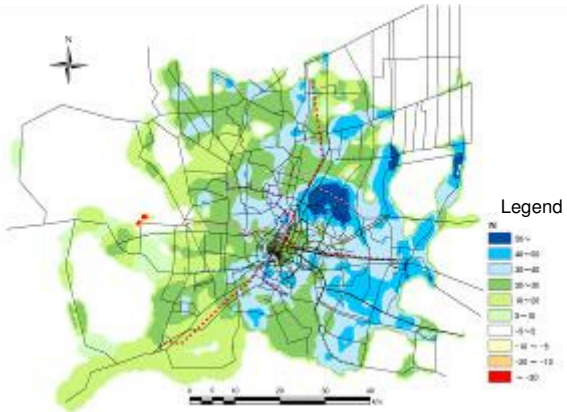

Figure16 CO reduction effects of the development of MRT network in 2030

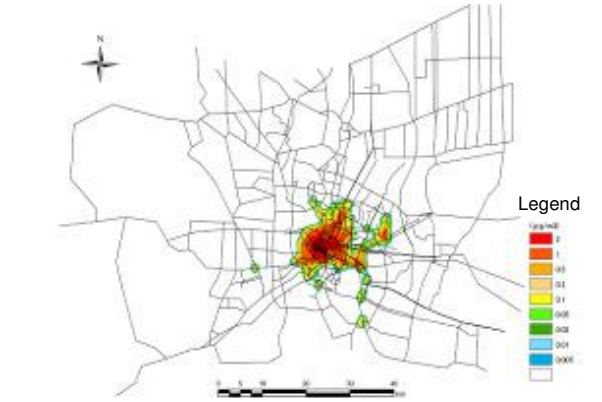

Figure17 Annual mean concentration of PM in 2010 (Only from buses and passenger cars)

Figure18 PM reduction effects of the development of MRT network in 2030

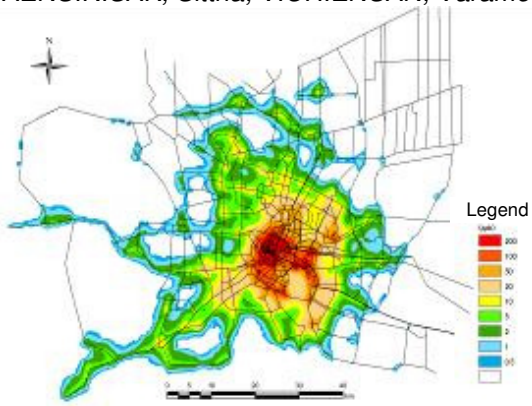

Figure19 Annual mean concentration of THC in 2010 (Only from buses and passenger cars)

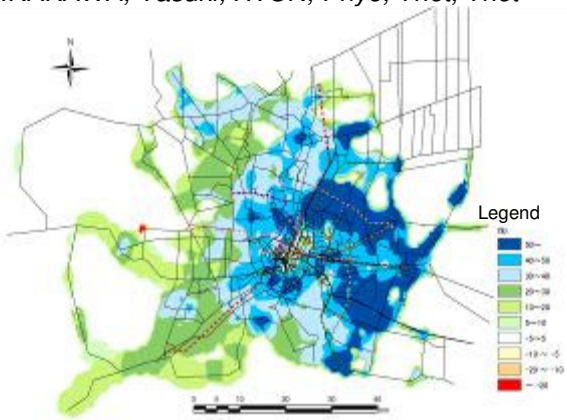

Figure20 THC reduction effects of development of MRT network in 2030

4. CONCLUSIONS

This study demonstrated that the amount of CO2 emission in the BMA area can be reduced by MRT link extensions. To estimate the impact of CO2 emissions on the full MRT network development in Bangkok, we developed a new approach of CO2 emission estimation which adopts a concept of transportation demand forecast modelling. Note that we consider not only modal-shift effect but also traffic congestion mitigation effects of the whole network from the MRT development. The method of estimating the amount of CO2 emission reduction could not be admitted in the existing approaches, such as CDM methodology, for traffic congestion mitigation affects the whole network. In the present study, we estimated this effect by using transportation demand forecasting and setting its boundary. To deepen the discussion in domestic and international arenas, it is necessary to tackle such calculations. Thus, this approach would be useful and desirable from the viewpoint of appropriate estimation of CO2 emission impacts of MRT development. Through this, it is easy to identify the conditions, what kinds of data should be prepared, and apply to other cities. However, it is necessary to verify the estimated values of CO2 emission reduction.

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