Ⅳ－16 Effect of Tire Models on Estimating Model Parameters for Reconstructing Traffic Accidents

M. Hadji Hosseinlou , T. Nakatsuji , T. Hagiwara
Faculty of Engineering, Hokkaido University

ABSTRACT

The main purpose of this study is to compare the effect of tire models on estimating unknown model parameters in reconstructing traffic accidents. The models including a two dimensional car-to-car impact model, Sakai's tire model, modified Sakai's tire model and Gim's tire model by using Box's complex method were used. Box's method was performed for estimating the model parameters. In this method, the parameters were estimated so as to minimize the difference between the calculated and observed rest positions of vehicles. In order to examine the effects of the tire models, an artificial traffic accident data and an actually observed traffic accident data were analyzed. The errors caused by the models were compared. It was concluded that the impact model combined with Gim's tire model was much accurate in reconstructing traffic accidents.

1. INTRODUCTION

Traffic accident reconstruction is a method that clarifies how an accident occurred or what happened during the accident. So far, the various programs have been proposed for reconstructing traffic accidents; CRASH, SMAC, IMPAC, and so on [1,2]. These programs are classified into two groups; energy loss models and restitution models. The reconstruction method adopted here is based on the latter one. The accident reconstruction is divided into three phases; pre-impact, impact and post-impact. For driving simulation of the pre-impact and the post-impact phases, Sakai's tire models (the old and modified models), Gim's tire model and two-wheel equivalence model were used [3,4,5,6]. The impact model is based on the two dimensional impact model which was proposed by Ishikawa [7,8]. This model was applied to determine the unknown velocities which were the two linear velocities and the one angular velocity for each vehicle..

In this work , we developed the method and compared the driving simulation models including the Sakai's tire models and Gim's tire model combined with the two-dimensional car-to-car impact model. Box's complex algorithm method was applied to estimate unknown parameters; the normal and the tangential restitution coefficients in the impact phase, as well as the friction coefficient, steering angle, slip ratio of the front tires and slip ratio of the rear tires in the post-impact phase.[9]. To compare the effect of the tire models in estimating the parameters by box's method, an artificial accident data was introduced. And then, the errors in estimating rest positions of vehicles in an actually observed traffic accidents were analyzed.

2. THEORETICAL MODELS

The impact model and the driving simulation models; Sakai's tire model, Gim's tire model and the two-wheel equivalence model, are explained briefly in the following.

2.1. Impact Model[7,8]

In this model, there are three degrees of freedom for each vehicle; two translations and one rotation. The model is analyzed in a coordinate system in which the lateral and longitudinal axis's are normal and tangential to the impact center, respectively. In order to apply the impact model, six equations are necessary: Four equations can be obtained from the law of conservation of linear and angular momentum. The last two equations are obtained from the constraint conditions at the impact center, in which the normal and the tangential restitution coefficients are defined. These coefficients can be calculated from the equations (1) and (2), as shown in the following ;

$$e_n = -RDS / RDS_0 \tag{1}$$

$$e_t = -RSS / RSS_0 \tag{2}$$

where

RDS : Relative deformation speed after collision.

RSS : relative sliding speed after collision.

0 : Subscript for relative speed of Vehicles before collision.

2.2. Driving Simulation Models[3,4,5,6]

Sakai's tire model, modified Sakai's tire model and Gim's tire model were employed to obtain the friction forces between the tire and the surface of road [3,4,5]. Then, the two-wheel equivalence model was applied to calculate the integrated forces of the tires at the center of vehicles [6].

2.2.1. Skai's tire model[3] (when slip angle is small)

Sakai's tire model is shown in Fig. 1. In this model, there are two main forces; the force acting in the lateral direction of the tire as the side force (SF) , and the force acting in the longitudinal direction of the tire as the braking force or traction force (DF). In Fig. 1, the steering angle and the slip angle of the tire are denoted by H and β, the velocity of the vehicle in the driving direction and the one in the direction perpendicular to the driving direction by Vx and Vy, the angular velocity and the distance between the tire and the gravity center of the vehicle by ω and l, respectively.

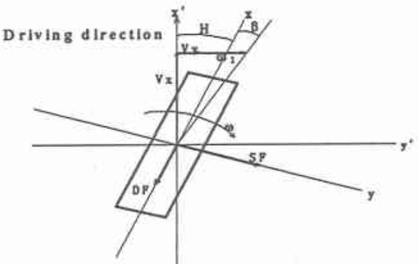


Fig.1 Sakai's tire model

According to Sakai's tire model, the braking force/traction force and the side force are obtained with the slip ratio (s) by the following equations.

1) When braking or free rolling ($s \geq 0$)

$$DF = -K_x s(1-f)^2 \cos\beta - F_z m_d f^2 (3-2f) hs$$
$$SF = K_x(1-s)(1-f)^2 \sin\beta + F_z \mu_d f^2 h(3-2f)\tan\beta \quad (3)$$

2) when accelerating ($s < 0$)

$$DF = -K_x s(1-f)^2 - F_z \mu_d f^2 (3-2f) hs$$
$$SF = \{K_x(1-s)(1-f)^2 \sin\beta + F_z \mu_d f^2 h(3-2f)\}\tan\beta \quad (4)$$

where

$$h = 1 \Big/ \sqrt{\tan^2\beta + s^2}$$
$$f = K_x \sqrt{\tan^2\beta + s^2} \Big/ (3F_z \mu_m)$$
$$s = (V_R \cos\beta - V_{roll}) / V_R \cos\beta \qquad (s \geq 0)$$
$$s = (V_R \cos\beta - V_{roll}) / V_{roll} \qquad (s < 0)$$

K_X : Braking stiffness.

F_Z : Tire normal load

μ_m : Maximum friction coefficient.

μ_d : Slip friction coefficient.

V_R : Tire velocity.

V_{roll} : tire rolling velocity.

S : Slip ratio

The eq.(3) and (4) are valid only in the following region:

$$\tan^2\beta + s^2 \leq (3\mu_m F_Z / K_X)^2 \quad (5)$$

Tire forces are obtained by the equations (7) for both braking and accelerating conditions, when

$$\tan^2\beta + s^2 > (3\mu_m F_Z / K_x)^2 \quad (6)$$

$$DF = -F_Z \mu_d sh$$
$$SF = \sqrt{(F_Z \mu_d)^2 - DF^2} \quad (7)$$

The slip angle of the front and rear tires (β_f, β_r) can be obtained from the following equations;

$$\beta_f = \mathrm{Tan}^{-1}\left(\frac{Vy}{Vx}\right) + \frac{\omega l_f}{V_x} - H \quad (8)$$

$$\beta_r = Tan^{-1}\left(\frac{Vy}{Vx}\right) - \frac{\omega l_r}{V_x} \quad (9)$$

where

V_x : Velocity of vehicle in the driving direction.

V_y: Velocity of vehicle in the direction perpendicular direction to the driving direction.

ω : Angular velocity.

l_f : Distance between C.G. of vehicle and front tire.

l_r : Distance between C.G. of vehicle and rear tire.

H : The steering angle.

Although the forgoing equations are complicated, they state that the slip ratio, friction coefficient and slip angle are very important parameters for calculating the forces of the tire; DF and SF. When the tire is locked (S=1), the coefficient of lock braking force μ_L is used instead of μ_d.

2.2.2. Modified Skai's tire model[4]

In the modified Sakai's tire model, we can treat the problems in which slip ratio and slip angle are relatively large. Furthermore , the friction coefficient depends on the velocity. In this model, the order of contact pressure is assumed to be equal to 4.

Longitudinal force(D_F) and lateral force(S_F) are obtained as follows:

$$D_F = C_X w l_h^2 s / 2 + (n+1)(2^n F_Z \mu_d) m_1 \cos\theta / n l^{n+1} \quad (10)$$

$$S_F = \{[(C_y w l_h^2 s_1 \tan\alpha)/2] + [(n+1)(2^n F_Z \mu_d) m_1 \sin\theta / n l^{n+1}]\} / m_2 \quad (11)$$

where

l_h : adhesion length of contact patch is obtained by the following equation:

$$l_h = \left(1 - (C_y w l^2 / 2)\sqrt{\tan^2\alpha + s^2} / 3\mu_S F_Z\right) l$$

C_y: Lateral spring constant of tread.

l: Contact length. W: Contact width.

α: Slip angle. S: Slip ratio.

μ_S: Max. friction coefficient.

F_Z: Vertical load.

m_1, m_2 : Parameters which are found as

$$m_1 = (l/2)^n (l - l_h) - 1/(n+1)[(l/2)^{n+1} - (l_h - l/2)^{n+1}]$$
$$m_2 = 1 + C_y w l_h^2 s_2 (\delta / C_y + 4l^2 / 3r^2 G'_y)(0.5 - s_2 l_h / 3l) / l$$

Cx: Longitudinal spring constant of tread.

n: Order of contact press which is equal to 4.

r: Tire radius.

μ_d: Friction coefficient which is equal to $\mu_0 - aV_m$.

μ_0: Dynamic friction constant.

a: Friction decreasing constant which is assumed o.oo5.

V_m: Average slip velocity . If adhesion contact length and contact length are equal ($l=l_h$), V_m is equal to zero, otherwise : $V_m = Vl\sqrt{1+(s^2-1)\cos^2\alpha} / (l - l_h)$

θ: Directional angle of the slip velocity with respect to the tire longitudinal axis which is found as:

In the case of braking $\theta = \tan^{-1}(\tan\alpha / s)$,

In the case of traction $\theta = \pi + \tan^{-1}[(1+s)\tan\alpha / s]$

S_1,: S_2 : parameters which are obtained as

In the case of braking $s>0$, $S_1 = 1$, $S_2 = 1 - s$,

In the case of traction $s<0$, $S_1 = s + 1$, $S_2 = 1$

G'_y : lateral rigidity of tire.

$\delta = C_y R^3 l^2 / (2k_y)$ In which $R = (k_y / 4E_i)^{1/4}$,

K_y: spring constant of carcase,

E_i : Bending rigidity.

Since, there is not enough space for much explanation here, it is recommended to refer reference about self-aligning torque calculation and other information.

2.2.3. Gim's tire model[5]

In this model, there are three forces and three moments acting between a pneumatic tire and road surface. The forces are normal, longitudinal and lateral. The moments are self-aligning torque, overturning and rolling resistance (shown in Figure 2). The interacting forces and moments are non-linear function of combined slip ratio, slip angle and camber angle.

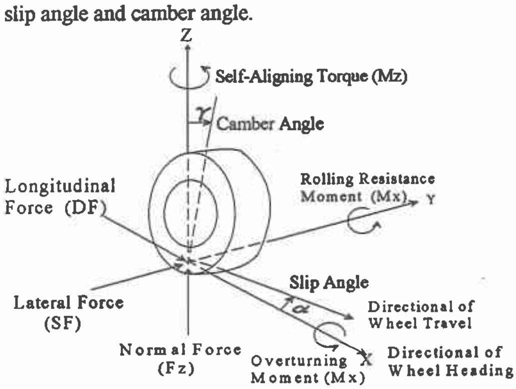


Fig. 2 Six components of forces and moments applied to a tire from the road surface

The longitudinal, lateral forces and self-aligning torque due to the both slip ratio (s) and slip angle(α) as well as camber angle (γ) during braking /traction and steering are obtained in the three possible combination.

(a) The lateral elastic displacements have the same direction (αγ>0) . For this case two possibilities are considered:

1. $S_\gamma < S_{\gamma c}$, $S_S < S_{SC}$ *and* $S_\alpha < S_{\alpha c}$ *at* $0 \le l_a \le l$:

The Longitudinal and lateral forces and self-aligning torque are available from following equations:

$$DF = C_s S_s l_n^2 + \mu_x^{(m)} F_z (1 - 3l_n^2 + 2l_n^3) \quad (12)$$

$$SF = C_\alpha S_\alpha l_n^2 + \mu_y^{(m)} F_z (1 - 3l_n^2 + 2l_n^3) + C_\gamma S_\gamma \quad (13)$$

$$M_z = M_{z\alpha} + m_1 (M_{zs\alpha} + M_{zs\gamma}) \quad (14)$$

where

DF : Longitudinal force.

SF : Lateral force.

M_z : Self-aligning torque

$M_{z\alpha}$: The component which is generated by lateral force :

$$M_{z\alpha} = \left[C_\alpha S_\alpha \left(-\frac{1}{2} + \frac{2l_n}{3}\right) + \frac{3}{2}\mu_y F_z S_n^2 \right] l l_n^2 \quad (15)$$

$M_{zs\alpha}$, $M_{zs\gamma}$: The components are produced by longitudinal force which has an offset due to slip angle and camber angle, respectively, between the wheel center plane and the tire tread base.

$$M_{zs\alpha} = \frac{2}{3} C_s S_s S_\alpha l l_n^3 + \frac{3\mu_x^{(m)} \mu_y F_z l}{5C_\alpha}(1 - 10l_n^3 + 15l_n^4 - 6l_n^5) \quad (16)$$

$$M_{zs\gamma} = |\overline{\eta}| DF \quad (17)$$

$|\overline{\eta}|$: an offset of longitudinal force produced by camber angle. $|\overline{\eta}| = S_\gamma (\rho_1^2 - l^2/2)^{1/2}$

ρ_1: Undeflected radius of tire.

m_1 : The parameter which is equal to 1 and -1 during braking and traction, respectively.

C_S : Longitudinal stiffness. C_α: Lateral stiffness.

C_S : Camber stiffness.

μ_x : Longitudinal friction coefficient.

μ_y : Lateral friction coefficient.

$\mu_x^{(m)}$: Modified longitudinal friction coefficient.

$\mu_y^{(m)}$: Modified lateral friction coefficient.

S_S: Longitudinal slip ratio.($S_S = |s|$)

S_γ : Lateral slip ratio due to camber angle. ($S_\gamma = |\sin\gamma|$)

S_α : Lateral slip ratio due to slip angle. ($S_\alpha = |\tan\alpha|$)

$S_{\gamma c}$: Lateral slip ratio due to the critical camber angle which is obtained as $S_{\gamma c} = \mu_y F_z / C_\gamma$

S_{SC}: Critical longitudinal slip ratio. ($S_{SC} = 3\mu F_Z / C_S$)

l: contact patch length.

l_a: Length of adhesion region of contact patch.

l_n , S_n : two non-dimensional parameter which are found as $l_n = 1 - S_n$, $S_n = \left[B_2 + (B_2^2 - B_1 B_3)^{1/2}\right] / B_1$ (18)

$B_1 = (3\mu F_Z)^2 - (3C_\gamma S_\gamma)^2$, $B_2 = 3C_\alpha S_\alpha C_\gamma S_\gamma$

$B_3 = -[(C_S S_S)^2 + (C_\alpha S_\alpha)^2]$

$S_{\alpha c}$: Lateral slip ratio of the critical slip angle which is obtained as $S_{\alpha c} = \frac{1}{C_\alpha}\left[(3\mu F_z)^2 - (C_s S_s)^2\right]^{1/2} - 3C_\gamma S_\gamma / C_\alpha$

2. $S_\gamma \ge S_{\gamma c}$, $S_S \ge S_{SC}$ *or* $S_\alpha \ge S_{\alpha c}$ *at* $l_a = 0$:

In this case there is only a sliding region without an adhesion region. The Longitudinal and lateral forces are obtained as follows:

$$DF = \mu_x^{(m)} F_z \quad (19)$$

$$SF = \mu_y F_z \quad (20)$$

The self-aligning torque can be obtained by eq.(14) in which :

$$M_{z\alpha} = 0 \quad (21)$$

$$M_{zs\alpha} = 3m_1 \mu_x^{(m)} \mu_y F_z l / 5C_\alpha \quad (22)$$

Meanwhile, $M_{zs\gamma}$ is also obtained by eq.(17).

(b) The lateral elastic displacements have opposite direction (αγ<0) with the condition of $C_\alpha S_\alpha \ge C_\gamma S_\gamma$.

In this case S_n is also calculated by eq (18), but in which :

$B_2 = -3C_\alpha S_\alpha C_\gamma S_\gamma$. And the Lateral slip ratio of the critical slip angle is equal to:

$S_{\alpha c} = \frac{1}{C_\alpha}\left[(3\mu F_z)^2 - (C_s S_s)^2\right]^{1/2} + 3C_\gamma S_\gamma / C_\alpha$

Again , two possibilities can be considered:

1. $S_S < S_{SC}$ *and* $S_\alpha < S_{\alpha c}$ *at* $0 \le l_\alpha \le l$. The longitudinal force can be obtained by eq.(12) and the lateral force and self_ aligning torque are found as follows.

$$SF = C_\alpha S_\alpha l_n^2 + \mu_y^{(m)} F_z (1 - 3l_n^2 + 2l_n^3) - C_\gamma S_\gamma \quad (23)$$

Furthermore, self_ aligning torque is calculated by eq.(14), but, in which $M_{zs\gamma} = -|\overline{\eta}| DF$ (24)

2. $S_S \ge S_{SC}$ *or* $S_\alpha \ge S_{\alpha c}$ *at* $l_\alpha = 0$: The Longitudinal and lateral forces and self-aligning torque ($M_{z\alpha}, M_{zs\alpha}, M_{zs\gamma}$) can be obtained by equations (19), (20), (21), (22) and (24).

(c) The lateral elastic displacements have opposite direction ($\alpha\gamma<0$) with the condition of $C_\alpha S_\alpha \le C_\gamma S_\gamma$.

The critical values of slip ratio and camber angle is as follows:

$$S_{\gamma c} = (3\mu_y F_z + C_\alpha S_\alpha) / 3C_\gamma$$

$$S_{sc} = [(3\mu F_z)^2 - (C_\alpha S_\alpha - 3C_\gamma S_\gamma)^2]^{1/2} / C_s$$

And depending on the values of S_S and B_1, S_n is determined as

$$S_n = \left[B_2 + (B_2^2 - B_1 B_3)^{1/2}\right] / B_1 \text{ for } S_S \neq 0 \text{ and } B_1 \neq 0$$

$$S_n = B_3 / 2B_1 \text{ for } S_S \neq 0 \text{ and } B_1 = 0$$

$$S_n = 0 \text{ for } S_S = 0$$

This case two possibilities are also considered:

1. $S_\gamma < S_{\gamma c}$ and $S_S < S_{SC}$ *at* $0 \le l_\alpha \le l$: The eq.(12) provides an expression for the longitudinal force. The lateral force is found by the following equation:

$$SF = C_\gamma S_\gamma (3l_n^2 + 2l_n^3) - C_\alpha S_\alpha l_n^2 + \mu_y F_z (1 - 3l_n^2 + 2l_n^3) \quad (25)$$

For obtaining the self-aligning torque, $M_{zs\alpha}$ and $M_{zs\gamma}$ are found by equations (16) and (24). And $M_{z\alpha}$ is available by following equation.

$$M_{z\alpha} = C_\alpha S_\alpha l l_n / 6 \quad (26)$$

2. $S_\gamma \ge S_{\gamma c}$ *or* $S_S \ge S_{SC}$ at $l_\alpha = 0$: The Longitudinal and lateral forces and self-aligning torque ($M_{z\alpha}, M_{zs\alpha}, M_{zs\gamma}$) can be obtained by equations (19), (20), (21), (22) and (17).

2.3. Two-wheel Equivalence Model[6]

The two-wheel equivalence model was applied for calculating the resultant forces at the gravity center of each vehicle. In this model, It is assumed that the rolling and pitching movements are negligible. The forces at the gravity center of the vehicle can be calculated by the resultant tire forces in the X-axis (Fx) and the y-axis (Fy);

$$F_X = DF_f \cos H + DF_r - SF_f \sin H \quad (27)$$

$$F_Y = DF_f \sin H + SF_f \cos H + SF_r \quad (28)$$

The rotation torque is resulted by eq.(12).

$$M = (DF_f \sin H + SF_f \cos H) l_f - SF_r l_r \quad (29)$$

These forces are a function of the forces of the tires and the steering angle. Consequently, the vehicle acceleration in both x and y directions and the angular acceleration can be obtained from the resulting forces.

3. MODEL PARAMETERS AND ESTIMATION METHOD

To reconstruct traffic accidents, we estimated the unknown parameters using above-mentioned models. We performed a driving simulation of the pre-impact phase based on the data collected from the accident site. This means that we can presume preliminary model parameters in the pre-impact phase. On the other hand the parameters were unknown in both the impact and the post-impact phases.

3.1. Model Parameters

Unknown parameters from the impact model are

e_n : Normal restitution coefficient.

e_t : Tangential restitution coefficient.

The unknown parameters from the driving simulation models are

u_i: Friction coefficient.

H_i = Steering angle.

$S.F_i$ = slip ratio of front tire.

$S.R_i$ = slip ratio of rear tire.

i = ID number of vehicle.

We applied Box's complex algorithm to estimate the above-mentioned ten unknown parameters based on the rest position of the vehicles.

3.2. Box's Complex Algorithm[9]

we estimated the unknown parameters using Box's algorithm. In this method, we estimated the parameters so as to minimize the difference between the calculated rest positions of the vehicles and the observed ones. Box's method is a kind of sequential search technique for finding a minimum objective function while avoiding entrapment into the local minimum.

The objective function is subjected to constraints as follows:

Minimize $F_k(P)$, Subject to $g \le p \le h$

where

$P : (e_n, e_t, u_1, H_1, \ldots, S.F_2, S.R_2)$.

g, h : Constraint vector.

k : Complex point.

The objective function is given below;

$$F_k(P) = \sum_{i=1}^{2} \left(\frac{x_i - x_{si}}{x_{ri}}\right)^2 + \left(\frac{y_i - y_{si}}{y_{ri}}\right)^2 + \left(\frac{\theta_i - \theta_{si}}{\theta_{ri}}\right)^2 \quad (30)$$

where

x_i, y_i, θ_i: Calculated distance and yaw angle.

x_s, y_s, θ_s: Observed distance and yaw angle.

x_r, y_r, θ_r: Ranges of distance and yaw angle.

We assume that the unknown model parameters are subject to the following constraints;

$$-1 \le e_n \le 1 \quad , \quad -1 \le e_t \le 1$$

$$0 \le u_i \le 1 \quad , \quad -\pi/4 \le H_i \le \pi/4$$

$$0 \le S.F_i \le 1 \quad , \quad 0 \le S.R_i \le 1$$

3.3. Comparison of Tire models in Estimating Model Parameters by Box's Complex Algorithm

Data from an artificial traffic accident was introduced to compare the effect of tire models in estimating the model parameters by Box's method for reconstructing traffic accidents. We assumed that an accident, as shown in Fig. 3, occurred on a street. We specified the model parameters in advance. Giving the initial positions, we calculated the trajectory of each vehicle using Sakai's tire model, modified Sakai's tire model and Gim's tire model. The locations of the vehicles were calculated every 0.01 seconds consecutively. Fig. 3 shows the position of the striking and the struck cars based on the artificial model parameters. The initial, impact and rest positions are denoted by points 1, 2 and 3, respectively.

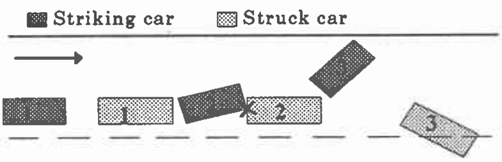


Fig. 3 Front to rear accident of two cars based on artificial data.

First, we selected model parameters randomly. Then, using the tire models combined with impact model, we calculated the rest position of each vehicle. We compared the estimated parameters with the assumed ones in the case of using the three tire models which are shown in Fig. 4. Using Gim's tire model, the difference between them was sufficiently small.

Fig. 5 and Fig. 6 show the differences between the calculated rest positions of vehicles and the assumed ones. we can see that the differences between calculated rest positions of vehicles and assumed ones, Using Gim's tire model , are less than the others for each vehicle.

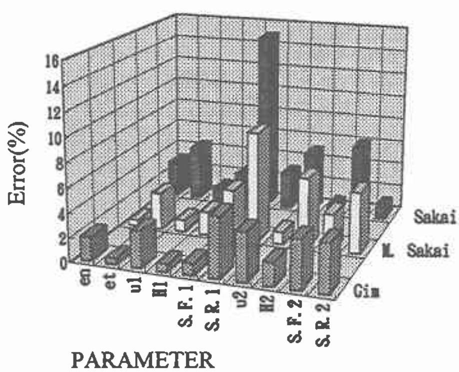
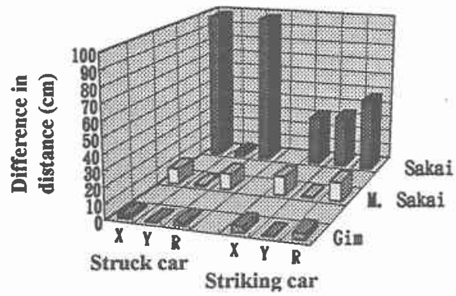


Fig. 4 The differences between assumed and estimated parameters using Gim's tire model, modified Sakai's tire model and old Sakai's tire model.

We can conclude that Gim's tire model can be much accurate than the two tire models in estimating the model parameters by Box's complex algorithm for reconstructing traffic accidents.



R: Resultant

Fig. 5 Distance differences between assumed rest positions and estimated ones using Gim's tire model, modified Sakai's tire model and Sakai's tire model.

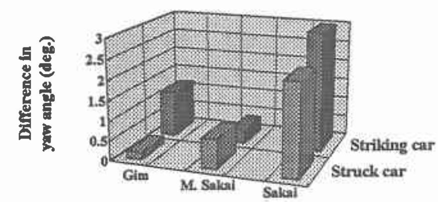


Fig. 6 Yaw angle differences between assumed rest positions and estimated ones using Gim's tire model, modified Sakai's tire model and Sakai's tire model.

4. ACTUAL TRAFFIC ACCIDENTS DATA

A side impact accident occurred at an intersection in Sapporo as shown in Fig. 7. The driving simulation of the pre-impact phase was performed based on the data collected from the accident site: The velocity of the striking vehicle before braking was 30 km/h. It had presumably decreased to 15 km/h before collision. The velocity of the struck vehicle was about 30 km/h. The initial, impact and actual rest positions are points 1, 2 and 3, respectively. Table 1 presents the estimated parameters.

Table 1 Estimated parameters by Box's method, using Gim's tire model(2th row), modified Sakai's tire model (3th row) and Sakai's tire model(4th row)

	e_n	u_1	H_1	$S.F_1$	$S.R_1$	u_2	H_2	$S.F_2$	$S.R_2$
-0.3	-0.9	0.25	-30°	0.7	0.8	0.3	-35°	0.6	0.6
-0.2	-0.8	0.45	-25°	0.55	0.55	0.6	-32°	0.5	0.7
-0.55	-0.64	0.48	2.86°	0.56	0.8	0.75	-31.5°	0.25	0.8

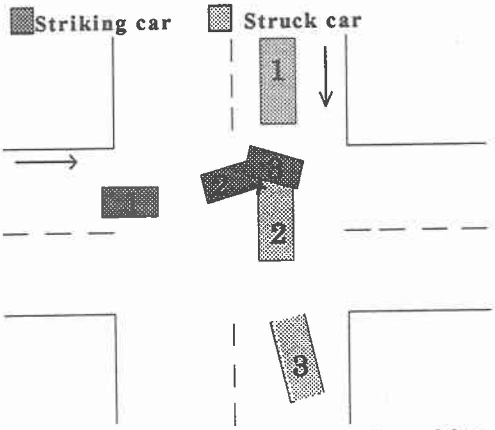
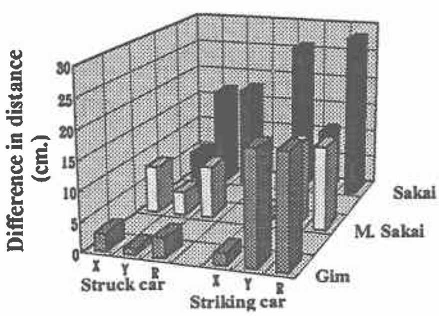


Fig. 7 Side impact accident based on observed data.

It is difficult to judge whether the parameters are reasonable or not. May be the parameyters are much reasonable when Gim's tire model and modified Sakai's tire model were used. In the case of the old Sakai's tire model, we have to examine carefully why the slip ratios of the 2-nd vehicle are so different between the front and the rear tires. Also, we have to investigate the validity of the ranges of constraints for all parameters, in combination with experimental data. We intend to apply Box's method and driving simulation model including Gim's tire model and modified Sakai's tire model for reconstructing traffic accidents by combining it with experimental data. This will help us to confine the ranges of the model parameters and to improve consequently the precision of estimation.

The differences between the observed and the estimated rest positions are shown in Fig. 8 and 9. We can see that the differences in the positions of both vehicles are very small. Moreover, it should be noted that when the Gim's tire model and modified Sakai's tire model were used the differences were less than the other.



R: Resultant

Fig. 8 Distance differences between observed rest positions and estimated ones using Gim's tire model, modified Sakai's tire model and old Sakai's tire model.

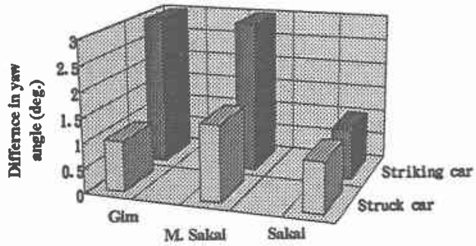


Fig. 9 Yaw angle differences between observed rest positions and estimated ones using Gim's tire model, modified Sakai's tire model and old Sakai's tire model.

5. CONCLUSIONS

From this study the following conclusions can be drawn:

1) The impact model, combined with the driving simulation model including one of the Sakai's tire model , modified Sakai's tire model and Gim's tire model, was applicable for reconstructing traffic accidents.

2) The driving simulation model including Gim's tire model was much effective in estimating model parameters by Box's complex algorithm for reconstructing traffic accidents.

REFERENCES

[1] Ronald L. Woolley, Charles Y. Warner and Thomas R. Perl,"An overview of selected computer programs for automobile accident reconstruction", Transportation Research Record 1068, 85-100, 1986.

[2] Philip H. Chenng, Michael j. Sens, and Jhon F. Wiechel, "An overview of the evolution of computer assisted Motor vehicle accident reconstruction", Proc. the passenger car meeting & exposition No. 871991, 13-27, 1987.

[3] Sakai, H.," Research on the Dynamic properties of tire ", JARI Technical report No. 46, 1978.

[4]Sakai H." Tire engineering", Grandprix press, 1987. (in Japanese)

[5] Gwanghun Gim and Parviz E. Nikravesh, " An analytical model of pneumatic tires for vehicles dynamices simulations.", Int. J. of vehicle design, 12-1, (1991).

[6] Abe Masato, Dynamics and control of vehicles, Kyoritsu press, 1979.

[7] Hirotoshi Ishikawa,"Impact model for accident reconstruction normal and tangential restitution coefficients", SAE paper No. 930654, 1993.

[8] Hirotoshi Ishikawa,"Computer simulation of automobile collision -Restitution coefficients", SAE paper No. 851729, 1985.

[9] J. Kuster & J. Mize,"Box(Complex Algorithm)", Optimization Techniques with FORTRAN 368-386, 1973.