Practical Estimation of Carbon Dioxide Emission for Automobile by Neural Network

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Abstract—Global warming and its mitigation measures such as GHG (Greenhouse Gas) reduction have been extensively discussed all over the world. The transport sector occupied about 20% within the GHG of Japan. Countermeasures in the road traffic are urgent, since about 87% of the GHG emission of the transport sector is emitted from automobiles. For the effective reduction of the GHG such as CO₂, the quantitative analysis is necessary. Though the emission from the individual vehicle depends on various factors such as engine revolution, speed, and acceleration, that relation is complicated. Therefore, there is a limit on the modeling by the regression analysis. Then, the model which estimates the CO₂ emission from the individual vehicle using neural network is developed in this study. By including this model in the traffic simulation, the estimation of CO₂ emission becomes possible. Therefore, it is possible to examine traffic countermeasures considering the environmental effect.

I. INTRODUCTION

In Japan, the transport sector occupies 19.4% within carbon dioxide emission of 12.14 hundred-million t-CO₂ [1]. The reduction of the CO₂ emission becomes a world-wide problem. In motor companies, researches and developments of improvement of fuel efficiency are advanced. It is important to calculate the volume of CO₂ emissions accurately in order to introduce traffic countermeasures to global warming. The emission of the vehicle is fluctuating by running conditions, etc. However, the CO₂ emission estimate model considering running conditions is not developed sufficiently. Then, the CO₂ emission estimate model considering running conditions is developed in this study. The relation between explanatory variables and the CO₂ emission is complicated. Therefore, a neural network model is used.

II. MEASUREMENT OF THE CO₂ EMISSION OF THE VEHICLE

The CO₂ emission is measured using actual vehicles in order to develop the CO₂ emission estimate model. The method for estimating the CO₂ emission from the fuel consumption of the vehicle is also considered, since the CO₂ generates by the burn of the fuel. However, it is difficult that the detailed fuel consumption data of the engine is collected. Therefore, amount of the CO₂ emission is obtained by measuring the flow rate and CO₂ occupancy of the exhaust gas.

Following devices are mounted on the experiment vehicle: the CO₂ occupancy measuring device, the exhaust gas flow meter, the battery as the equipment operates. The adapter is installed in the muffler of the vehicle, and sensors and tubes are mounted in the adapter. The photograph of the muffler adapter is shown in Figure 1. By installing the recording device of speed, engine revolution, the running condition is recorded. The illustration of these equipment is shown in Figure 1.

Figure 1. Measuring devices on the experimental vehicle

The laboratory experiment using the chassis dynamo is a standard method on the exhaust gas measurement. The measurement accuracy for this method is high in order to use large-scale measuring device. However, the situation of the real road cannot be reflected in order to measure in the laboratory by the rotation of the tire. In this study, it is a feature to collect the data with running of real road using the compact device.

The data is collected in the 1 second interval for 2 vehicles. The characteristics of vehicles are summarized in Table 1.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of vehicle</td>
<td>Petrol passenger car</td>
<td>Hybrid passenger car</td>
</tr>
<tr>
<td>Engine</td>
<td>1.49 litter</td>
<td>1.49 litter</td>
</tr>
<tr>
<td>Fuel</td>
<td>Gasoline</td>
<td>Gasoline</td>
</tr>
<tr>
<td>Fuel consumption running at 10-15 mode</td>
<td>18.2 (km/litter)</td>
<td>30 (km/litter)</td>
</tr>
<tr>
<td>CO₂ emission running at 10-15 mode</td>
<td>135 (g/km)</td>
<td>77 (g/km)</td>
</tr>
</tbody>
</table>
The vehicle-B is almost same length and width as the vehicle-A. And, the engine of vehicle-B is same volume as the engine of vehicle-A. However, the CO₂ emission for the hybrid vehicle is less than vehicle-A in running at 10 - 15 mode.

It is necessary to collect the data in proportion to various roads and traffic situations in order to develop the CO₂ emission estimate model. In the experiment, the vehicles are operated on arterial road (56 km), urban expressway (22 km), and inter-city expressway (22km). The limiting speed of urban expressway is 50 – 80 km/h, and the limiting speed of inter-city expressway is 70 – 100 km/h.

III. DEVELOPMENT OF CO₂ EMISSION ESTIMATE MODEL

A. Explanatory variables of CO₂ emission estimate model

The CO₂ emission from the vehicle receives various effects such as engine revolution, running speed, acceleration, deceleration, road gradient, size of engine, etc. In this study, the running speed and the acceleration (including deceleration) are used as explanatory variables of a CO₂ emission estimate model [2]-[5]. In this study, CO₂ emission estimate models are developed for two vehicle type (vehicle-A, B).

B. Linear Regression Model

In this study, the linear regression model shown in equation (1) is defined.

\[ D_{CO_2} = \theta_\alpha \cdot v + \theta_\alpha \cdot a_\alpha + \theta_\alpha \cdot a_- + \theta_\alpha \]  

where,

\[ D_{CO_2} \]: CO₂ emission (g/s), \( v \): travel speed (km/h),
\[ a_\alpha \]: acceleration (km/h/s), \( a_- \): deceleration (km/h/s),
\[ \theta_\alpha, \theta_\alpha , \theta_\alpha , \theta_\alpha \]: parameters.

Parameters of the CO₂ emission estimate model of the passenger car (vehicle-A) is shown in Table 2. Parameters of each explanatory variable are significant at significance level 5%. The t-statistic of the constant term (\( \theta_\alpha \)) is 114.0. The value of constant term is the emission as the speed and the acceleration are zero. Therefore, it is correspondent to the emission in the idling. The parameter and the t-statistic of the acceleration are bigger than the parameter and the t-statistic of the deceleration.

Estimated value of CO₂ emission for the hybrid passenger car (vehicle-B) can be shown in Table 3. Parameters and t-statistics of the acceleration and the deceleration are same tendency of the vehicle-A. In the vehicle-B, the constant term is almost zero. The hybrid passenger car is stopped the engine, when there is no necessity to run with the engine power. Then, the CO₂ emission estimate model is developed for the vehicle-B excluding the constant term. Parameters of the model is shown in Table 4.

The CO₂ emission estimate models, which consider the characteristic of each vehicle, are developed.

The relationship between observed value of the CO₂ emission and estimated value of the vehicle-A is shown in Figure 2. If the CO₂ emission is over than 3 g-CO₂/s, the estimated value is less than the observed value. Therefore, the linear regression model cannot sufficiently explain the phenomenon in the CO₂ emission.

<table>
<thead>
<tr>
<th>Table 2. Parameters of the CO₂ emission estimate model (vehicle-A)</th>
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</thead>
<tbody>
<tr>
<td>variable</td>
</tr>
<tr>
<td>travel speed (( \theta_\alpha ))</td>
</tr>
<tr>
<td>acceleration (( \theta_\alpha ))</td>
</tr>
<tr>
<td>deceleration (( \theta_\alpha ))</td>
</tr>
<tr>
<td>constant term (( \theta_\alpha ))</td>
</tr>
</tbody>
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<table>
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<tr>
<th>Table 3. Parameters of the CO₂ emission estimate model (vehicle-B)</th>
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<tr>
<td>variable</td>
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<tr>
<td>travel speed (( \theta_\alpha ))</td>
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<tr>
<td>acceleration (( \theta_\alpha ))</td>
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<tr>
<td>deceleration (( \theta_\alpha ))</td>
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<tr>
<td>constant term (( \theta_\alpha ))</td>
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<tr>
<th>Table 4. Parameters of the CO₂ emission estimate model (excluding the constant term) (vehicle-B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>variable</td>
</tr>
<tr>
<td>travel speed (( \theta_\alpha ))</td>
</tr>
<tr>
<td>acceleration (( \theta_\alpha ))</td>
</tr>
<tr>
<td>deceleration (( \theta_\alpha ))</td>
</tr>
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</table>

Figure 2. The relationship between the observed value and the estimated value of the CO₂ emission (the linear regression model) (vehicle-A)
C. Neural Network Model

Explanatory variables and the CO$_2$ emission are complicatedly related. Therefore, the neural network model is examined in this study. It is features that the neural network model can describe the complicated and non-linear phenomenon. The model is developed using the hierarchical neural network which is a kind of the neural network model. The neural network structure of the CO$_2$ emission estimate model is shown in Figure 3.

Figure 3. The neural network structure of the CO$_2$ emission estimate model

Explanatory variables are identical with the linear regression model. This model is composed of a neural network of 3 layers.

The training of the neural network model is carried out using running data the same as the linear regression model. The running data of passenger car (vehicle-A) and hybrid passenger car (vehicle-B) are used.

The relationship between observed value and estimated value of the CO$_2$ emission of the vehicle-A is shown in Figure 4.

Figure 4. The relationship between the observed value and the estimated value of the CO$_2$ emission (the neural network model) (vehicle-A)

In the region of 2 g-CO$_2$/s or less, by comparing with the linear regression model, the observed value improved the difference. However, in the region over 2 g-CO$_2$/s, the difference is large. In the region over 3 g-CO$_2$/s, the emission is still underestimate. It is necessary to improve the estimate model.

The CO$_2$ emission estimate result of the vehicle-A is shown in Figure 5. This figure is estimated the CO$_2$ emission at the speed every 10 km/h and the acceleration every 0.5 m/s$^2$. The emission increases a little, even if the speed rises in the deceleration area. Opposite to the deceleration area, the emission increases greatly, if the speed rises in the acceleration area. In the neural network model, the nonlinear relation can be expressed.

The CO$_2$ emission estimate result of the vehicle-B is shown in Figure 6.

Figure 5. The CO$_2$ emission estimate result by using the neural network model(vehicle-A)

The emission increases, as the speed rises, as the acceleration increases. However, there is a part that the emission decreases for the high acceleration area.

In the vehicle-A, CO$_2$ over 1 g-CO$_2$/s is emitted at 0 km/h of speed. In Figure 7, the CO$_2$ emission for idling and deceleration are almost 0. This is shown features of the hybrid vehicle.

D. Improved Neural Network Model

The neural network model according to the condition is examined in order to improve the neural network model. This applies neural network model which differs in proportion to the condition.

In acceleration condition and deceleration condition, the load of the engine is different. Therefore, by dividing in case with the positive acceleration and case with the negative acceleration (deceleration), the model is developed. Individual neural network is construct to be the structure which inputs speed and
acceleration. This neural network structure is shown in Figure 7.

The learning is carried out using learning data (vehicle-A, vehicle-B) which is identical with regression model and simple neural network model. The relationship between observed value and estimated value of the CO$_2$ emission of the vehicle-A is shown in Figure 8. In the simple neural network model, in the region over 2 g-CO$_2$ at the CO$_2$ measuring value, the estimated value tended to estimate small. However, it has been improved a little in the improved neural network model. It is necessary to add the explanatory variable for further improvement in future, since the improved neural network model has a difference between observed value and estimated value yet.

In this study, the RMSE (root mean square error) is used as the index which shows the estimate error. The RMSE is shown in equation (2).

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (E_i - O_i)^2}
\]

where,

\(n\) : number of data,
\(E_i\) : \(i^{th}\) estimated emission (g-CO$_2$),
\(O_i\) : \(i^{th}\) observed emission (g-CO$_2$)

The RMSE of the CO$_2$ emission of each model is shown in Figure 9. Vehicle-A,B are compared. The vehicle-B is bigger for RMSE about 4 times. Though an output of the engine changes even in equal speed and acceleration by the charge situation of the battery, it seems to be a cause that this cannot have sufficiently modeled the hybrid vehicle. In the vehicle-A, the RMSE is big in the linear regression model, and RMSE of neural network model, improved neural network model becomes small in order. And, RMSE of the improved neural network model is similarly small on the vehicle-B. Therefore, it is good that the improved neural network model is used as a CO$_2$ emission estimate model.

The estimated value of CO$_2$ emission after the learning of every speed and acceleration is shown at Figure 10, 11. On the vehicle-A (passenger car), CO$_2$ emission of the neural network model and the improved neural network model is compared. In the region with the high speed and high acceleration, the CO$_2$ emission is largely estimated of improved neural network model. In the vehicle-B (hybrid vehicle), the CO$_2$ emission is estimated same tends in low speed region and deceleration region. In the simple neural network model, the tendency that the CO$_2$ emission increased cannot be observed in the part, as the speed increase, as the acceleration increases in the positive acceleration region. However, the CO$_2$ emission increases in
the improved neural network model, as the speed rises, as the acceleration increases. Therefore, stabilized estimate can be carried out in the improved neural network model.

Vehicle A, B are compared. In the region with the low speed, and the negative acceleration, the CO$_2$ emission of the vehicle-B is less. However, in the region with the high speed, and the positive acceleration, the emission is almost same as the vehicle-A. The hybrid vehicle demonstrates the effect in the place with many acceleration and deceleration of arterial road in the city. However, the effect is smaller in expressways. This fact seems to have appeared in the estimate result.

E. Emission factor of CO$_2$

Here, the emission factor is calculated independence of speed band. The CO$_2$ emission factor is defined as CO$_2$ emission per 1 km. The emission factor can also use the case in which the environmental loading quantity is calculated by using a traffic assignment. Generally, the emission factor is calculated in decided running pattern such as 10 – 15 modes, etc. [6]. However, the emission factor is calculated by the CO$_2$ emission independence of speed band, since there is the running data of the real road. Therefore, this emission factor is affected to the traffic situation and the running route. The actual road situation should be considered.

Emission factors independence of speed band are shown in Figure 12. The red line shows an emission factor at 10-15 mode which the manufacturer has announced. When the travel speed is low, the emission factor is large value. Especially, when the travel speed is 15 km/h or less, the emission factor is large value. This band is affected the traffic congestion. Therefore, if the travel speed is improved according to the traffic improvement countermeasure, the CO$_2$ emission is reduced.

Next, the emission factor independence of speed band of vehicle-B is shown in Figure 13. The effect by the speed is smaller than vehicle-A. And, the emission factor is not very large value even in the speed of 15 km/h or less. The vehicle-B is a hybrid vehicle. When the travel speed is low, the ratio of utilizes the motor power is high. The CO$_2$ emission is low value, if the speed is 45 - 65 km/h. In vehicle-A and B, the emission characteristics is different. Therefore, it is necessary that a petrol passenger car and a hybrid passenger car are estimated by dividing, in order to accurately estimate the CO$_2$ emission using a traffic assignment model, etc.

IV. COMPARISON ANALYSIS OF THE CO$_2$ EMISSION BY THE RUNNING PATTERN

In case of the countermeasure of a traffic flow smoothing, whether it expects the reduction of CO$_2$ emission is examined. Therefore, the emission by the difference between the running patterns is compared. Here, it is analyzed for the road section of about 1.6 km around the Osaka Castle, shown in Figure 14.

The Tanimachi-suji, which is the analyze road section, is an arterial road in which there are many traffic volume. Ten
signaled intersections exist in this road section. Regulation speed of this road section is 60 km/h.

The change of the running speed in some investigations is shown in pattern 1 of Figure 15. It begins from the condition of the signal stop, and the vehicle stops in the red signal on the way. Since travel time including the signal stop is the 183 seconds, the overall speed is 31 km/h.

In this study, three virtual running patterns are set. The pattern 2 does the running at 40 km/h constant rate. The pattern 3 and 4 receive the effect of the precedence car, and it assumes the situation which repeats acceleration and deceleration. The pattern 3 repeats acceleration and deceleration between 38 km/h and 42 km/h in the 8 seconds period. This acceleration and deceleration are 1 km/h/s. And, the patterns 4 repeats acceleration and deceleration between 36 km/h and 44 km/h in the 8 seconds period. This acceleration and deceleration are 2 km/h/s.

The CO$_2$ emission in each running pattern is shown in Figure 16. First, the vehicle-A is examined. In comparison with the pattern 1 and 2, the CO$_2$ emission of the pattern 2 is 63% of the pattern 1. Therefore, there is reduction possibility of the CO$_2$ emission of about 1/3 by the smooth running. In the patterns 3, which repeats acceleration and deceleration at 1 km/h/s, it increases 10% of CO$_2$ emission in comparison with the pattern 2. And, in the pattern 4, which repeats acceleration and deceleration at 2 km/h/s, it increases 17% of CO$_2$ emission in comparison with the pattern 2. Therefore, in the situation which repeats acceleration and deceleration by the traffic congestion, the CO$_2$ emission increases.

Next, the vehicle-B, which is the hybrid car, is examined. The CO$_2$ emission of pattern 2 is less than pattern 1. In the pattern 3 and 4, which repeat acceleration and deceleration, the CO$_2$ emission increases as well as the vehicle-A. In the pattern 1 (the real running pattern), the CO$_2$ emission of the vehicle-B is 42% of the vehicle-A in comparison with the vehicle-A,B. The CO$_2$ emission of the vehicle-B at the 10-15 running mode is 57% of the vehicle-A. Therefore, CO$_2$ reduction effect of the hybrid car is bigger than the 10-15 running mode.

V. CONCLUSION

The purpose of this study was the model for accurately estimating environmental effect quantity by urban highway improvement and traffic operation management was developed. A CO$_2$ emission estimate model considering running condition was developed. Results of this study are:

1) Models were developed for 2 kinds of vehicle using (1) a linear regression model, (2) a neural network model, (3) an improved neural network model. As the result, the improved neural network model was estimated with the small RMSE. It seems to be good that the improved neural network model is used.

2) The CO$_2$ emission by the running pattern was analyzed. As the result, it was proven that there was the drastic CO$_2$ reduction effect by the running which possibly eliminates acceleration and deceleration. In running patterns examined, it was proven that the CO$_2$ reduction effect of the hybrid car was bigger than 10-15 mode running of the auto manufactuter announcement.

Future works are 1) measurement procedure is devised in order to raise measuring precision, 2) data collection, model construction are carried out in more many cars, 3) the structure of the CO$_2$ emission estimate model considering the characteristic of the hybrid car is examined.

REFERENCES