ESTIMATION MODEL OF VEHICLE EMISSION CONSIDERING VARIATION OF RUNNING SPEED

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Abstract: In this paper, the authors propose a model which estimates vehicle emission such as nitrogen oxides to more precisely evaluate the differences of emission in the various vehicle running patterns appearing in the various traffic condition. Vehicle speed and acceleration within the study highway section are used for the estimation. In the study, the emission model of nitrogen oxides for a diesel vehicle which estimates the instantaneous emission from the relationship among the emission, the engine revolution and the torque, is formulated. Then, the model parameters are calibrated using the emission data obtained on a chassis dynamometer by the running patterns which represent various real traffic conditions. As a result, it is confirmed that the model has high accuracy. However, the variance of the estimates gets larger when the model is applied to a shorter highway section.

Key Words: emission model, nitrogen oxides, speed variation

1.INTRODUCTION

Local air pollution is still serious problem and traffic congestion is considered as one of the main causes. Therefore, it is important to estimate the local vehicle emission taking traffic condition into consideration to propose effective traffic management measures. To estimate the emission by the change of the traffic condition, an emission factor per unit distance by average travel speed is often used. This method can estimate the emission easily by the improvement of the traffic condition at the macro level, however we can not get appropriate estimates in the section such as the neighborhood of the intersection where the speed variation is large because the average emission for the long distance is estimated using the long distance test running patterns in the average speed model. Also, the emission may vary by the difference of running patterns in the different traffic and road conditions at the same travel speed and there is a problem of the validity of the running patterns to use for the measurement of the emission.

As the estimation model of exhaust gas which can consider acceleration and deceleration, there is an elemental model which was formulated dividing running pattern into element of the acceleration, the deceleration, the constant-speed and the idling. Penic and Upchurch (1992) has estimated the model every each element about oxides of nitrogen, hydrocarbon, carbon monoxide and fuel consumption based on the data of the speed, the acceleration and the emission. However the elemental model has a problem that the spatial expansion of the emission in case of acceleration cannot be considered.

On the other hand, the models have been proposed taking influence of the speed variation into account as for fuel consumption. Post *et.al.* (1984) proposed the model which estimates instantaneous fuel consumption using the proportional relationship between the engine power and the fuel consumption. Biggs and Akcelik (1986) proposed the model which estimates instantaneous fuel consumption by modeling running energy consumption from the motion equation of the vehicle. Oguchi *et.al.* (1996) analyzed fuel consumption using on-road measurement data by short trip unit and proposed the fuel consumption estimation model which consists of factors of travel time, travel distance and speed variation. However, as for the emission such as nitrogen oxides, the model are considered based on the model which supposed a same characteristic of the emission as the fuel consumption and the model was calibrated by the relationship between the emission and the fuel consumption measured under a stable running state (Post *et.al.*(1984), Taylor and Young(1996)), there is not an example in which the model is calibrated using the emission data of the real running pattern based on the model which considered an each characteristic of the emission.

In the study, therefore, we try to build a model which estimates the emission from the vehicle speed profile in the study highway section using the relationship between the engine condition and the emission and calibrate the model parameters using data measured by the real running pattern on a chassis dynamometer. First, we formulate the model which estimates instantaneous emission from the relationship among the emission, the engine revolution and the torque. If these relations can be formulated, it is possible to formulate the model for any polluted emission. In the study the emission model of nitrogen oxides of the diesel vehicle are formulated and the model parameters are calibrated using the emission data which could be obtained in the chassis dynamometer test by the running patterns which represent various traffic conditions obtained from the on-road running survey. And we verify the model by analyzing the relationship between the aggregating distance and the estimation accuracy and we clarify the characteristic of this model. Moreover, as an example of comparison with the other models, we analyze the estimation accuracy of proposed model and average speed model.

2.FORMULATION OF VEHCLE EMISSION MODEL

2.1 Framework of Estimation Model of Vehicle Emission

In the study, we try to formulate a model which estimates vehicle emission from the study highway section by describing the vehicle emission in the section as the change of the running condition which is expressed by the vehicle speed and acceleration. At first, the instantaneous emission is formulated as a function of the speed and acceleration using the relationship between engine status such as engine revolution and torque, and the emission. Next, cumulative emission is calculated by integrating the instantaneous emission.

Total emission F [g] in the study highway section and the instantaneous emission f [g/sec] can be expressed using engine revolution n [revolution per sec] and engine torque τ [N/m] as

$$\frac{dF}{dt} = f(n, \tau). \quad (1)$$

The engine revolution n has a relationship to vehicle speed definitely. There is following relationship if a clutch is connected:

$$n = \frac{v r_i}{2\pi R}, \quad (2)$$

where v is instantaneous vehicle speed [m/sec], R is effective radius of tire [m] and r_i is gear ratio at ith gear, multiplied by final reduction gear ratio.
Also, the effective engine torque can be written as a following equation by the vehicle kinematic equation using the vehicle speed and acceleration.

$$\tau = \frac{R_t R}{\eta r_i}, \quad (3)$$

$$R_t = \mu_r \cdot M \cdot g + \mu_a \cdot A \cdot v^2 + M \cdot g \cdot \sin\theta + (M + m_i)\alpha, \quad (4)$$

where R_t is total resistance [N], η is total transmission efficiency, μ_r is rolling resistance parameter, M is vehicle mass including occupants and any other load [Kg], μ_a is a aerodynamic resistance parameter [kg/m^3], A is area of vehicle's front projection [m^2], θ is grade of road in angle, which is positive in case of uphill, g is gravity acceleration [m/sec^2], m_i is equivalent mass of a rotated part at ith gear [Kg] ($m_i = m_1 + m_2 \cdot r_i$, where m_1 and m_2 is an independent part and a dependent part of equivalent mass from the gear position, respectively and α is instantaneous vehicle acceleration [m/sec^2].

Therefore, the instantaneous emission can be formulated as a relationship with speed, acceleration by finding out the relationship among the engine revolution, the torque and the emission from the engine map and supposing the formulation type of $f(n,\tau)$. By integrating the instantaneous emission in the time in the highway section, the estimation equation of the emission per total distance section can be obtained.

Strictly speaking, in case of the same n, τ, the emission in the regular condition (the condition which the engine is operating in some constant n, τ) is different from in the transient condition. Also, the emission is different in the condition of the engine, e.g. one immediately after start or one fully warmed up. Here, we suppose that we are in the condition in which we can ignore these influence and that it is the same emission in case of the same n, τ although there are actually many cases in which the influence mentioned above cannot be ignored. For example, at a gasoline-powered vehicle which is injecting fuel by the electronic control using the catalytic converter rhodium, these assumption cannot be applied because the difference of the emission by the transient condition. On the other hand, it is assumed that the assumption mentioned above can be applied for the most part at the large-sized diesel vehicle.

2.2 Formulation of the Model for the Nitrogen Oxides for Diesel Vehicles

In this part we will formulate a model for the nitrogen oxides of the diesel vehicle. The instantaneous emission of nitrogen oxides f is proportional to the engine power Pe based on the previous research. Therefore, the model can be described as follows:

$$f = k' \cdot Pe + f_i \ : \ Pe > 0,$$

$$= f_i \qquad : \; Pe \leq 0 ,$$

where k' is a parameter and f_i is the emission of nitrogen oxides in idling.

On the other hand, the engine power is proportional to the product of the engine revolution and torque. From this, the $f(n,\tau)$ can be written as follows:

$$f(n,\tau) = k \cdot n\tau + f_i \; : \; \tau > 0 , \tag{5}$$

$$= f_i \qquad : \; \tau \leq 0 ,$$

where k is a parameter.

Plugging Equations (2), (3), and (4) into (5), the instantaneous emission can be expressed as:

$$f = \frac{dF}{dt} = \delta \left(\frac{k \cdot v \cdot R_t}{2\pi\eta} \right) + f_i = c_1 \delta v + c_2 \delta v^3 + c_{3i} \delta \alpha v + c_4 , \tag{6}$$

where $c_1 = k(\mu_r + \sin\theta)Mg / 2\pi\eta$, $c_2 = k\mu_a A / 2\pi\eta$, $c_{3i} = k(M + m_i) / 2\pi\eta$, $c_4 = f_i$, δ: 1 when $R_t > \tilde{0}$ and 0 $R_t \leq 0$. The parameter c_{3i} varies by gear ratio. For example, suppose gear ratio of low gear (1st gear) is about 4, that of over top (5th gear) is about 0.8 and final gear ratio is about 4, then the parameter c_{35} is approximately 1.3 times large as c_{31}. And the condition that $R_t > 0$ can be obtained by equation(6) as:

$$\alpha > -\left(\frac{c_1 + c_2 v^2}{c_{3i}} \right) . \tag{7}$$

Equation (7) should be used to apply the equation (6) to real running pattern.

The total emission F [g] in running distance X [m] is derived by integrating instantaneous emission f, equation (6), during running time T [sec]. In the equation there is a parameter c_{3i} which depends on the gear position. The gear position is appropriately operated by the driver and depends on the operation manner of the driver. In estimating the instantaneous emission, the effect of the gear position could not be neglected in principle but it can be assumed constant for a fairly long highway section. Here we suppose two cases of the gear ratio as follows.

Model* (i) *: constant gear ratio

As mentioned above, differences of c_{3i} between lower gear and higher one is not so large. Therefore, suppose that c_{3i} is constant (= c_3) and that it gives an average value, the model can be revised as follows:

$$F = c_1 \cdot Z_v + c_2 \cdot Z_{v3} + c_3 \cdot Z_{\alpha v} + c_4 T , \tag{8}$$

where $Z_v = \int \delta v dt$, $Z_{v3} = \int \delta v^3 dt$ and $Z_{\alpha v} = \int \delta \alpha v dt$.

Model* (ii) *: gear ratio as a function of vehicle speed.

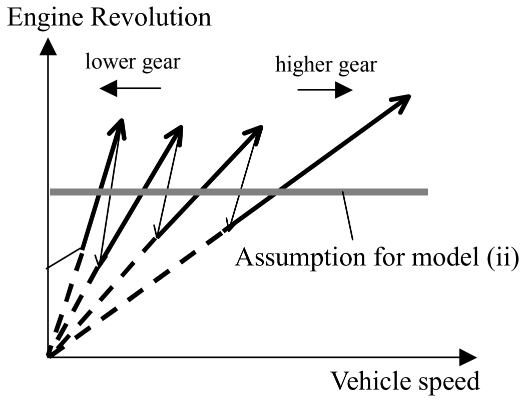


Figure 1 Relation Between Vehicle Speed and Engine Revolution

The gear position is chosen by the driver for necessary speed and acceleration to be achieved according to the traffic and road condition. Figure 1 shows the relationship between the engine speed and revolution in acceleration abstractly. Generally, when the vehicle speed is low in which the large torque is needed, the lower gear position, e.g. large gear ratio, is chosen and the gear position is shifted up to high with small gear ratio as the vehicle speed increases. Here, we simplify the relationship and introduce into the model. That is, we suppose that the relationship between the engine revolution and the speed is the straight line as the engine revolution becomes constant as shown in figure 1 and we think that gear ratio r_i is chosen according to this. In this case, the relation of following inverse proportion is obtained from the relation of the equation (2) between the vehicle speed v and engine revolution n.

$$r_i = c / v, \tag{9}$$

where c is a constant parameter. Substituting (9) for the equation (6), F can be obtained as follows.

$$F = c_1 \cdot Z_v + c_2 \cdot Z_{v3} + c_{3a} \cdot Z_{\alpha v} + c_{3b} \cdot Z_\alpha + c_4 T , \tag{10}$$

where $c_{3a} = k(M + m_1) / 2\pi\eta$, $c_{3b} = k \cdot c \cdot m_1 / 2\pi\eta$ and $Z_\alpha = \int \delta \alpha dt$.

The model (i) and (ii) consist of four and five parameters and variables, respectively. In the first clause, the parameter c_1 is related with rolling and grade resistance and Z_v is a variable related with running distance. If a vehicle is running with driving force, that is $\delta = 1$, through the whole section, Z_v is equal to running distance. In the second clause, the parameter c_2 is related with aerodynamic resistance. The effect of this clause is negligibly small if vehicle speed is low, but the faster vehicle speed is, the larger the effect is rapidly. A variable $Z_{\alpha v}$ is related with the speed variation. Oguchi *et.al.*(1996) pointed out $Z_{\alpha v}$ is equivalent to the summation of the energy needed only in accelerating conditions, named Acceleration Energy Equivalence (AEE). A variable Z_α in the model (ii) is also related with speed variation, but it is derived in case change of gear ratio. It means the summation of the increment of the speed. Anyway we can estimate the emission of nitrogen oxides if we can estimate these aggregated variables Z_v, Z_{v3}, $Z_{\alpha v}$, Z_α and travel time T in the study highway section using the models.

3.CALIBRATION OF MODEL PARAMETERS

3.1Parameter Calibration by Vehicle Emission Data

To examine fitness of the model proposed in the previous section, we calibrated model parameters using time-dependent emission data and vehicle velocity patterns observed by the tests on a chassis dynamometer. In the study, we used large-sized diesel trucks as test

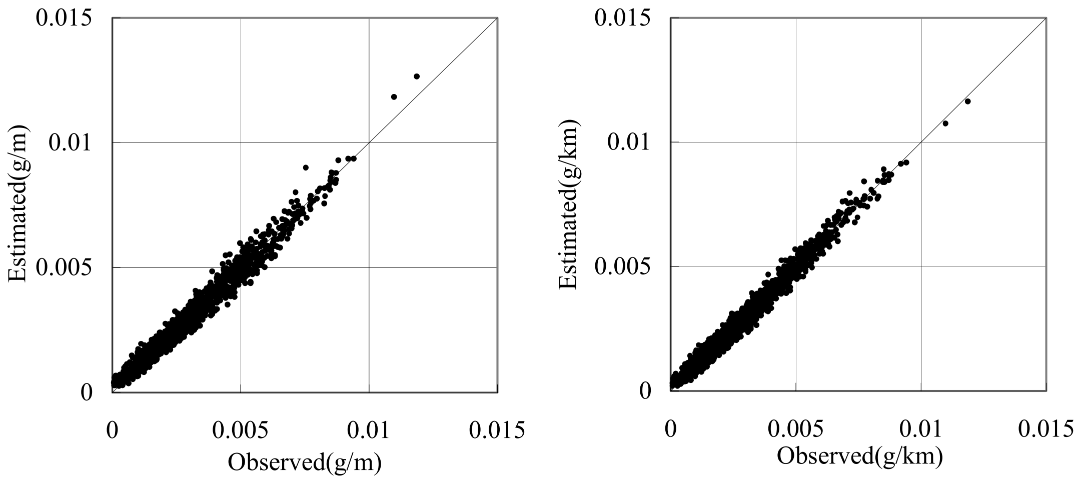
Table 1 Specification of Test Vehicle A

Total Length(mm)	8480	Maximum Power(PS/rpm)	210/2850
Total Width(mm)	2260	Maximum Torque(kgm/rpm)	55/1700
Total Height(mm)	2760	Gear Ratio	
Vehicle Mass(kg)	3680	1st	6.378
Passenger Capacity(per.)	2	2nd	3.627
Maximum Load Mass(kg)	4100	3rd	2.307
Total Vehicle Mass(kg)	7890	4th	1.452
Engine Type	Diesel, NA	5th	1
Compression Ratio	18.5	6th	0.723
Total Engine Displacement(cc)	8226	Final Reduction Gear Ratio	4.555

Table 1 Result of Model Calibration

# of Data=5460

	Model (i)		Model (ii)	
R	0.984		0.987	
R^2	0.968		0.973	
	parameter	(t-value)	parameter	(t-value)
c_1	0.000906	(77.30)	0.00103	(91.70)
c_2	2.66E-06	(91.94)	2.57E-06	(97.52)
c_3	0.00726	(265.03)		
c_{3a}			0.00589	(124.87)
c_{3b}			0.00277	(34.24)
c_4	0.00485	(168.21)	0.00362	(81.32)

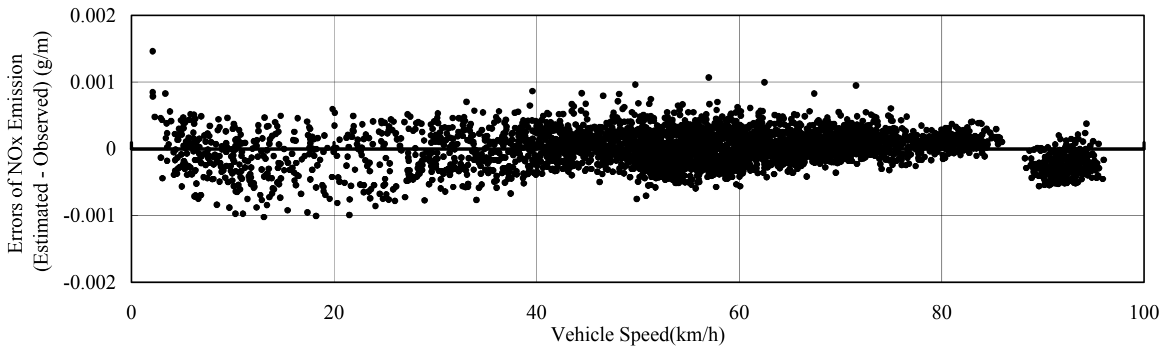


(a)Model (i) (b)Model (ii)

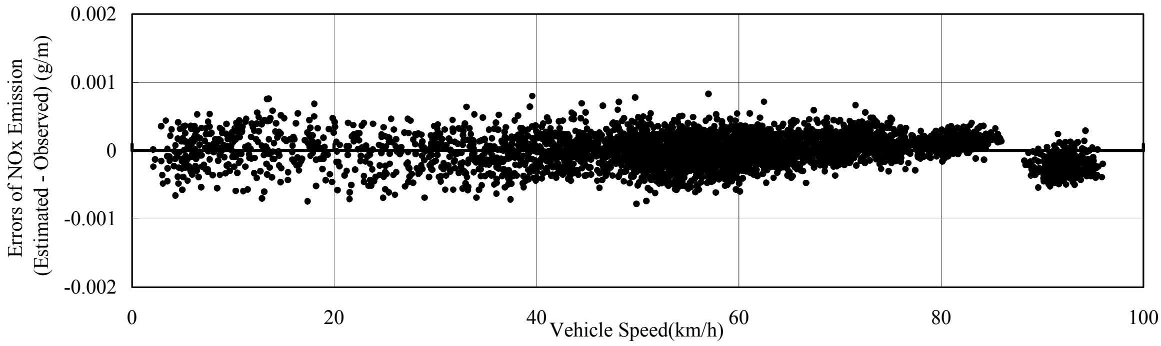
Figure 2 Observed-Estimated Relation of Nitrogen Oxides Emission vehicles. Table 1 shows the specification of one of the test vehicles (call Vehicle A). The data were obtained by chassis dynamometer tests using two sets of several running patterns, named “PWRI modes”(Oneyama *et.al.* (1999)) and “JARI modes”(Hirai *et.al.* (1996)), which represent various road types and traffic condition. These test patterns include traffic congestion in the urban arterials, suburban by-pass in which signal density is low, congested flow and free flow in the expressway. The number of modes tested in the vehicle A is 24 and total test running time is about six hours. We measured emission data such as nitrogen oxides, carbon dioxide and vehicle running data such as velocity, acceleration and engine revolution by every 0.2 seconds. Also, the load of the test vehicle was in the half loaded condition and grade of road is 0%. The vehicle was sufficiently warmed up to stabilize the emission.

These data were aggregated by every 100 meters, and we estimated the model parameters for the model (i) and the model (ii) by multiple regression analysis. The result is shown in Table 2 and Figure 2. It gets good estimated accuracy with two models, but the accuracy of the high concentration emission area, namely the condition that the vehicle starts accelerating with the lower gear, is improving by considering an effect of gear ratio specifically in the model (ii).

To examine the differences of the proposed two models, we analyzed the relationship between vehicle speed and errors shown in Figure 3. The model (i) tends to underestimate the emission especially in the low-speed area, from 5km/h to 30km/h. The model (ii) seems to improve this tendency shown in the model (i). In the model (i), the parameter c_3 with respect to the acceleration is constant, not depending on speed. So in the low-speed area, it is estimated smaller than the case to have considered a gear ratio. In this case, the emission



(a) Model (i)



(b) Model (ii)

Figure 3 Vehicle Speed and Errors

with respect to the acceleration is underestimated, but at the same time the parameter c_4 with respect to travel time is overestimated. Therefore, the emission tends to be underestimated in the area from 5 km/h to 30 km/h in which effect of acceleration excels. On the other hand, in the area less than 5 km/h in which the effect of travel time excels, it tends to be overestimated. In the model (ii), these tendencies are comparatively improved because an effect of gear ratio in the low-speed area is considered in the model.

Besides, we can see the fact that the emission is underestimated in the area in which the speed exceeds 90 km/h. The reason is considered to be the effect that the emission increases because the linear relationship between the emission and the engine power is severed with the high load operation in this area.

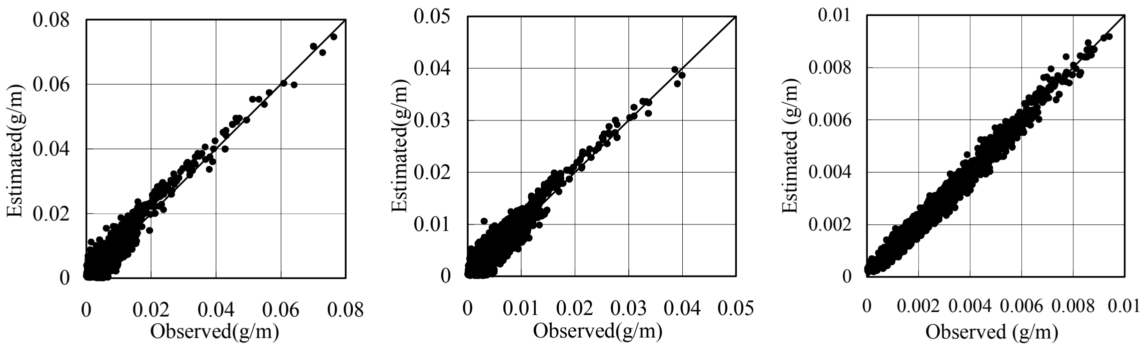
4. MODEL ACCURACY BY DISTANCE OF HIGHWAY SECTION

In this section, we analyze the relationship between the aggregating distance of highway section and the estimation accuracy of the emission using the actual data. We have calibrated parameters of the model in the previous section with the aggregating distance of highway section temporarily as 100 meters. Because the relationship between the vehicle emission and the explanation variables in the model has linear proportion, the parameters should become constant regardless of the aggregating distance unless the real data contradict the model. However, at the short aggregating distance, there may be large differences of the vehicle emission because of the difference of the engine's burning condition, measurement delay of the emission and so on. On the other hand, in case of the long aggregating distance, there may be the partiality to the estimation result with the case that the parameters that were calibrated at the short aggregating distance are used.

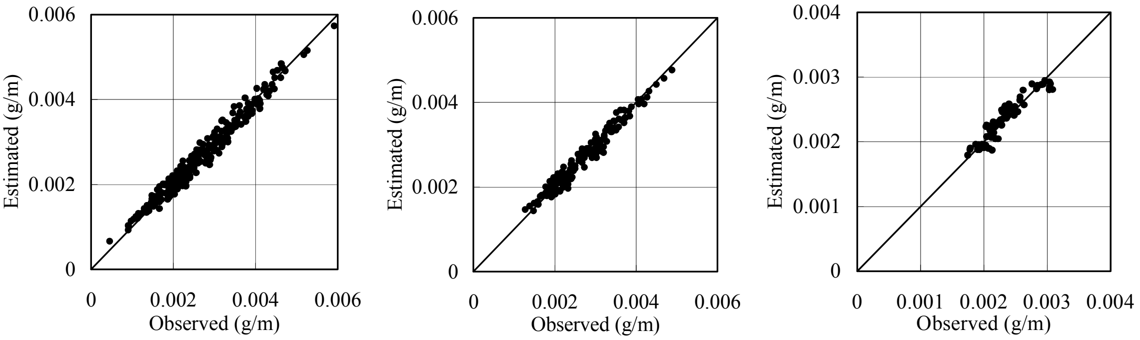
Therefore, we studied the estimation accuracy by changing the aggregating distance of the study highway section using the same emission and running pattern data used in the previous section. To see the differences by the aggregating distance in the same parameters, the parameters calibrated in the previous section, by the aggregating distance is 100 meters, were used in this analysis.

Figure 4 shows relationship between the observed and the estimated value according to the aggregating distance. The error becomes smaller as the emission becomes larger. Also, the error becomes larger in the small part of the emission, and this tendency becomes strong especially with short aggregating distance. In case of the large emission, the estimation accuracy is kept high comparatively because the contribution in the travel time is large and in this case the idling emission is stable. On the other hand, in the part of the small emission, the contribution in the change of the running condition is large and it shows that the emission in running tends to change.

Figure 5 shows relationship between the aggregating distance in the highway section and the standard deviation of errors based on the result of figure 4. When the aggregating distance becomes less than roughly from 50 to 100 meters, the error is increasing rapidly. It is thought that when the aggregating distance becomes short the factor of the emission change which cannot be explained by the model increases, and that the various deviations that exist between the engine condition and the emission, for example the emission in the transient condition, clarify as the aggregating distance becomes short, i.e. the running time excluding the idling time becomes short. Besides, various reasons can be considered, for



(a) Distance = 5meters (b) Distance = 10 meters (c) Distance = 100 meters



(d) Distance = 500meters (e) Distance = 1000m (f) Distance = 5000 meters

Figure 4 Examples of Observed-Estimated Relationship of Nitrogen Oxides Emission According to Aggregating Distance

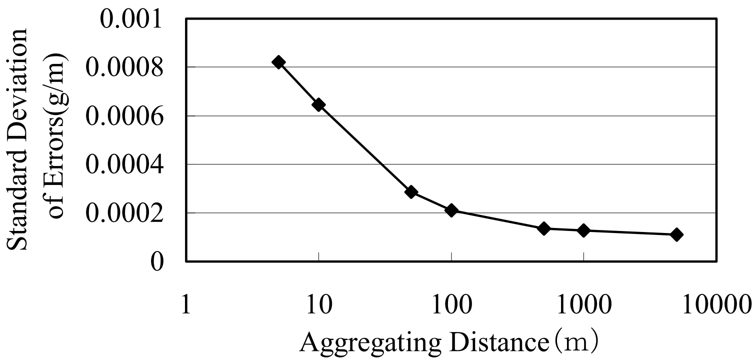


Figure 5 Relationship between Aggregating Distance and Standard Deviation of Errors (Model (ii))

example the problem of the measurement precision, by the presence of the time lag between the emission of the engine burning and the running condition of the vehicle. In any case, it is considered that the aggregating distance of about 10 meters is the limit of accuracy of this model.

Incidentally, the relationship between the aggregating distance and the error depends on the characteristic of the vehicle emission. It is considered that the error becomes larger at the vehicle as emission is mainly influenced by the transient engine condition and the vehicle with the unstable emission characteristics.

5.COMPARISON WITH AVERAGE SPEED MODEL

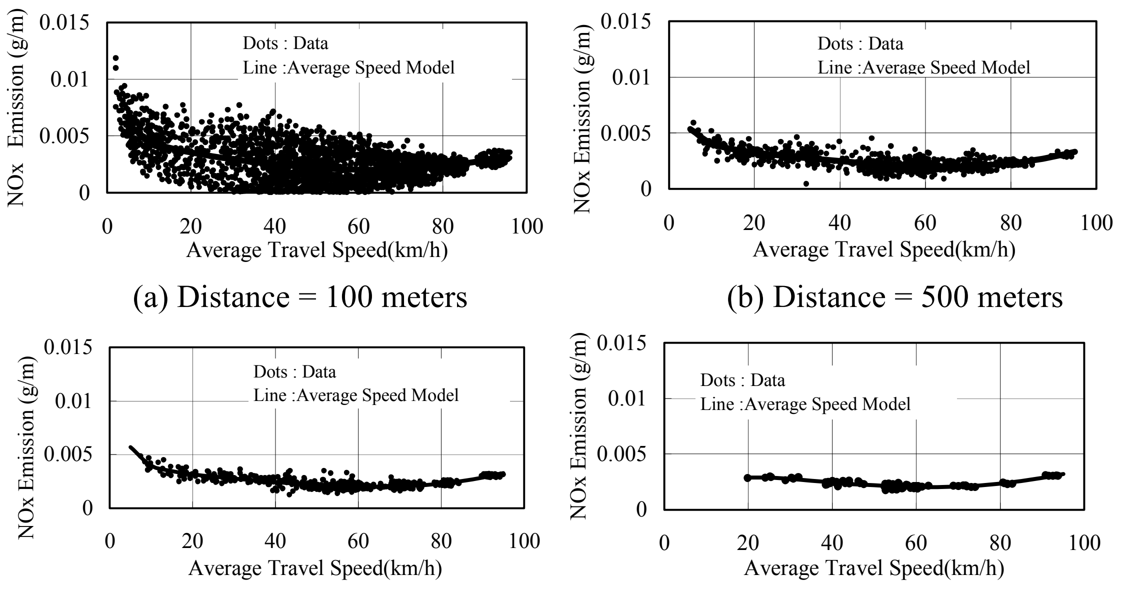
In this section, we try to compare the accuracy between the emission model using an average speed as an explanation factor and the model proposed in the study. Emission factors according to the average speed are often used for the estimation of the emission level to have considered the difference of a traffic condition by the macro level, especially in Japan. This method enables us to estimate the emission handily while considering influence by the traffic measures. However the same average travel speed differs in the running pattern, the difference of the running pattern cannot be considered in the method. In this section, we will show the usability of proposed model in the short highway section, such as intersections, in which the speed change is large in comparison with the average speed model, as well as we will clarify the applicability of the average speed as an handier and more useful model.

The relationship between the vehicle speed and the emission level is generally expressed as follows:

$$f = a_1 + a_2 / v + a_3 v + a_4 v^2 + a_5 v^3 , \qquad (11)$$

where f is an emission factor, e.g. the mass of emission per unit distance [g/m], v is an average travel speed[km/h], a_1, a_2, a_3, a_4 and a_5 are parameters.

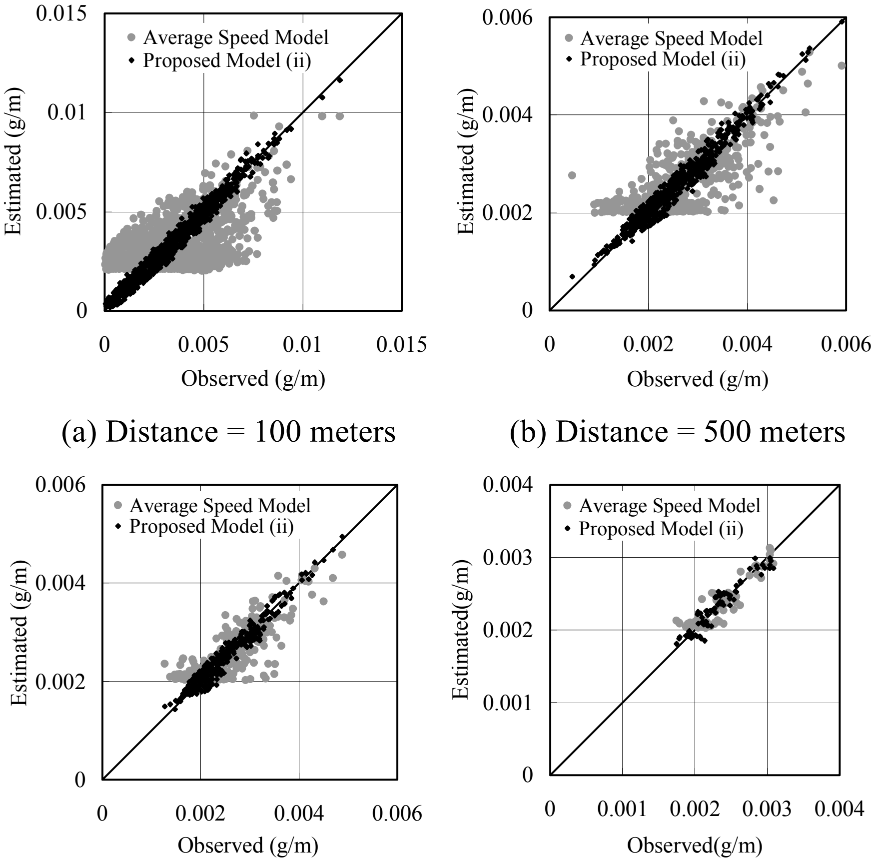
Generally, the emission is often a convex function of the average travel speed for unit running distance. In other words, in the low speed area the emission reduces as the average travel speed goes up by the decrease of both the idling time and number of times of the acceleration and the deceleration. On the other hand, the emission increases from some average speed as the speed goes up because of an increase of the engine load by higher speed running. As an example, Figure 6 shows a relationship between average travel speed and the nitrogen oxides emission for the diesel truck in this study. At the case of figure 6(a) in which aggregating distance is short, the differences between observed and estimated values become larger because of the effect of differences of running characteristics at the



(a) Distance = 100 meters (b) Distance = 500 meters

(c) Distance = 1000 meters (d) Distance = 5000 meters

Figure 6 Relationship between Average Speed and Nitrogen Oxides Emission



(a) Distance = 100 meters (b) Distance = 500 meters

(c) Distance = 1000 meters (d) Distance = 5000 meters

Figure 7 Examples of Observed-Estimated Relationship
(Proposed Model and Average Speed Model)

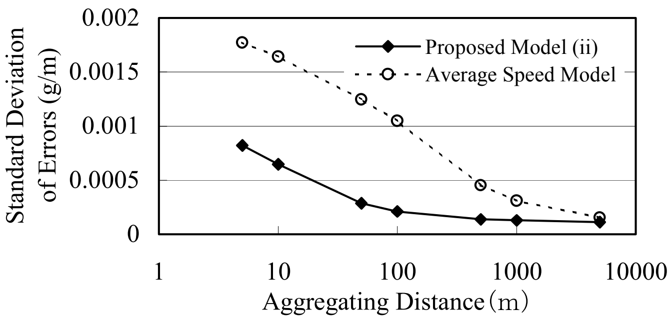


Figure 8 Aggregating Distance and Standard Deviation of Errors
(Proposed Model and Average Speed Model)

same running distance, that is mainly that of acceleration and deceleration. On the other hand, as the aggregating distance is getting longer, the difference becomes comparatively small because the running characteristics become averaged. In figure 6, the relation curve between average travel speed and the nitrogen oxides emission in the equation (11) from each data is shown all together.

We analyzed the relationship and the estimation error between the estimated and observed values about the average speed model and the proposed one by changing aggregating distance from 10 to 5000 meters by the same vehicle data (Vehicle A) used in chapter 3.

Figure 7 shows relationship between the observed and the estimated values according to the aggregating distance. Also, figure 8 shows relationship between the aggregating distance and the standard deviation of errors. As the aggregating distance becomes short, the error becomes large by the average speed model. It means that it is difficult to estimate precisely the emission only by the average speed. Specifically, the tendency is obvious in the area that the emission is small. Even in such a case, the proposed model that considered vehicle speed variation can estimate the emission precisely.

On the other hand, because the deviation of the acceleration and the emission becomes small on the average when the aggregating distance gets for some degree to be large, an estimation error become sufficiently small by the average speed model. In the calculation example, in case of the aggregating distance of about 5000 meters the error becomes the same degree almost in two models.

6.CONCLUSIONS

In the study, we built a model which estimates the emission from the vehicle speed profile in the highway section. We showed an idea of the model to estimate instantaneous emission from the relationship among the emission, the engine revolution and the torque. Then, the emission model for nitrogen oxides from diesel vehicles was formulated. In the model, the emission can be estimated using aggregated variables related to vehicle speed and its speed variation. The parameters of the model were calibrated using chassis dynamometer tests by the running patterns which represent various traffic conditions. And the model was verified by analyzing the relationship between the aggregating distance and the estimation accuracy. At last we compared the accuracy between an average speed model and the model proposed in the study.

The model estimating the nitrogen oxides proposed in the study has high accuracy. Especially, the accuracy of the low speed area is improved in the model (ii) by taking the change of gear ratio by the vehicle speed into consideration. This model can explain the variation of the emission by the fluctuation of vehicle speed in the shorter highway section, which cannot be explained well by the average speed model. Thus the model has a advantage to estimate the local emission more precisely in the highway section in which it is necessary to consider the fluctuation of vehicle speed, for example, when evaluating the effect of the emission around the intersection by the signal control measure and when estimating the emission in the congested highway section.

The result obtained in the study is only for nitrogen oxides from a diesel vehicle based on a limited data. So this model should be formulated and calibrated for the other emission such as hydrocarbon and particle matter using so many emission data.

Another problem to estimate the emission is how to estimate the variables calculated by the vehicle speed profile. To estimate the emission by the result of a traffic simulator or the other traffic flow analysis, the procedure to relate the result of traffic analysis to the variables of the emission model is needed. Another option is to measure the vehicle speed directly. Recent new technologies developed to measure the speed and the acceleration using mobile positioning devices such as GPS and PHS, and video sensing technique are useful.

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