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Estimation of Road Surface Friction Coefficients for Winter Period Rear-End Collision Traffic Accidents

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1. Introduction

There is a strong need for the establishment of road management standards which would objectively differentiate roads according to their function, importance and volume of traffic. In formulating these management standards, there is no doubt that the most suitable indicator to express the standard of the road surface is the coefficient of slip friction. During the winter period, the most typical type of accident is the rear-end collision, and this is very closely related to the road surface coefficient of friction. When analyzing the behavior of a car involved in a collision, the simplest method is to express the vehicle as a particle[1,2] in a model. In other words, by ascertaining the initial speed and the braking distance involved, and by making use of an elementary knowledge of mechanics, it is possible to infer both the road surface's coefficient of friction and the restitution coefficient at the time of the accident. However, in order to gain a clear picture, what should be understood is that the road surface coefficient of friction is largely dependent on the slip ratio of the tires. When representing the vehicle as a particle in a model, it is conventionally thought of as a solid moving object due to the fact that the tires are tacitly thought to be in a locked condition. However, in recent years there has been a great increase in the number of autos equipped with ABS (Anti-skid Braking System), so there has been a corresponding rise in the number of cases in which wheels do not lock, even during emergency braking. In our research, in order to express the movements of vehicles at the time of traffic accidents, we have used a tire model[3] and a driving model[4], with combining a impact model[5] to carry out the development of an integrated accident reconstruction model that can reconstruct a complete picture of the accident. Next, along with collecting data relating to rear-end collision accidents in wintry conditions, we are working on identification of the types of vehicles actually involved in the accidents and their friction coefficients at the time of skidding, by working out estimates with the accident reconstruction model we have developed. In this respect, we have carried out our investigation concerning differences in friction coefficients due to the type of vehicle and the pre and post accident conditions, along with a comparison of other models previously used, taking vehicles as elements. Furthermore, it is considered that road management policies can greatly influence traffic safety, and therefore, it is possible to carry out a reverse calculation of the friction coefficient, which allows us to simulate vehicle movements, and thus avoid accidents, when improvements are made to road surfaces.

2. Traffic Accident Reconstruction Model

(1) Previously used model[1,2]

When expressing a car as a simplest element, two cars collision is considered as a one dimensional collision. In the case of a one dimensional collision, the collision occurs either at the front or the rear, along the auto's vertical axis, and therefore, the changes in the shape of the car, and its movement, are all in the direction of this axis. The striking and struck vehicles and their respective masses, M_1 and M_2, the danger recognition speed, the distance from the initial position to the point of collision, D_{10} and D_{20}, and the distance from the point of collision to the point where the vehicles come to rest, D_1 and D_2, are all known. Also, the coefficient of friction, μ, is taken as being constant, both before and after the collision. The speeds immediately before the collision, V_{10} and V_{20}, and the speeds immediately after the collision, V_1 and V_2, are:

$$V_{10} = \sqrt{V_{100}^{\ 2} - 2\mu g D_{10}} \qquad (1)$$

$$V_{20} = \sqrt{V_{200}^{\ 2} - 2\mu g D_{20}} \qquad (2)$$

$$V_1 = \sqrt{2\mu g D_1} \qquad (3)$$

$$V_2 = \sqrt{2\mu g D_2} \qquad (4)$$

Here, by including both objects in a total dynamic system, without adding external forces, and because the momentum before and after the collision is unchanged,

$$M_1 V_{10} + M_2 V_{20} = M_1 V_1 + M_2 V_2 \qquad (5)$$

Using equation (5), if we substitute equations (1), (2), (3) and (4), we can express the unknown velocities and friction coefficient.

Key words: Accident reconstruction, Tire model, Impact model, Driving simulation model, Friction coefficient
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(2) Integrated model

A model has been created by which the restitution coefficients at the time of the collision and slip ratio and steering angle after the collision, along with the friction coefficient of the road surface, can be estimated. Information relating to skid marks on the road surface, as well as evidence provided by interviewing the drivers involved, such as the location at which danger was first realized and the speed at the time, is also included. Details of the supposed position of the collision are also used in the model, along with the position where the vehicles finally ended up. In other words, an integrated model, called the reconstruction model, has been put together by combining the tire model, the driving model, and the impact model. Here, we will introduce an outline of this reconstruction model. Concerning the verification of the model's details and its validity, more details are given in the reference literature.

(a) Tire model [3)]

A tire model is used for obtaining the friction forces between the tire and road surface. There are three main forces in the model; the force acting in the lateral direction of the tire as the side force, the force acting in the longitudinal direction of the tire as the braking force or traction force, and the moment acting in the opposite direction of wheel yawing. These forces are obtained by the function which establishes the relationship among slip angle, camber angle, slip ratio and friction coefficient. Although there are many models, according to assumptions of slip angles and camber angles, here we have adopted Gim tire model which takes account of the influence of the slip angle and slip ratio, as well as the camber angle. This model does not consider the effects of bending or twisting.

(b) Driving model [4)]

Based on the forces acting on the vehicle, as the driving model, which sets out the vehicle's movements, we have employed a two wheel vehicle parity model, the simplest available. Although it is supposed that a vehicle's movement is two dimensional, along two planes, it is possible to ignore rolling and pitching. the forces and moments acting on the vehicle's center can be expressed as a compound of the forces acting on the front and rear wheels.

(c)Impact model [5)]

This is a method of relating the total behavior of a vehicle at the time of undergoing a collision. It involves employing a technique to infer speeds before and after the impact, by examining the damaged condition of the auto and working out the amount of energy that was lost in the impact. It also involves methods to estimate speeds by expressing the condition of the anelastic collision through a restitution coefficient. Furthermore, it has been performed by introducing a method proposed by Ishikawa, that involves adding a tangential direction restitution coefficient to the vertical direction restitution coefficient. Here, in accordance with Ishikawa's model, work has been carried out to construct a program. Restitution coefficients for both directions can be expressed as shown below,

$$e_n = -RDS / RDS_0 \quad (6)$$

$$e_t = -RSS / RSS_0 \quad (7)$$

where

RDS : Relative deformation speed after collision,

RSS : Relative sliding speed after collision,

0 : Subscript for relative speed before collision.

3. Model Parameter Estimation

(1) Unknown parameters

There are stiffness factors and other parameters relating to the material characteristics and properties of the tires and the vehicles which are assumed to be already known. The restitution coefficients in both directions, e_n and e_t, from the impact model and the friction coefficient, μi, the steering angle, δi, and the front and rear wheel slip ratios, S_{Fi} and S_{Ri} from the tire and driving models in post-impact phase are the unknown parameters. The appended letter, i, is used to differentiate between the striking vehicle and the struck vehicle. Also, because these unknown parameters essentially change with time, and the friction coefficient with space, but the data that is left at the site and the data which can be obtained from examining it is very limited. Therefore, in this research, they have been assumed as constant values. That is to say that the average value estimated for each parameter was tried. Data of pre-impact phase is assumed from the accident site conditions and driver's witness.

(2) Box complex method [6)]

Here, we try and carry out adjustments to the parameter values in order to bring them as close as possible to real vehicle positions measured after collisions. The objective function, J, is expressed as the difference between the calculated final resting positions and actual ones. The calculated position and direction of vehicle i are expressed by x_i, y_i, and θ_i, and the position and direction of an actual vehicle by x_{si}, y_{si}, and θ_{si}.

$$J=\sum_{i=1}^{2}\left[\lambda_x(x_i-x_{si})^2+\lambda_y(y_i-y_{si})^2+\lambda_\theta(\theta_i-\theta_{si})^2\right] \quad (8)$$

The minimum estimation of unknown parameters is carried out. Here, λ is a dimensionless factor and standard deviation is used. As a method to solve it numerically, the Box Complex Method is used. The following restrictive conditions apply to the range of values gained for each parameter.

$$\begin{array}{ll} -1 \leqq e_n \leqq 1 , & -1 \leqq e_t \leqq 1 \\ 0 \leqq \mu_i \leqq 1 , & \delta_{min} \leqq \delta_i \leqq \delta_{max} \\ 0 \leqq s_{Fi} \leqq 1 , & 0 \leqq s_{Ri} \leqq 1 \end{array} \quad (9)$$

4. Traffic Accident Data

In order to analyze the characteristics of traffic accidents in the winter period, especially the correlation between road surface management and accidents involving skidding or sliding, in December 1995 data was collected in Sapporo city, taking 26 winter- type rear-end accidents that occurred there as the objects of the study. Table 1 records data for each of the twenty six accidents, detailing vehicle weights (M_1 and M_2), danger recognition speeds (V_{100} and

V_{200}), braking distance to the impact point (D_{10} and D_{20}), and distances from the impact point to the final resting position (D_1 and D_2). The append 1 refers to the striking vehicle and the append 2 refers to the struck vehicle. Sixteen of the twenty six accidents occurred on frozen roads and ten occurred on snow covered roads.

Table 1 Winter rear-end collision traffic accidents (Mass, initial speed, braking and stopping distance)

No	M_1 (kg)	V_{100} (km/h)	D_{10} (m)	D_1 (m)	M_2 (kg)	V_{200} (km/h)	D_{20} (m)	D_2 (m)
1	1350	20	6.0	3.1	1140	0.0	0.0	3.1
2	1260	20	10.8	0.8	990	0.0	0.0	0.8
3	1190	20	9.6	0.5	1320	0.0	0.0	0.7
4	1310	30	16.2	0.5	1040	0.0	0.0	0.8
5.	1370	32	35.4	0.0	1310	0.0	0.0	505
6	930	30	26.3	0.4	1180	0.0	0.0	0.8
7	1180	30	5.2	6.9	1140	0.0	0.0	7.2
8	1350	30	11.0	0.8	780	0.0	0.0	0.8
9	1620	30	11.1	0.7	1810	0.0	0.0	1.5
10	1070	30	7.3	0.9	1370	0.0	0.0	0.4
11	1240	40	19.0	1.0	650	0.0	0.0	1.0
12	1670	40	23.8	1.1	2080	0.0	0.0	2.0
13	1650	40	40.2	0.4	1370	0.0	0.0	1.5
14	1210	40	25.7	0.0	1710	0.0	0.0	1.0
15	1050	40	39.9	0.5	800	0.0	0.0	1.2
16	1290	40	20.4	1.0	780	0.0	0.0	1.0
17	1290	40	10.0	0.0	1240	0.0	0.0	0.4
18	1050	50	24.4	1.0	1170	0.0	0.0	0.6
19	1280	50	35.8	2.1	1190	0.0	0.0	5.1
20	1340	35	15.2	0.4	780	0.0	0.0	0.7
21	1930	30	10.6	0.5	1370	0.0	0.0	1.0
22	1620	35	13.5	1.2	1100	0.0	0.0	0.5
23	2230	30	4.7	0.6	1160	0.0	0.0	0.6
24	1530	20	4.2	0.5	1280	0.0	0.0	1.3
25	1370	20	5.1	0.2	1470	0.0	0.0	0.2
26	1640	25	4.7	0.3	1390	0.0	0.0	0.1

M_1、M_2 : Mass　　V_{100}、V_{200} : Initial Speed (km/h)
D_{10}、D_{20} : Braking distance　　D_1、D_2 : Stopping Distance

(1) Numerical analysis

Using the twenty six rear-end collision type accidents shown in Table 1 as the objects of our study, the road surface friction coefficients at the time of the accidents were estimated. In previous models to estimate the friction coefficients, it was assumed that there were no differences before and after the collision, or between the striking and struck vehicles. In contrast to that, in our integrated model the coefficient value is arrived at by taking account of an assumed difference in the interaction between the tires and the road surface, due to differing conditions before and after the impact and the two different vehicles involved. To be precise, before the impact the braking conditions are taken as being locked.

Figure 1 shows the striking vehicle's friction coefficient after the collision, thought to differ greatly depending on the driver's actions. The horizontal axis friction coefficient (μ_c) is estimated as in the previous model, whilst for the vertical axis the friction coefficient (μ_I) is inferred by the integrated model. The almost straight line distribution throughout the chart means that the estimated values for both methods were close.

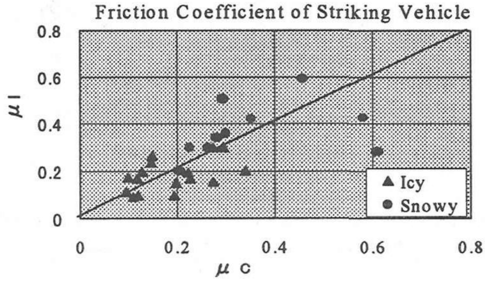

Figure 1 Effect of estimation method on friction coefficients of striking car.

Accidents on an icy road surface are distributed relatively closely on a 45 degree line. In contrast, excluding two exceptions, values estimated for snow covered road surfaces are higher in the integrated model than corresponding values in the previous model. It is thought that this is because the values estimated in the integrated model take into account the fact that on a frozen road surface braking remains in a locked condition after the impact has occurred. On the other hand, when dealing with snow covered road surfaces, because the wheels are not locked and the slip ratio is therefore slightly less than 1, the friction coefficient becomes greater.

Figure 2 compares the friction coefficients for the striking vehicle before and after the impact.

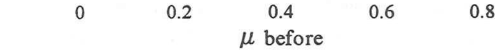

Figure 2 Friction coefficient of striking vehicle before and after collision.

The horizontal axis shows the friction coefficients before the collision, and the vertical axis shows them after the impact. Even here, regarding accidents in snow covered road conditions, and again excluding two exceptions, it is evident that there is a tendency for friction coefficients after the impact to be greater than those before it.

Figure 3 shows the relationship between the friction coefficient of the striking vehicle and the struck vehicle, after the impact. The difference in friction coefficients between the vehicles is not large. Four of the friction coefficients for striking vehicle on a frozen road surface are at the 0.1 level. Distribution is concentrated along a 45 degree line for both snow covered and frozen road surfaces.

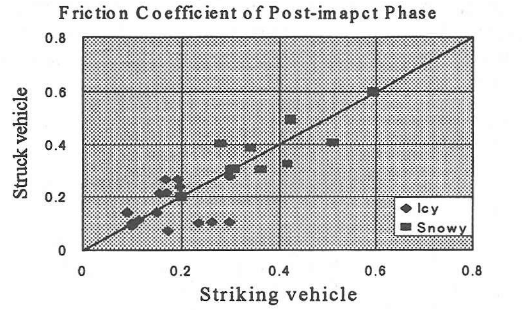

Figure 3 Comparison of friction coefficient of struck car with that of striking car after collision.

(2) Accident avoidance slip friction coefficient

Taking twenty six rear-end collision accidents as the objects for our study, we carry out a reverse calculation to estimate the friction coefficient that would have been necessary in order to enable the striking vehicle to stop in time, before making contact with the other vehicle at the point of impact. In Figure 4, the vertical axis shows the original friction coefficient value at the time of the accident along with our calculated reverse- estimate of the friction coefficient value that would have been necessary in order to avert the collision. The horizontal axis shows the individual accident numbers, with numbers one through sixteen representing accidents that occurred on frozen road surfaces, and numbers seventeen through twenty six representing those that happened on snow covered roads.

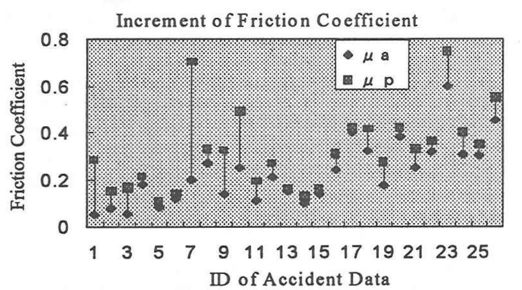

Figure 4 Increment of friction coefficient required to prevent the accidents. (μ_a: when accidents occurred, μ_p: when accidents were prevented)

The results show that it would be possible to avoid many traffic accidents by using ice preventing chemicals or special paving if they could raise the friction coefficient value of the road surface just a little; from 0.05 to 0.1 in the case of frozen road surfaces, and from 0.1 to 0.15 in the case of snow covered road surfaces. The solid line in Figure 5 shows the friction coefficients estimated at the time of the accidents arranged in ascending order and expresses the reverse cumulative distribution and the rate of occurrence of collisions corresponding to the friction coefficients. In the same way, the wavy line shows the possibility of avoiding those collisions, by a cumulative distribution of the friction coefficients necessary to avoid the accidents. The two curves intersect at a friction coefficient value of approximately 0.2, so this means that if the road surface friction coefficient becomes smaller than this value, then the danger of more accidents occurring becomes greater, and that 0.2 is the threshold value. This is one measurement that can be used when setting up road management standards for winter periods.

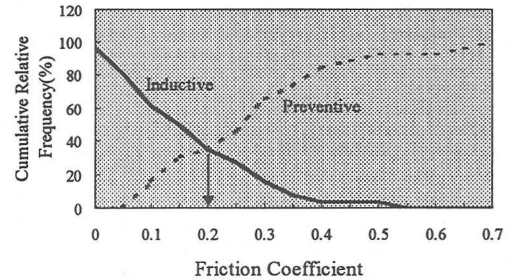

Figure 5 Friction coefficient required to prevent traffic accidents in winter.

5. Conclusions

From this study the following results can be drawn:

1) A big difference was found between the resulting estimated friction coefficient values from the integrated model and the previous model. Particularly, in the case of snow covered surfaces, when the wheels did not lock, where the difference was comparatively large.

2) In snow and ice conditions, braking conditions were different before and after the collision, and in many cases, because the tire slip ratio changed, a difference was found in the friction coefficients before and after the accident.

3) It is possible that many accidents could be avoided if measures to combat icy roads, such as spreading chemicals or using frost resistant paving, were introduced to raise friction coefficients slightly higher than those when accidents occurred. A raise of it from 0.05 to 0.1 in the case of frozen road surfaces, and from 0.1 to 0.15 in the case of snow covered road surfaces would be sufficient.

4) If the friction coefficient drops below a value of 0.2, then the rate of accident occurrence becomes greater than the rate of accident avoidance. The higher the value gets above 0.2, the higher the rate of accident avoidance.

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