EVALUATION OF ENVIRONMENTAL IMPROVEMENT POLICY IN AN URBAN NETWORK USING ROAD TRAFFIC SIMULATION

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ABSTRACT

In this study, we estimate the CO_2 emissions in an urban road network and evaluate a specific environmental traffic policy in order to investigate the contribution of the transport sector to global environmental problems. We calculate the CO_2 emissions as a function of the running condition of a vehicle, and investigate traffic conditions in an urban road network. In addition, the emission calculation is used to evaluate the effectiveness of urban transport policy by considering the effect on environmental loading.

Keywords: CO_2 emission, urban transport policy, traffic simulation

1. INTRODUCTION

In Japan, "Eco-Model Cities," which would achieve the ambitious targets set for GHG (greenhouse gas) emission reductions, have been proposed. These cities would adopt sustainable city planning with traffic policy based on public transport and a reduction in environmental loading from automobiles, etc. In this study, the volume of GHG emissions, such as CO_2, in urban areas is used as a fundamental unit of environmental loading, and many examples of GHG reduction goals for entire cities are given. However, fluctuations in gas emissions from individual vehicles, and under different road traffic conditions, have a considerable effect on GHG emissions from the transport sector. It is important to calculate the volumes of GHG emissions accurately in order to introduce countermeasures to global warming. To this end, a method for calculating the volume of GHG emissions from an individual running vehicle is examined. Changes in traffic volume in an urban road network are estimated using microscopic traffic simulation, and the volume of GHG emissions from an individual vehicle is estimated. The GHG emissions in a given area can be estimated by using microscopic traffic simulation in conjunction with a model for predicting CO_2 emissions.

The effectiveness of urban transport policy is also examined on the basis of the results of emission calculations by considering the effect on environmental loading. In particular, the environmental effectiveness of urban transport policy is discussed, using the environmental loading in an urban road network based on the CO_2 emissions of individual vehicles. Finally, the study proposes an urban transport policy which will result in environmental improvements.

2. PROCEDURES FOR URBAN ROAD ENVIRONMENTAL IMPACT ASSESSMENT

Accurate calculation of GHG emissions in the transport sector is fundamental to assessing environmental traffic policy. In this study, we assess the environmental impact of an urban road network mainly in terms of CO_2 emissions.

2.1 Urban road network environmental impact assessment

In many cases, an environmental impact is examined for the whole urban area. Here, the environmental impact of the transport sector is examined. In this study, an urban road network (East–West 7.1 km, North–South 8.5 km) in Kyoto city, shown in Figure 1, is considered.

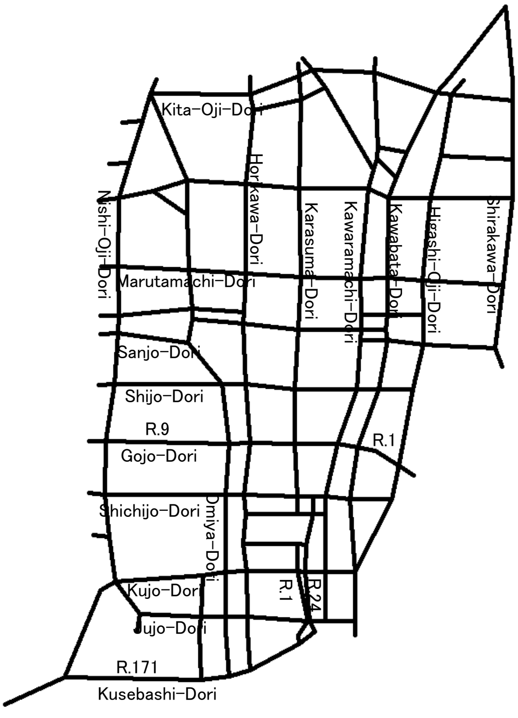

Figure 1 – Road network in Kyoto City

The urban road network shown in this figure is composed of 518 links (road sections) and 237 nodes. The origin–destination (OD) traffic volume for 7:00 AM–10:00 AM is considered. The OD table was compiled based on the fourth Keihanshin passenger trip survey.
In this study, two methods—1) traffic assignment, and 2) traffic simulation—are used. The two methods are applied to the same road network (Figure 1).

2. 2 Environmental impact assessment method

The environmental impact of an individual vehicle can be assessed using a model for predicting exhaust gas emissions. Various studies have shown that the CO_2 and NO_x contents of exhaust gases are affected by the speed, acceleration, and engine rotational frequency of the vehicle. We estimate the CO_2 emissions and the travel conditions by performing a running experiment, using a CO_2 density measurement device, an exhaust gas flow meter, and a speed-recording device. The experiment is performed over a distance of about 100 km and carried out three times per vehicle. The data are recorded every second.
The environmental impact of vehicles differs greatly with the running pattern even when the average speed is constant. CO_2 emissions over two different road sections are therefore estimated and compared. Road section 1, from Katsuragawa Parking Area on the Meishin Expressway, is about 1 km long, and road section 2, in R. 423 in Suita city, is about 1 km long. The same small vehicle is used throughout this experiment. The running pattern and CO_2 emissions are shown in Figure 2. In road section 1, the CO_2 emission per unit time is high as the vehicle accelerates from 0 to 80 km/h. In road section 2, when the speed is around 50 km/h, the CO_2 emission per unit time is low. The running indices for the two road sections are shown in Table 1. Distances travelled, travel times, and average speeds for the two road sections are similar. However, CO_2 emissions for road section 1 are almost double those for road section 2. If the only variable used in the prediction model is the average speed, the estimated CO_2 emissions may differ greatly from the actual values. Therefore, running speed and acceleration per second are also used as variables in the model for CO_2 emissions prediction.

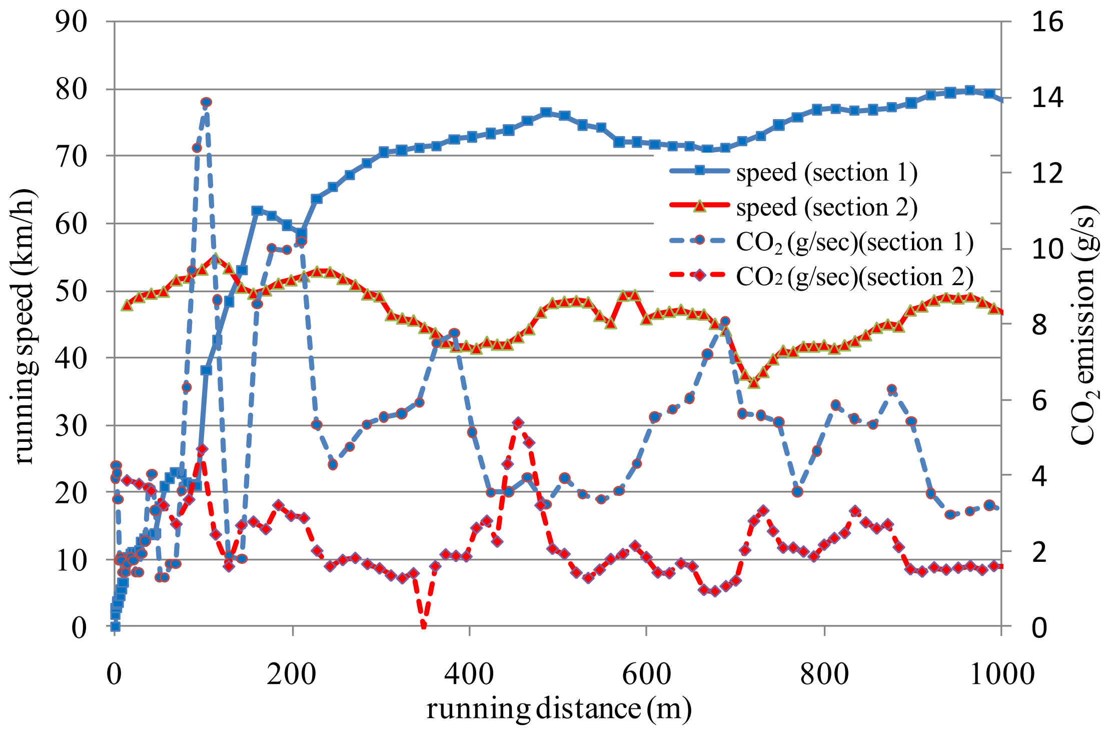

Figure 2 – Running pattern and CO_2 emissions for two road sections

Table I – Running indices for two road sections

	Road section 1	Road section 2
Road classification	Inter-city expressway	National road
Distance (m)	1,008	1,004
Travel time (s)	75	78
Average speed (km/h)	48.4	46.4
CO_2 emission (g CO_2)	345.8	172.2

The CO_2 emissions prediction model is defined by the following equation.

$$D_{CO_2} = a \cdot V + b \cdot \delta_{Acc+} \cdot Acc + c \cdot (1 - \delta_{Acc+}) \cdot Acc + d \qquad (1)$$

D_{CO_2} : CO_2 *emission* (g/s), V : *Travel Speed* (km/h), Acc : *Acceleration* $(km/h/s)$,

a, b, c, d : *parameters*,

$$\delta_{Acc+} = \begin{cases} 1 : if \ Acc \geq 0 \\ 0 : if \ Acc < 0 \end{cases}$$

The vehicle's accelerator operation and brake operation mechanisms differ. Increases and decreases in the quantities of exhaust gas caused by acceleration and deceleration do not seem to be symmetric. A model containing acceleration and deceleration parameters was constructed. Since CO_2 emissions differ greatly with vehicle type, CO_2 emission models for a number of different vehicle types were produced. The parameters of the CO_2 emission models are shown in Table 2.

Table 2 – Parameters of CO_2 emission forecasting models

	Medium-sized truck (diesel fuel)	Small-sized truck (diesel fuel)	Medium-sized passenger car (gasoline fuel)	Small-sized passenger car (gasoline fuel)	Light-sized car (gasoline fuel)	Hybrid passenger car (gasoline fuel)
d (constant)	−0.015	0.027	0.297	0.726	0.386	−0.048
a (speed)	0.141	0.212	0.0430	0.00574	0.0123	0.024
b (acceleration)	0.171	0.017	0.00996	0.0233	0.102	0.134
c (deceleration)	0.012	0.002	0.00996	0.0271	0.0226	0.057
No. of samples	15,980	16,930	14,973	12,821	15,697	26,285
Correlation coefficient	0.61	0.63	0.79	0.45	0.65	0.49

In the hybrid passenger car, when the vehicle stops, the engine also stops. The constant parameter is therefore almost zero for the hybrid passenger car model. The measuring device used in the investigation is simple and can be mounted on the vehicle. Therefore, the measurement accuracy is not higher than that in laboratory experiments using a dynamometer. The correlation coefficient is low in some cases because various factors, such

as the road gradient, affect CO_2 emissions. The route is chosen to go through roads of various classifications. This CO_2 emission prediction model can be used in various areas.
In addition, air pollution from NO_x, suspended particulate matter (SPM), CO, and SO_2 emissions are estimated. The emission coefficient of a vehicle is examined at average speed steps of 10 km/h.
In the traffic assignment method, the environmental impact is calculated using the index of traffic volume and link travel time calculated in the frame of usual traffic assignment model. Therefore, existing traffic assignment system can be used.
In the traffic simulation method, the environmental impact is calculated using the data of speed, acceleration in the every time step of the simulation.

2.3 Outline of road traffic simulation

Traffic simulation, which is one of methods used to estimate traffic volume in environmental impact assessments, is described. In this study, a microscopic road traffic simulation model CaTS (car-following-based traffic simulation) is used. The outline of CaTS is shown in Table 3. Features of this simulation model are 1) the time interval is 0.1 s, and 2) it reproduces the movement of the vehicle in detail, including at intersections.

Table 3 – Outline of the simulation model CaTS

Calculation time step	0.1 s
Route choice model	・The shortest path is decided from the average link travel time in 15 min units. ・Calculation of the shortest path search is executed in 1 min intervals. ・The minimum route to the destination is chosen for each link at the inflow point.
Speed decision model	・Using the car-following model, the speed is decided on the basis of the vehicular gap.

The car-following model, which is an important element of traffic simulation, is described. On the basis of the vehicular gap shown in Figure 3, the following-speed is decided using equation (2).

$$v = \frac{\log(L/6.032)}{0.037} \qquad (2)$$

v: running speed (km/h)、L: length between vehicles (m)

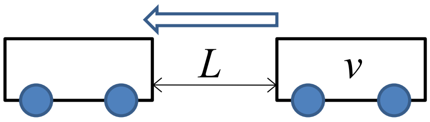

Figure 3 – Running speed decision process

The running speed is modified by limit of acceleration and limit of deceleration. CO_2 emissions are calculated from the running speed and the acceleration every 0.1 s using the CO_2 emission prediction model.
Calculation procedure of the simulation model is shown in Figure 4. Data such as the origin, destination, departure time, running speed, running position, passed link number, and CO_2 emissions for every vehicle are stored in the computer.

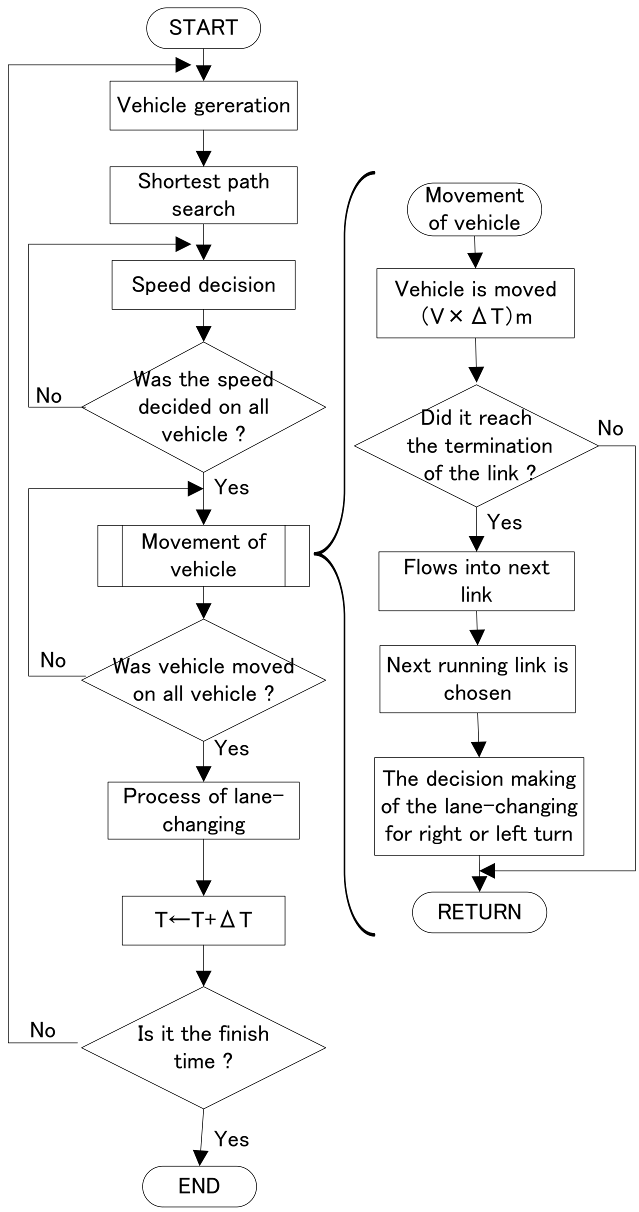

Figure 4 – The flowchart for the CaTS simulation model

Using car ownership statistics in Japan, the vehicle type ratios are set at medium-sized truck 4%, small-sized truck 7%, medium-sized passenger car 22%, small-sized passenger car 33%, and light-sized car 34%; 5% of medium-sized passenger cars and 5% of small-sized passenger cars are hybrid passenger cars. Therefore, the vehicle type ratios are medium-sized passenger car 21%, small-sized passenger car 31%, hybrid passenger car 3%.

3. NECESSITY OF LOCAL ENVIRONMENTAL ASSESSMENT

The reduction of GHG emissions is discussed at national level, such as at Conference of the Parties (COP). Other factors, such as reduction in the number of shopping bags used, and control of air conditioner usage, are also put forward as targets. In the transport sector 1) switching from automobile use to public transport, 2) use of automobiles with small environmental loadings, and 3) reduction in idling stops, etc. have been proposed. There have been few trials examining the reduction of GHG emissions at the zone unit level. Generally, CO_2 emissions are closely related to vehicle running conditions. In this study, which aims to obtain accurate CO_2 emission predictions, local differences, zone units, link units, and vehicle units are examined. NO_x and SPM are examined at the zone unit level.

Two techniques (the traffic assignment method, and the traffic simulation method) which enable calculation of the environmental loading quantity at the road section (link) unit level are used. The stochastic user equilibrium traffic assignment method, which describes user route choice behavior in the random utility model, is used as the traffic assignment method. The expected level of traffic flow as a traffic equilibrium is calculated. Here, the OD traffic volume for 3 h (7:00 AM to 10:00 AM) is used. From the traffic assignment, traffic volume, average travel time, and average speed of each link unit at traffic equilibrium can be calculated. CO_2 emissions are calculated by multiplying the mileage by the CO_2 emission coefficient at the average speed. NO_x, SPM, CO, and SO_2 emissions can be similarly calculated from emission coefficient and mileage. “Traffic assignment” is a fundamental method for estimating future traffic volumes, and it seems to be effective in calculating average environment loads. In the traffic simulation method, CO_2 emissions are estimated from the running condition of individual vehicles, and the total is calculated at the adequate totaling unit. It is possible to discuss the problem of applying practical methods to realistic CO_2 emission prediction by comparing and examining these two methods.

Estimated results of all the mileage and environmental loading quantities of the whole urban road network obtained by each method are shown in Table 4.

Table 4 – Estimated results from traffic assignment and traffic simulation methods

Index	All vehicle types		Small automobiles		Large automobiles	
	Traffic assignment method	Traffic simulation method	Traffic assignment method	Traffic simulation method	Traffic assignment method	Traffic simulation method
Traffic volume (vehicles)	166,700	167,231	148,363	148,836	18,337	18,395
Total travel distance (km)	823,554	702,345	732,963	625,087	90,591	77,258
CO_2 emissions (t)	255.1	347.0	158.4	251.4	96.7	95.6
NO_x emissions (kg)	249.7	321.9	79.1	100.2	170.6	221.7
SPM emissions (kg)	13.6	17.3	4.8	5.9	8.8	11.5
CO emissions (kg)	540.2	656.5	421.8	498.6	118.3	157.9
SO_2 emissions (kg)	10.9	15.0	8.1	11.2	2.8	3.8

Although the calculation time is 7:00 AM to 10:00 AM, in the traffic simulation, vehicles running before 7:00 AM, and vehicles running at 10:00 AM, are not included in the total. In this regard, the traffic assignment method is different from the totaling method. Therefore, compared with the traffic assignment method, calculations on the basis of total mileage give relatively small values in traffic simulation. However, the estimated values for CO_2 emissions are relatively high in traffic simulation. This tendency is similar for other pollutants, that is, the environmental loading obtained using the usual average CO_2 emission (traffic assignment method) gives a relatively small estimate. It has also been proven that large differences arise (about 1.6 times the environmental loading) for small automobiles, although the differences in CO_2 emissions are small for large automobiles. This is also considered to be related to the difference between gasoline-powered vehicles and diesel-powered vehicles. When other emission materials are calculated from the total of the environmental loading of individual vehicle units (traffic simulation method), the values obtained are 1.18–1.38 times the values calculated using the traffic assignment method.
Next, the estimated results for CO_2 emissions of a link unit obtained by each of the methods are compared. Link unit CO_2 emissions are shown in Figures 5 and 6.

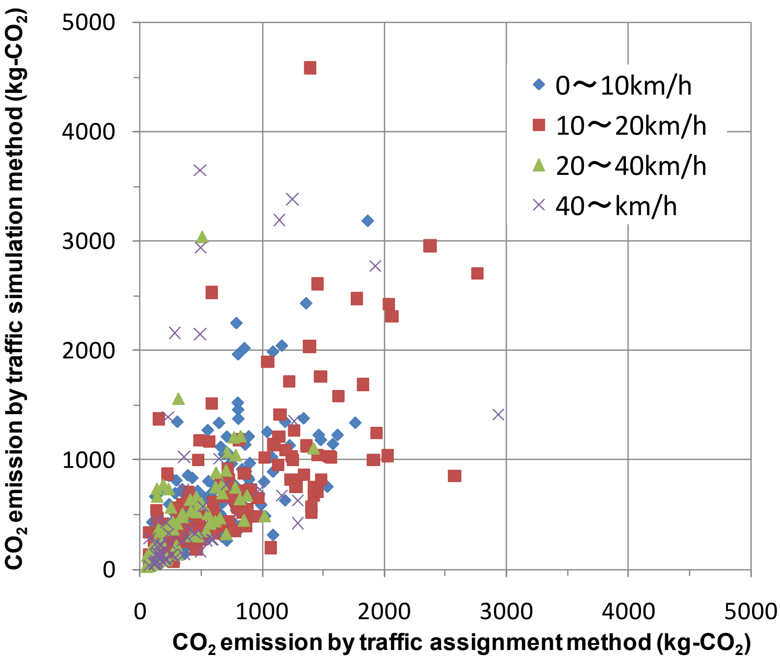

Figure 5 – Comparison of CO_2 emissions for each link

The average speed used is the 3 h average travel speed of the traffic simulation method. The estimated results are shown in Table 5. The root mean square (RMS) values show the degree of the difference between CO_2 emissions estimated using the traffic assignment method and the traffic simulation method; this is expressed by the following equation.

$$\mathrm{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - A_i)^2} \qquad (3)$$

n : number of links;
S_i, A_i: CO_2 emission of link i in the traffic assignment method, traffic simulation method

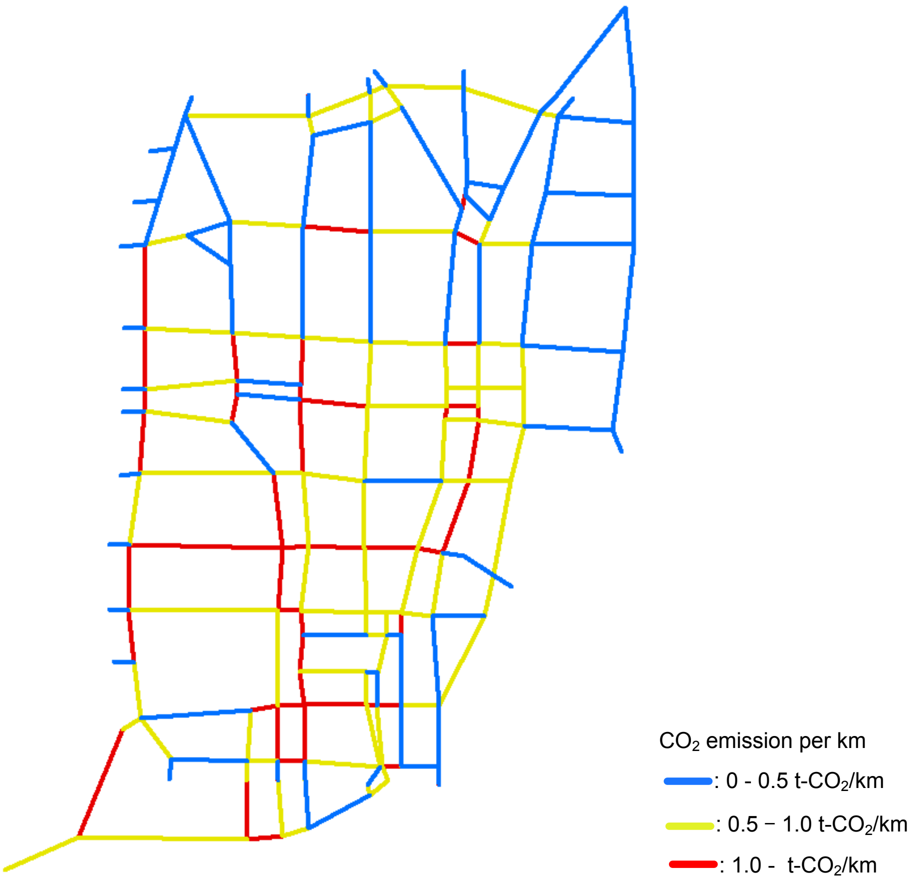

Figure 6 – CO_2 emissions per km for each link

Table 5 – Difference in CO_2 emissions for each method

Average speed	Number of links	Average CO_2 emissions for the traffic assignment method (kg CO_2)	Average CO_2 emissions for the traffic simulation method (kg CO_2)	RMS index
0–10 km/h	175	596	1,351	25.2
10–20 km/h	116	640	563	14.4
20–40 km/h	72	704	472	16.8
>40 km/h	58	444	232	16.4

Therefore, the degree of difference is smaller, the RMS value is small. This value becomes relatively small when estimated at average speeds over 10 km/h using the traffic assignment method. Calculated results obtained using the two methods differ greatly at 0–10 km/h (traffic congestion areas). In the traffic simulation method, the CO_2 emissions values are more than doubled. In the traffic assignment method, sequential traffic changes, such as acceleration, deceleration, and stopping at intersections, are not considered. Since the emissions differ even if the same average speed is observed, this gives a highly accurate traffic simulation. Therefore, in the traffic assignment method, the relatively small estimates are a result of insufficient consideration being given to traffic jams.

Traffic simulation and traffic assignment should be used properly by the purpose of the analysis. The input data for these calculations are different. Based on these results, this study uses the traffic simulation method.

The spatial distribution of road traffic CO_2 emissions in the city is examined. The CO_2 emissions for each section of the urban road network are added together to give the total in a zone. The CO_2 emissions of each zone are shown in Figure 7.

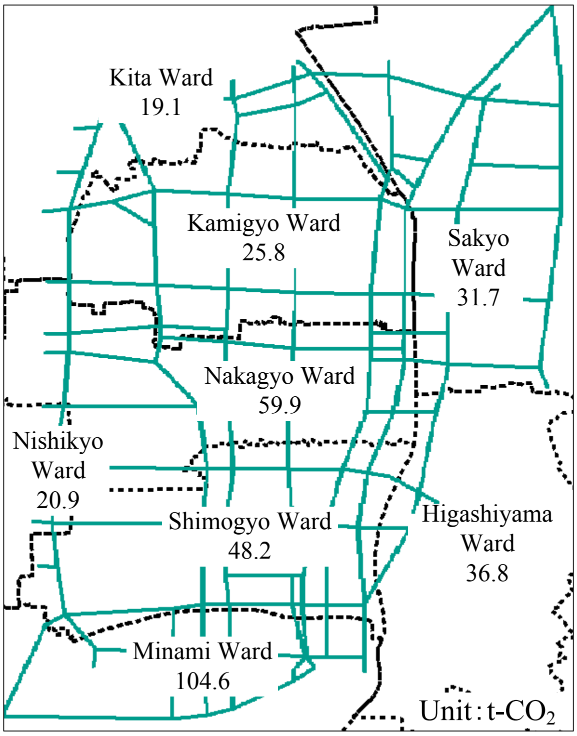

Figure 7 – Spatial distribution of CO_2 emissions

Minami ward, which is the location of the industrial sector, has the highest CO_2 emissions in the city, reflecting the traffic volume. In Nakagyo ward and Shimogyo ward, which correspond to the central business district (CBD), the effects of traffic congestion are seen, and the CO_2 emission estimate is high.

Kamigyo, Nakagyo, and Shimogyo wards are examined as they are situated entirely within the study area. In 2007, CO_2 emissions from automobiles in Japan were 217 million t of CO_2. The land area of Japan is 377,930 km^2, so the average CO_2 emission per year is 574 t-CO_2/km^2. The total combined area of Kamigyo, Nakagyo, and Shimogyo wards is 21.31 km^2, so the emissions for an average 3 h is 4.19 t of CO_2. Therefore, the result of the calculation in these three wards is 32 times the average emission.

4. EVALUATION OF URBAN TRANSPORT POLICY WITH REGARD TO ENVIRONMENTAL LOADING

In this section, an evaluation of the environmental aspects of two urban transport policies is carried out.

4.1 Hybrid vehicle popularization plan

In Japan, car tax reduction for low emission vehicles has helped to make vehicles with a high environmental performance popular. The effect of hybrid vehicles, which use both an engine and an electric motor, is particularly obvious in traffic jams. It is therefore considered beneficial for some vehicles to be hybridized.
The relationship between the degree of hybridization and CO_2 emissions is shown in Figure 8.

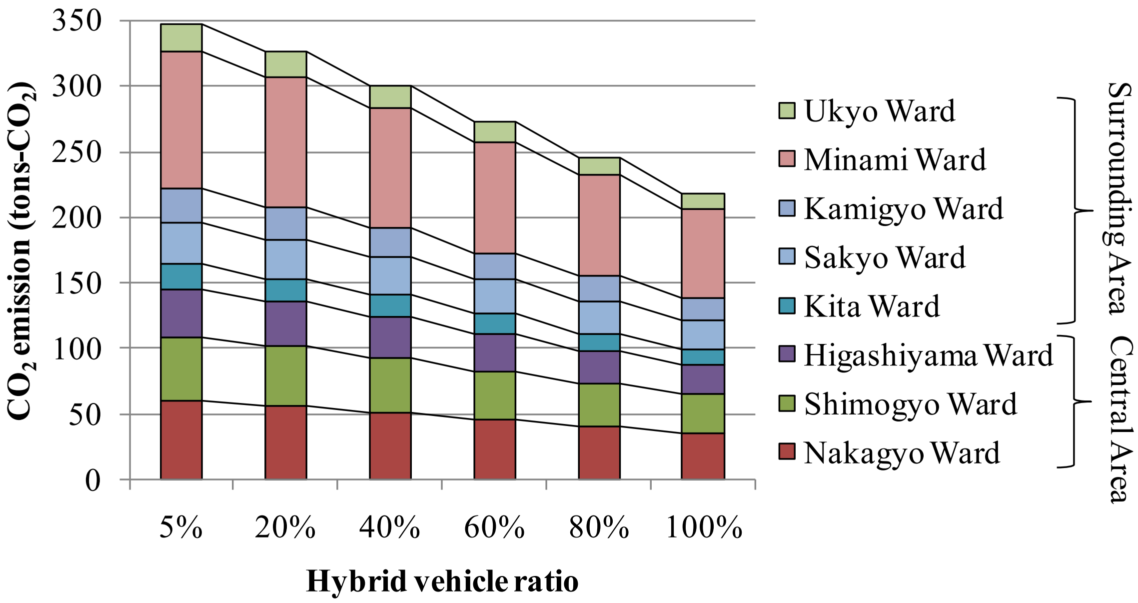

Figure 8 – Relationship between degree of hybridization and CO_2 emissions

When the degree of hybridization is 100%, the CO_2 emissions for the whole road network is 37%. The CO_2 reduction achieved by hybridization differs by zone. This is because the congestion level varies from zone to zone.

4.2 Traffic demand management (TDM)

All over the world, traffic policies such as road pricing are implemented to reduce traffic jams in city centers. In this study, traffic flow changes and environmental loading quantities are examined. Specifically, we look at reducing the constant rate in OD traffic volume which has the central city area (Nakagyo ward, Shimogyo ward, Higashiyama ward) as the origin or destination, as shown in Figure 9. The proportion of traffic which has the central city area as the origin or destination is 59.6% of all OD traffic volume.
This analysis uses the traffic simulation method, though it is also possible on the calculation by the traffic assignment method.
The relationship between OD traffic volume reduction rate and average speed is shown in Figure 10. For a 20% reduction, the average speed in the central city area increases by 1.6 km/h. Since the traffic volume in the surrounding area also decreases, the average speed in the surrounding area increases by 1.4 km/h. Therefore, this traffic policy reduces traffic jams.

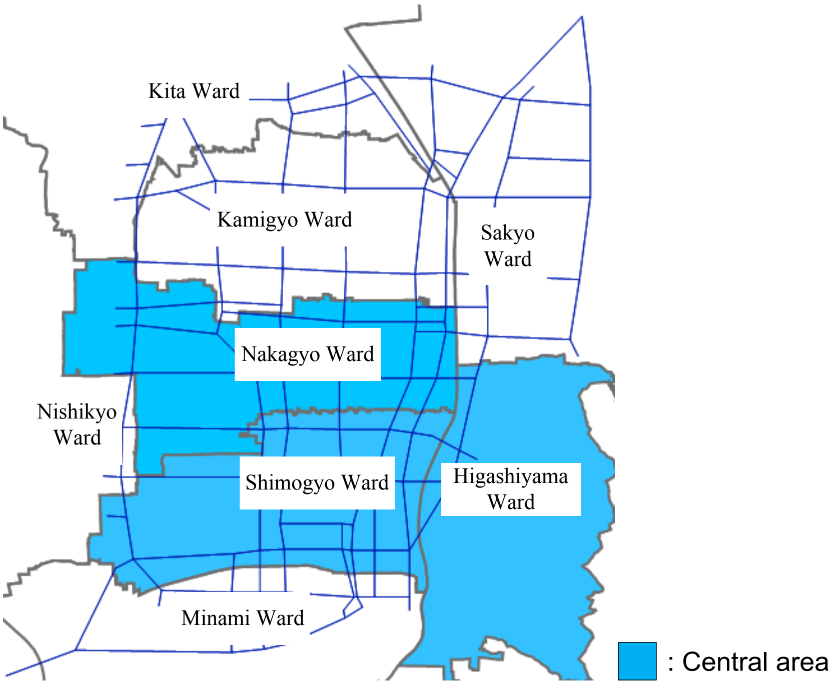

Figure 9 –TDM policy target area

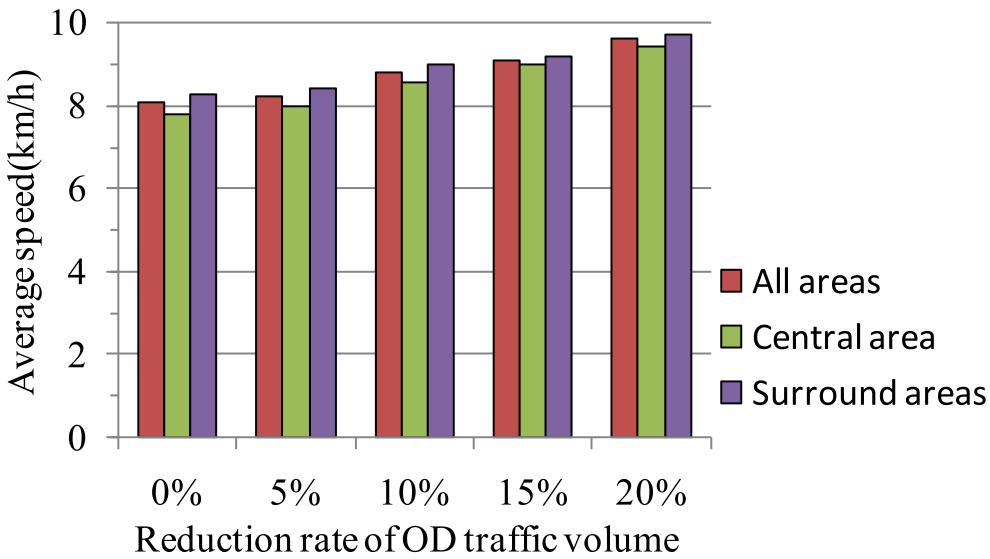

Figure 10 – Relationship between reduction rate and average speed

CO_2 emission reductions as a result of this traffic policy are now examined. The relationship between OD traffic volume reduction rates and CO_2 emissions is shown in Figure 11. When the OD traffic volume was reduced to 20%, emissions were reduced by 22% in the central city area. Emission reductions of 19% were achieved in the surrounding area, and overall reductions of 20% were achieved.

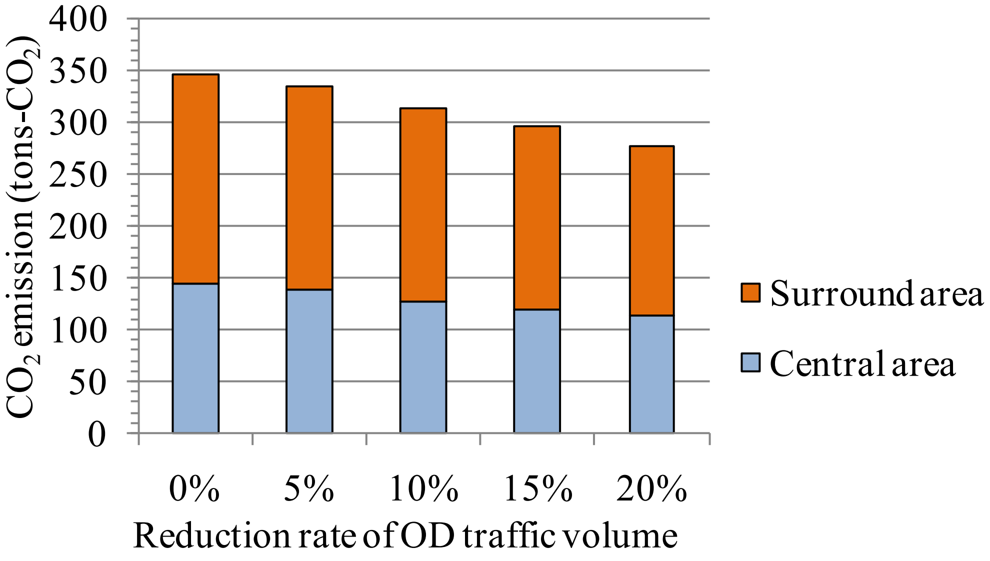

Figure 11 – Relationship between reduction rate and CO_2 emissions

4.3 Comparison of two traffic policies

With increased hybrid vehicle use, a hybridization degree of 56% is necessary to achieve CO_2 emission reduction quantities equal to a 20% reduction in OD traffic volume. These two traffic policies are different in character: automobile manufacturers promote hybridization, and traffic managers promote traffic demand countermeasures. The methods cannot be easily compared because the ease of implementation of the two policies is different. The simultaneous changes in CO_2 emissions obtained using the two traffic policies are examined. A hybridization rate of 50% and a 10% OD traffic volume reduction in the central city area both give CO_2 emissions of 259.9 t of CO_2. This represents a 25% CO_2 reduction rate. When a hybridization rate of 50% is used on its own, CO_2 emissions are reduced by 17%. When the OD traffic volume in the city center is reduced by 10%, CO_2 emission are reduced by 10%. Therefore, the individual effects are less than the combined effects. Traffic jams decrease when traffic demand control is carried out, but the effect of hybridization seems to fade a little. The combined policy is effective for CO_2 emission reduction.

5. CONCLUSIONS

The effects of environmental traffic policy are evaluated to examine global environmental loading. The main results of this study are as follows.
1) A quantitative environmental loading, which used road traffic simulation for the urban road network in Kyoto City, was executed. Realistic, accurate CO_2 emission predictions, based on a detailed description of the road traffic conditions, became possible. It was proven that the results of calculations based on the traffic assignment method generally give underestimates.
2) Environmental loading reduction in the urban road network by increasing the use of hybrid vehicles was calculated. The spatial distribution of the environmental effect in the city was deduced from the travel route of vehicles and the number of traffic jams. From this

examination, it was proven that local environmental impact assessments of urban road networks are also possible.
3) Environmental loading reduction based on traffic demand countermeasures was estimated in order to examine the potential effects of environmental traffic policy on the urban road network. It was possible to show the effectiveness of quantitative environmental traffic operation based on the environmental loading calculation.
In CO_2 emission reductions using urban traffic policy a) travel behavior changes with traffic regulation, and b) the role of public transport must be considered. Extensive quantitative examination of environmental loading reduction measures is necessary for the formulation of realistic traffic regulation technology. Future problems for study in this area are:
i) Efficient use of technology in urban area environmental policies for examination of local GHG emissions at the micro traffic scale.
ii) Examination of the environmental effects of synthetic traffic measures to increase use of low-pollution automobiles, along with transport sector policies such as environmental taxes, congestion reduction, etc.
iii) Clear evaluation of the economic consequences of GHG emissions and formulation of an achievable transport policy.

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