Study on the Modeling Method Suitable for Pavement Rutting

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Abstract: In case of fitting geometric model of pavement rutting to the real data, the model of a high order function has the well advantage of fitness. However, it also has the disadvantage of versatility. In this study, we developed the pavement rutting models with quadratic function and spline function for quantification of pavement rutting characteristics on road surface. The two developed models are verified in respect of the adaptability of these shapes and the accommodation for the simulation method of the vehicle dynamics using the road profile data of the PIARC EVEN experiment in 1998. As a result, it is indicated that the spline function is applicable for representing pavement rutting characteristics.

Keywords**:** *Rutting, Pavement Rutting Model, EVEN Data, Road Profile, CarSim*

1. Introduction

A paved road surface is in contact with a vehicle directly through its tire therefore its condition is closely associated with vehicle running[1)]. It also greatly affects road user's ride quality, safety and the living environment of roadside resident. Therefore, it is important to keeping track of the conditions and evaluate the conditions of the paved road surface, then make the suitable maintenance at the appropriate time according to the evaluation[2)].

A major distress mode of the paved road is caused by road surface characteristics, such as rutting (pavement rutting), roughness and crack. Rutting and roughness are a special concern because these will affect road user and roadside resident directly.

A longitudinal profile such as roughness has associated with elements which are related to the road user's rating[3)]. On the other hand, for the problems of a transverse profile such as the rutting, although there are the attempts being made to evaluate the rutting which affects the vehicle stability and controllability[3)], it has not yet reached to establish the evaluation index with the road user's point of view.

In Japan today, rut depth as an index for maintenance of the rutting has some disadvantages[2)]. For instance, the index has problems the measurement method and definition of the rut depth differs from one administrator to another and it is does not reflect the road user's point of view.

There are two experimental approaches to estimate the road profile which affects vehicle behavior and road users. One approach is to use the actual vehicle with real road conditions. And the other is to use the simulation based on the vehicle dynamics (vehicle dynamics simulation). Recently vehicle dynamics simulation have developed and its achievements have become a center of attraction because it can do experiments to diagnose the road profile safely, rapidly and efficiently with same driving situation[3)-6)]. The experiment for the rutting evaluation with the simulation has studied to concentrate on the vehicle dynamics[3)]. However, the rut shape which is the object of investigation, especially the rutting caused by flowing which depends on heavy traffic, did not take into account the actual shape at the existing road, although it approximated only depression in the wheel path.

Against this background, for the purpose of quantitative grasp of the rut shape, we developed the geometrical models of the rutting (the pavement rutting models) which simplified and approximated by use of comparatively easy functions and which have a moderate flexibility. The developed models were verified in respect of the adaptability of these shapes for actual road profile data and the applicability for the simulation method of the vehicle dynamics.

The actual road profile is using part of the data which is obtained from the second Permanent International Association of Road Congress – World Road Association (PIARC) International Experiment to Harmonize Longitudinal and Transverse Profile Measure and Reporting procedure (EVEN Project)[1)]. While there are various types of vehicle dynamics models or simulation

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software depending on the purpose for which they employed. In this study, the CarSim which developed by University of Michigan Transportation Research Institute (UMTRI) has been used as the vehicle dynamics simulation[7].

2. Analysis of the Rut Shape

(1) Actual Profiles

In the EVEN Project in Japan, fifteen sections which include national highways, prefectural roads and national expressways were selected as a test site in Hokkaido; and measurements were carried out in July 1998. In this study, Site No.4 which includes severe rutting with flowing is selected as the object of rut shape analysis, in consideration of the rutting caused by flowing has dominated in the existing distress with rutting. Actual profiles at the analysis were obtained by use of a rolling inclinometer, static inclinometer and rod and level; a rolling inclinometer has been used to obtain a continuous profile and the measurements have been adjusted with the static inclinometer and rod and level measurements[1]. The distance of measurement section was 100m and lane width was 2.9m. A sampling interval of transverse profile is re-sampled to100mm, and reference point is set at lane center. **Fig.1** shows an example of actual profile data.

(2) Definition of Rut Depth

Rut depth is the index to evaluate the rutting for rehabilitation or maintenance activity, and it is mentioned above that the method of rut depth measurement differs respectively depend on each administer. The definition of rut depth is the procedure to calculate the depth of rutting from measurements. Generally, the definition of rut depth measurement are roughly distinguished into two types which are the Average Method and the Peak Method as shown in **Fig.2**. The Peak Method tends to indicate deep value rather than the Average Method. Therefore, in this study, the Peak Method defines the rut depth from fail-safe point of view. Here, rut depth is deeper value between D_1 and D_2 shown in **Fig.2**.

(3) The Pavement Rutting Characteristics

As shown in **Fig.1**, it seems that the each wheel paths are located around $\pm 1000mm$ from lane center in horizontal direction and the shape looks like a parabola. Furthermore, the shape is asymmetric about a line of central and the vertex of the parabola has a bias toward positive direction.

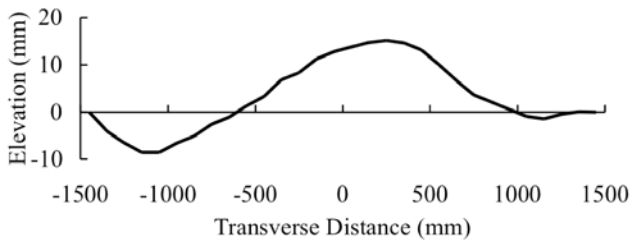
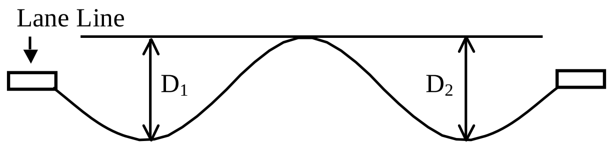


Fig.1 An Example of Transverse Profile

(a) Definition of the Average Method



(a) Definition of the Peak Method

Fig.2 Definitions of Rut Depth Measurement

Following chapters provide the development of the rutting models with the analysis mentioned above.

3. Geometrical Design of the Pavement Rutting Model

(1) Selection of Functions

Based on the characteristics of the rut shape, the important factors are as follows:

a) Rut depth

b) Rut width

c) Horizontal direction of rutting (wheel path)

In addition to these factors, easy reproduction and understanding with independent rut shape modification at right-and-left are required.

Therefore, as the functions which satisfy the conditions mentioned above, quadratic function and a spline function are noted to design the rutting model. A quadratic function satisfies the condition as parameters, while a spline function gives the feature points to represent the characteristics of rutting.

Hereafter, the model which is designed by quadratic function is referred to as “QFM” (the Quadratic Function Model) and the model which is designed by spline function is referred to as “SFM” (the Spline Function Model).

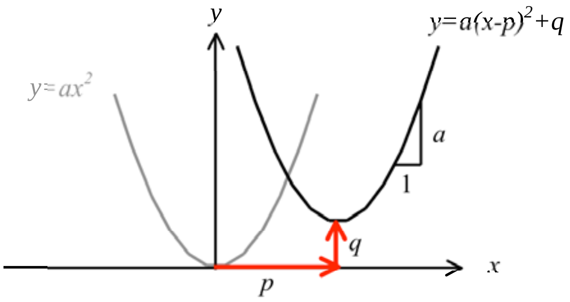


Fig.3 Quadratic Function

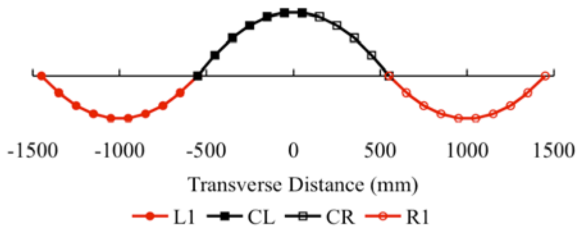


Fig.4 Designed by the Combination of Quadratic Functions

(2) Designed by a Quadratic Function

The fundamental form of quadratic function which is used for the design of QFM is shown in Equation 1. Here, the vertical axis is shown as x and the transverse axis is shown as y.

$$y = a(x - p)^2 + q \qquad (a \neq 0) \tag{1}$$

Equation 1 is shifted to the horizontal direction by p unit and shifted to the vertical direction by q unit. If the value of a which gives the width of parabola is negative, the parabola will open downward. If the value of a is positive, the parabola will open upward (**Fig.3**). For the purpose of QFM design, each parameters which is described in Equation 1 is defined as follows:

y: Vertical direction (mm)
x: Horizontal direction (mm)
a: The parameter which displays rut width
p: Direction of rutting (mm)
q : Rut depth (mm)

and a is obtained from Equation 2.

$$a = \frac{y - q}{(x - p)^2} \tag{2}$$

As shown in **Fig.4**, the combination of four quadratic functions constitutes QFM because the independent rut shape modification at right-and-left is required. The design requirements are as follows:

a) Reference point is vertex of Parabola-CL(CR) shown in **Fig.4**.

b) Horizontal directions of rutting are at $\pm 1000mm$ from reference point.

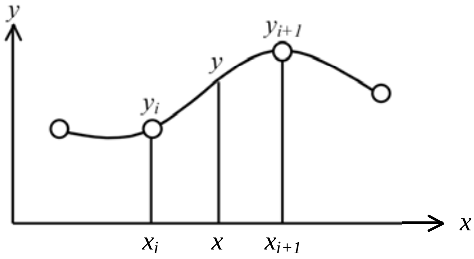


Fig.5 Spline Function

c) To equate the gradient at tangent, and to make the model simple, the points which combine each parabola are "Reference point" and "Point of ±500mm from the reference point".

Based on above mentioned, the equations which construct QFM are shown in Equation 3-6, and parameter a is shown in Equation 7-10. The subscript in parameter a corresponds to the parabola shown in **Fig.4**. q_L and q_R shows rut depth at the right-and-left wheel path respectively.

$$\text{CL:} \quad y = a_{CL} x^2 \qquad (-500 \le x \le 0) \tag{3}$$

$$\text{CR:} \quad y = a_{CR} x^2 \qquad (0 < x \le 500) \tag{4}$$

$$\text{L1:} \quad y = a_{L1}(x + 500)^2 - q_L \qquad (-1500 \le x < -500) \tag{5}$$

$$\text{R1:} \quad y = a_{R1}(x - 500)^2 - q_R \qquad (500 < x \le 1500) \tag{6}$$

$$a_{CL} = \frac{-q_L / 2}{(-500)^2} \tag{7}$$

$$a_{CR} = \frac{-q_R / 2}{500^2} \tag{8}$$

$$a_{L1} = \frac{q_L / 2}{(-500 + 1000)^2} = \frac{q_L / 2}{500^2} \tag{9}$$

$$a_{R1} = \frac{q_R / 2}{(500 - 1000)^2} = \frac{q_R / 2}{500^2} \tag{10}$$

(3) Designed by a Spline Function[8)]

In this study, SFM is designed by use of cubic spline which is most common spline. Cubic spline represents the approximate function between x_i and x_{i+1} as follows (**Fig.5**). As for N data points ($i = 0, 1, 2, \cdots, N-1$),

$$y(x) = y_i + a_{1i}(x - x_i) + a_{2i}(x - x_i)^2 + a_{3i}(x - x_i)^3 \tag{11}$$

where,

$$\frac{dy}{dx} = a_{1i} + 2a_{2i}(x - x_i) + 3a_{3i}(x - x_i)^2 \tag{12}$$

$$\frac{d^2 y}{dx^2} = 2a_{2i} + 6a_{3i}(x - x_i) \tag{13}$$

By the connection condition at $x = x_i$

$$y_i + a_{1i}h_i + a_{2i}h_i^2 + a_{3i}h_i^3 = y_{i+1} \tag{14}$$

$$a_{1i}h_i + 2a_{2i}h_i + 3a_{3i}h_i^2 = a_{1(i+1)} \tag{15}$$

$$2a_{2i}h_i + 6a_{3i}h_i = 2a_{2(i+1)} \tag{16}$$

where,

$$h_i = x_{i+1} - x_i \tag{17}$$

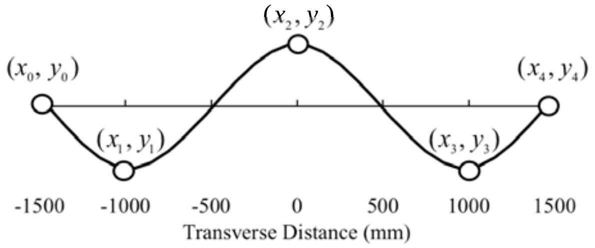


Fig.6 Designed by Cubic Spline

When the derivering value of the second derivative is u_i, it is represented to simultaneous equations as follows.

$$\begin{Bmatrix} 2(h_0+h_1) & h_1 & & & 0 \\ & \ddots & & & \\ & h_{i-1} & 2(h_{i-1}+h_i) & h_i & \\ & & \ddots & & \\ 0 & & & h_{N-2} & 2(h_{N-2}+h_{N-1}) \end{Bmatrix} \begin{Bmatrix} u_1 \\ \vdots \\ u_i \\ \vdots \\ u_{N-1} \end{Bmatrix}$$

$$= \begin{Bmatrix} v_1 \\ \vdots \\ v_i \\ \vdots \\ v_{N-1} \end{Bmatrix} \tag{18}$$

where,

$$v_i = 6\left[\frac{y_{i+1}-y_i}{h_i} - \frac{y_i - y_{i-1}}{h_{i-1}}\right] \tag{19}$$

$$(i = 1, 2, \cdots, N-1)$$

when natural cubic spline,

$$\begin{cases} u_0 = 0 \\ u_N = 0 \end{cases} \tag{20}$$

Hence, the coefficients of Equation 11 are

$$a_{1i} = \frac{y_{i+1}-y_i}{x_{i+1}-x_i} - \frac{1}{6}(x_{i+1}-x_i)(2u_i + u_{i+1}) \tag{21}$$

$$a_{2i} = \frac{u_i}{2} \tag{22}$$

$$a_{3i} = \frac{u_{i+1}-u_i}{6(x_{i+1}-x_i)} \tag{23}$$

The design conditions of SFM suppose the following five points as shown in **Fig.6**.

a) Lane edges (the reference of rut depth measurement)

$$\begin{cases} (x_0, y_0) = (0, 0) \\ (x_4, y_4) = (0, 0) \end{cases}$$

b) Horizontal direction of rutting

$$\begin{cases} (x_1, y_1) = (-1000, y_1) \\ (x_3, y_3) = (1000, y_3) \end{cases}$$

c) Lane center

$$(x_2, y_2) = (0, y_2)$$

Here, r_L and r_R shows rut depth at the right-and-left wheel path respectively, y_1 and y_2 are as follows:

$$y_1 = \begin{cases} y_2 - r_L & (y_2 \geq 0) \\ 0 - r_L & (y_2 < 0) \end{cases} \tag{24}$$

$$y_3 = \begin{cases} y_3 - r_R & (y_2 \geq 0) \\ 0 - r_R & (y_2 < 0) \end{cases} \tag{25}$$

Because the design conditions determine that N=5, Equation 18 is represented as follows:

$$\begin{Bmatrix} 2(h_0+h_1) & h_1 & 0 \\ h_1 & 2(h_1+h_2) & h_2 \\ 0 & h_2 & 2(h_2+h_3) \end{Bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} = \begin{Bmatrix} v_1 \\ v_2 \\ v_3 \end{Bmatrix} \tag{26}$$

When Equation 26 is described as

$$\mathbf{AB} = \mathbf{C} \tag{27}$$

and

$$\mathbf{B} = \mathbf{A}^{-1}\mathbf{C} \tag{28}$$

Then, u_1, u_2 and u_3 are obtained.

As a result, SFM is obtained from Equation 11 by giving of rut depth and height of lane center.

(4) Characteristics of Models

The purpose of this section is to keep track of the characteristics of two models based on the actual features of rutting as follows:

a) Lane edges

b) Horizontal direction of rutting

c) Lane center (vertex)

d) Flexibility of shape variation

a) In consideration of the present circumstances, lane edges which are reference points of the rut depth measurement should preferably be 0. **b)** This study has supposed that the horizontal direction of rutting which is defined the lowest point at $\pm 1000mm$ from lane center. **c)** Lane center is a vertex in the modeling. **d)** Flexibility of shape variations include easy reproduction with independent rut shape modification at right-and-left.

Table 1 shows the characteristics of QFM and SFM respectively. As shown in **Table 1**, QFM has the ability to accurately reproduce the transverse position such as horizontal direction of rutting with easy reproduction and understanding. However, the vertex gets moving when the lane edge becomes 0 because the lane edge is not able to obtain the constant value. If rut depth differs respectively depend on each wheel path, height at the lane edge is different between right-and-left.

Table 1 Characteristics of Models

	QFM (Quadratic Function Model)	SFM (Spline Function Model)
i) Lane edges	Variable; when the lane edge is adjusted to 0, it is necessary to move the entire model up and down. In particular, if rut depth differs respectively depend on each wheel path, height at the lane edge is different between right-and-left	Constant; the calculation conditions give the height of lane edge as 0.
ii) Horizontal direction of rutting	Constant; the minimum value of height is taken at only the designed position which is $\pm 1000mm$ from vertex in this study.	Variable; because the direction of rutting is given as the pass requirement, it does not necessarily take minimum height.
iii) Lane central(vertex)	Constant: when the lane edge is adjusted to 0, the vertex is not necessarily constant.	Variable; because the vertex is given as pass condition as well as ii), it does not necessarily take maximum height.
iv) Flexibility of shape variation	Right-and-left independent rut depth could be changed. However, if the right-and-left rut depth is different, the height of the lane edge would be diverse. The formulas could be reproduced comparatively simple and easy constitution.	Right-and-left independent rut depth could be changed. Flexibility of SFM is higher than QFM because it passes over the given point (especially lane edge). The formulas are more complex than QFM, and there are relatively computational effort.

On the other hand, SFM always takes the constant value at the lane edge and has high flexibility of shape variations. However, because the direction of rutting/the vertex is given as the pass requirement, it does not necessarily take minimum/maximum value.

Therefore, to verify the influence of the characteristics mentioned above, the adaptability of these shapes for actual road profile data and the applicability for the simulation method of the vehicle dynamics are inspected in next chapters.

4. Adaptability of shapes

A quadratic function satisfies the condition as parameters, while a spline function gives the feature points to represent the characteristics of rutting. As mentioned above, QFM and SFM have different characteristics respectively for the modeling of rut shapes. Hence, to quantify the influence of these characteristics, the adaptability of developed models and actual shapes are confirmed by use of EVEN data.

In this study, the cross sections of 10m intervals (from longitudinal distance L=140m to L=240m) are used for the analysis of adaptability, although the cross sections of EVEN data was measured at 5m intervals.

(1) Comparison of Correlation Coefficient

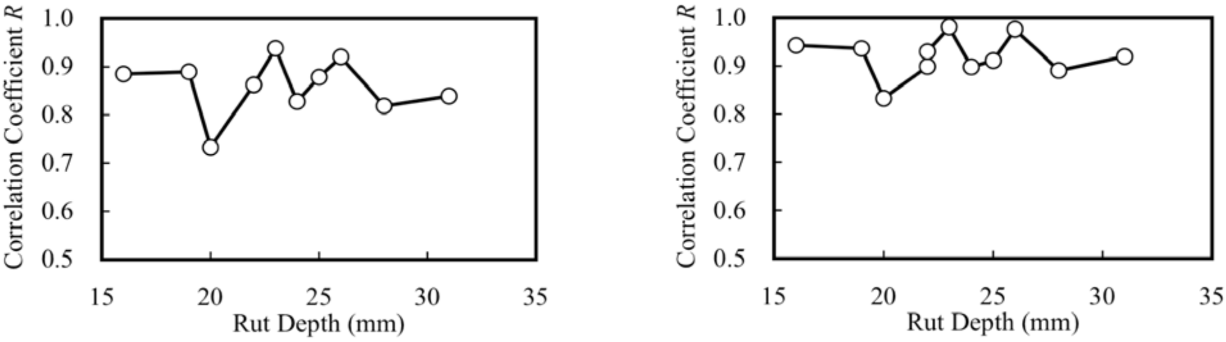
By making the same horizontal sampling interval at the model and actual data, rut shapes can be compared by the correlation coefficient (R).

The reference point for comparison of the shape is the maximum height near the lane center at actual data.

The comparison results by the correlation coefficient is shown in **Fig.7**. If the measure of the evaluation of correlation is 0.8, **Fig.7(a)** indicates that QFM gains approximately good correlation as more than 0.8 at almost all of cross sections, except one section. On the other hand, as shown in **Fig.7(b)**, SFM achieves high correlation as nearly 1.0 at many sections.

However, it seems that the relationship between rut depth and correlation coefficient does not exist. To consider the above causality, the comparison of the cross section which indicates high correlation between actual data and models is shown in **Fig.8** and which indicates low correlation between actual data and models is shown in **Fig.9**.

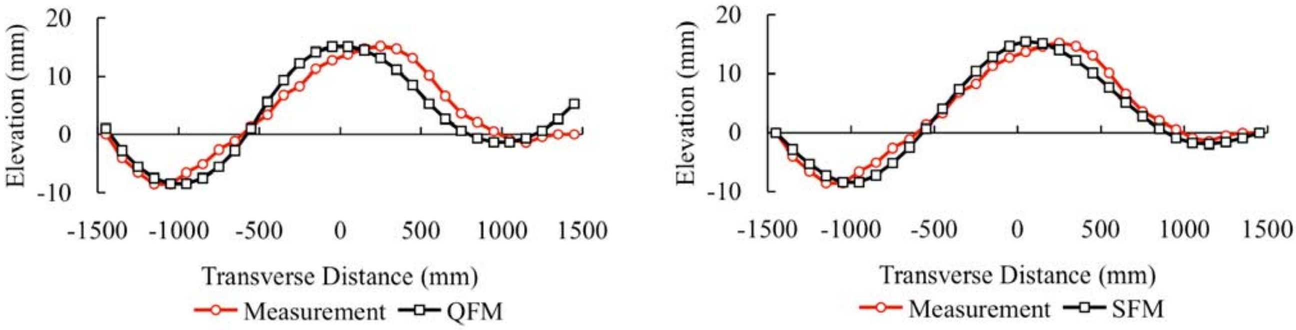
Here, in **Fig.7**-**Fig.9**, the quadratic function model is shown as "QFM", the spline function model is shown as "SFM" and actual shape is shown as "Measurement".



(a) Correlation Coefficient Between QFM and Measurement

(b) Correlation Coefficient Between SFM and Measurement

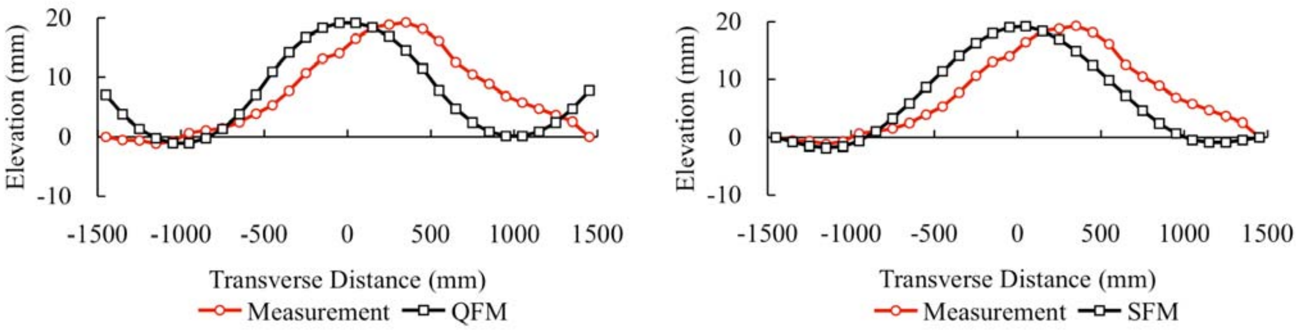
Fig.7 Comparison of Correlation Coefficient



(a) QFM (R=0.94, L=220m)

(b) SFM (R=0.98, L=220m)

Fig.8 Comparison of High Correlation Cross Section



(a) QFM (R=0.73, L=240m)

(b) SFM (R=0.83, L=240m)

Fig.9 Comparison of Low Correlation Cross Section

As shown in **Fig.8(a)** and **Fig.9(a)**, it is obvious that the lane edge height of QFM differs from that of Measurement. In case of QFM, if rut depth of right-and-left is extremely different as shown in **Fig.9(a)**, correlation falls due to the increase in the error of the lane edge.

In regard to SFM on practical use, as shown in **Fig.8(b)**, it can be admitted that the direction of rutting does not necessarily take minimum height.

As the features common to QFM and SFM shown in **Fig.9**, protuberant rutting which is the bulge of the entire section causes the correlation decrease. The vertex of models remains fixed on lane center in consideration of general versatility, although the vertex of Measurement is biased as shown in Fig.9.

(2) Comparison of the rut slope

A rut slope is defined here as the absolute value of inclination of the line which connects the vertex and the horizontal direction of rutting (**Fig.10**). The rut slope is able to compare the distortion of the rutting. **Fig.11** shows the comparison result of the models and the actual rut slope. In the figure, the rut slope of QFM is shown as "QFM

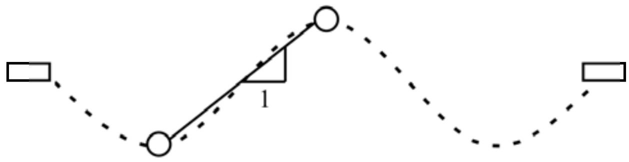
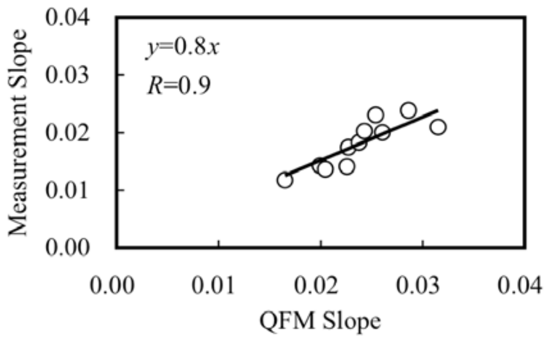
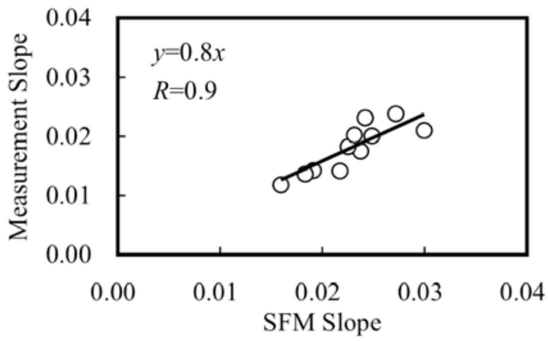


Fig.10 Rut Slope



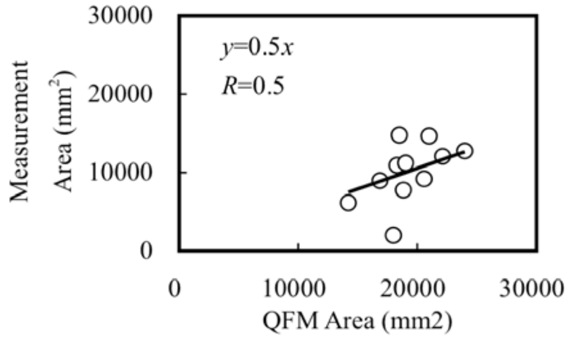
(a) Comparison Result of QFM



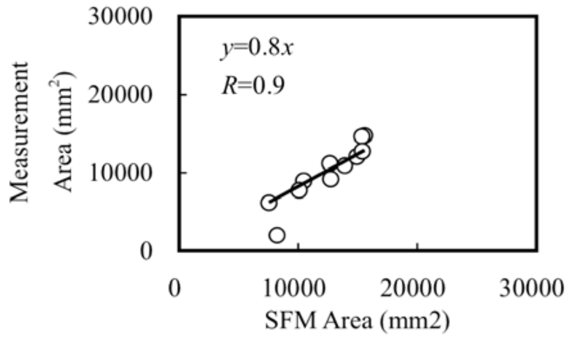
(b) Comparison Result of SFM

Fig.11 Comparison Result of Rut Slope

Fig.12 Rut Area



(a) Comparison Result of QFM



(b) Comparison Result of SFM

Fig.13 Comparison Result of Rut Area

Slope", the rut slope of SFM is shown as "SFM Slope" and the slope of actual shape is shown as "Measurement Slope".

As shown in **Fig.11**, the rut slope of each model is about 20 percent larger than that of Measurement. As the result common to QFM and SFM, high correlation coefficient as 0.9 proves the strong relationship between model and Measurement. Because there are few distortions, the design conditions are applicable to QFM and SFM. Moreover, it can also be admitted that the direction of rutting does not necessarily take minimum height.

(3) Comparison of the Rut Area

A rut area is defined by the area between the pavement surface and the straight line which connect the vertex and lane edge. The rut area increase as the depression of wheel path increases. The rut area has ability to compare the state of depression of rutting. **Fig.13** shows the comparison result of the models and the actual rut area. In the figure, the rut area of QFM is shown as "QFM Area", the rut area of SFM is shown as "SFM Area" and the area of actual shape is shown as "Measurement Area".

As shown in **Fig.13(a)**, altogether, QFM Area is approximately 50 percent large compared with Measurement Slope. It is caused by the lane edge which is not necessarily 0 as shown in **Fig.9(a)**. QFM is not suited to describe the depression of rutting because there is a little relationship between QFM and Measurement as correlation coefficient 0.5.

On the other hand, SFM Slope differs only approximately 20 percent from Measurement Slope. Therefore, SFM has ability to represent the depression of rutting correctly.

In consideration of above mentioned , the modification of QFM is necessary to describe the depression of rutting correctly.

5. Applicability to Vehicle Dynamics Simulation

The studies which evaluate the road surface safely and rapidly with various simulators without actual traveling have been reported[4)-6)]. Then, the examination which uses the simulation would be demanded more and more from safety point of view. Therefore, this chapter examined applicability to the simulation of QFM and SFM by use of the CarSim which developed by University of Michigan Transportation Research Institute(UMTRI).

(1) Overview of the CarSim[7)]

The CarSim is a software package for simulating and analyzing the way of cars, light trucks and utility vehicle respond to driver control on 3D road surface with various environmental conditions .

(2) Test Conditions

The pavement rutting affects stability and controllability of the vehicle. For this reason, double lane-change manoeuvre (DLC test) is investigated to verify the applicability of the models .

Conditions of DLC test which is established referring to JASO (Japanese Automobile Standards Organization) and ISO (International Organization for Standardization) are as follows:

a) Measurement Parameter

The vehicle lateral acceleration which is affected by the pavement rutting and directly related to stability and controllability of the vehicle is addressed in the DLC test. Moreover, yaw-angle is measured to verify the validity of the test.

b) Vehicle Running Speed

JASO provides that the running speed of lane change test is 80km/h to 120km/h at 10km/h intervals. However, in this study, because the selection section from EVEN project is national highway, vehicle running speed set to 40km/h and 60km/h.

c) Test Track

The lane width and shift distance is modified to 2.9m, although the track dimension is described by the ISO. Track dimension for the DLC test is represented in **Fig.14**.

The road surface characteristics are the highest (L=220m) and the lowest (L=240m) correlation cross section as shown in **Fig.8** and **Fig.9**.

d) Others

In JASO C707, the lane-change test of the drivers should be carried out multiple times to reduce the difference of the test result. In CarSim, however, to execute the exact running of the given conditions, the test carried out only one time for each condition. Therefore, the total tests were twelve times. The test conditions formed and shown in **Table 2**. Here, in the table, the rut shape with quadratic function model is shown as "QFM", the rut shape with spline function model is shown as "SFM" and the actual shape is shown as "Measurement".

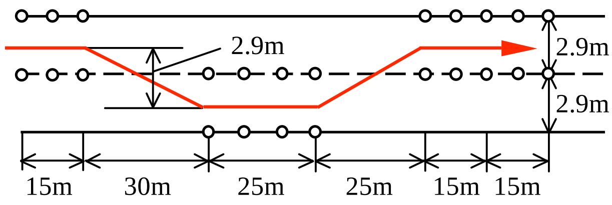


Fig.14 Double Lane-Change Track

Table2 Test Conditions

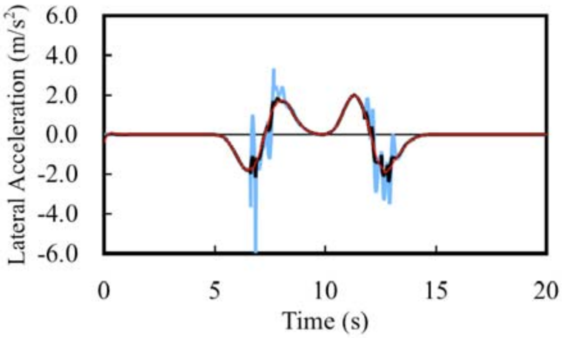
Sections	Rut Shapes	Speed
The Highest Correlation Cross Section (L=220m)	QFM SFM Measurement	40km/h
		60km/h
The Lowest Correlation Cross Section (L=220m)	QFM SFM Measurement	40km/h
		60km/h

(3) Simulation Result Comparison

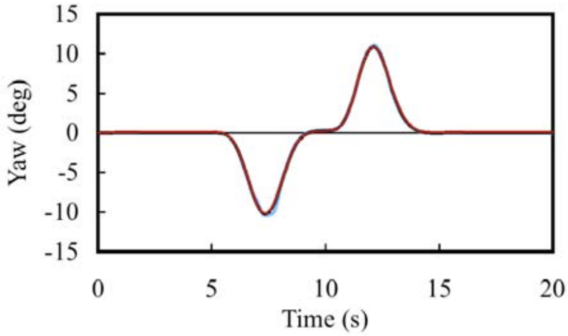
The comparison results of lateral acceleration and yaw-angle are shown in **Fig.15** and **Fig.16**, respectively. Here, in the figures, the simulation result of the rut shape with quadratic function model is shown as "QFM", the simulation result of the rut shape with spline function model is shown as "SFM" and the simulation result of the actual shape is shown as "Measurement".

In **Fig.15**, when comparing with QFM and the actual shape of lateral acceleration, there are sudden wave occurs which are not related to the highest correlation cross section(L=220m) and the lowest correlation cross section (L=240m). In particular, the sudden wave occurs at the peak point of the lateral acceleration, we consider that is caused by error of the lane edge. On the other hand, there are approximate agreement when comparing with SFM and the actual shape of lateral acceleration although there are still remain some small differences. Therefore, we consider that SFM has the high applicability in simulation.

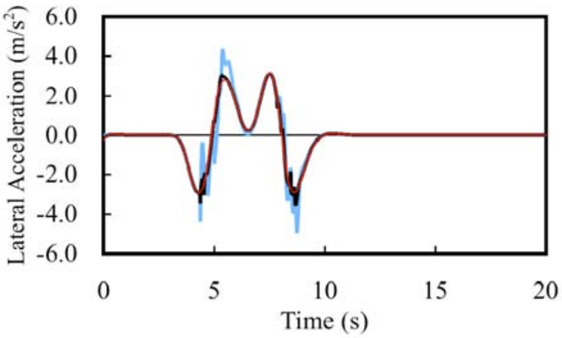
Furthermore, in **Fig.16**, the result shows that there are



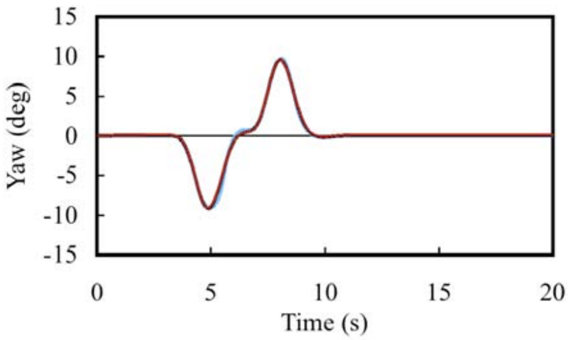
(a) L=220m, V=40km/h



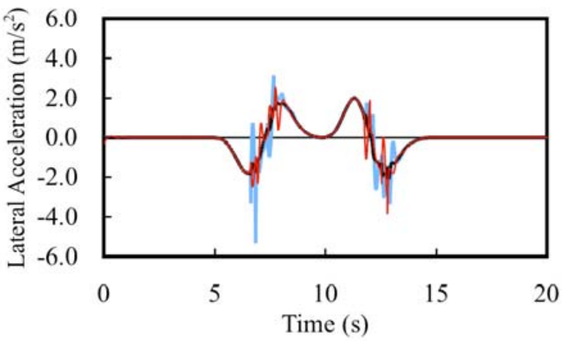
(a) L=220m, V=40km/h



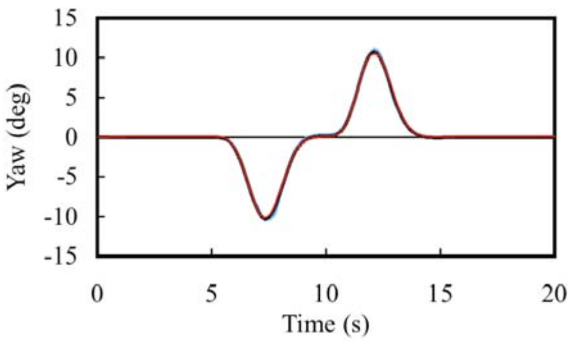
(b) L=220m, V=60km/h



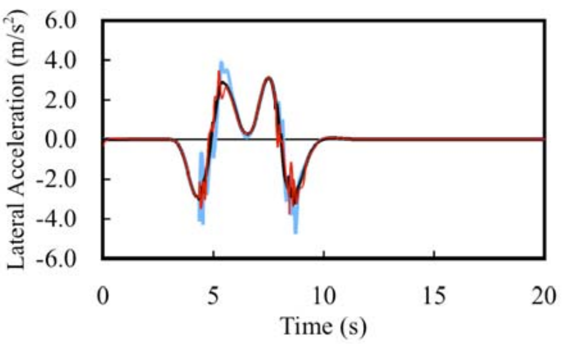
(b) L=220m, V=60km/h



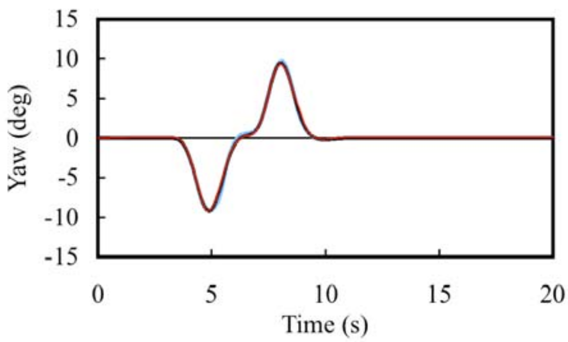
(c) L=240m, V=40km/h



(c) L=240m, V=40km/h



(d) L=240m, V=60km/h



(d) L=240m, V=60km/h

Fig.15 Comparison of Lateral Acceleration

(— QFM — SFM — Measurement)

Fig.16 Comparison of Yaw-Angle

(— QFM — SFM — Measurement)

well agreement when comparing QFM and SFM with the wave of the actual shape. From this point of view, we consider that the experiment result should be suitable in DLC test, because the turn movement other than the given condition do not happen. In addition to this, in the simulation, it is shown that the applicability is independent from running speed, in QFM and SFM.

Therefore, if we applies QFM for the simulation, it is necessary to reduce the error of the lane edge. For SFM, on the other hand, is applicable for the simulation.

6. Conclusions and Future Works

In this study, we developed the geometrical models of rutting which simplified and approximated by use of comparatively easy functions. Then the developed models were verified to in respect of the adaptability of the rut shape.

The results in this study are summarized as follows:

(1) A rutting is located around ±1000*mm* from the lane center, rut shape is a parabolic and asymmetry to the lane center. Here we developed two types of model: the quadratic function model (QFM) which is constructed by quadratic functions and the spline function model (SFM) which is constituted by cubic spline function. QFM satisfies the design conditions as the parameters. On the other hand, SFM gives the feature points to represent the characteristics of the rutting.

(2) We proposed the comparison methods which including correlation coefficient, rut slope and rut area, to verify the applicability of rut shape. As a result, although the rut depth of QFM has the minimum value at the horizontal direction of the rutting, the height of the lane edge will not be 0, therefore, the result brings a low adaptability. This is remarkable particularly in severe protuberant rutting and when the right-and-left rut depth is more different. Therefore, the design method of QFM is necessary to be improved. On the other hand, although the rut depth of SFM does not necessarily take minimum value, the result on practical is in tolerance and shows the high adaptability.

(3) We have discussed the adaptability of the model's simulation by using CarSim, the general vehicle dynamics simulation software. As the result, in QFM, sudden wave occurs which is considered to be caused by the error of the lane edge. On the other hand, it shows that SFM has the high applicability in simulation although there are still remain some small differences.

In rut modeling, we found that SFM has a wide model in application range comparing with QFM. On the other hand, QFM has an advantage for the easy reproduction and computational effort. Therefore, to make a full use of the advantage of QFM, to improve the method, and to extend the application range, is our further study.

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