

A CAR-FOLLOWING MODEL APPLIED REACTION TIMES DISTRIBUTION AND PERCEPTUAL THRESHOLD

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Abstract: In recent years, the importance of Car-following models has increased significantly, although car-following behavior has been studied for an half of a century. In most cases, the simulation model results are used in actual field. However, correct verification about their result is not attained.

Most models do not consider about reaction time as various and in reality, it is general to use fixed value or random variable for the reaction time. As a result, it causes the rigidity of models, and the "time difference" between the actual behavior and models so, acceleration and deceleration at time (t) are simultaneously. Therefore, reaction time is used as lognormal distribution, and "perceptual threshold" was estimated from the acceleration rate versus relative speed to improve acceleration and deceleration rate.

Goodness of fit of the model is examined by Root Mean Squared error (RMSE) comparing to other models. Consequently, the new model performed better description of actual driver's behavior.

Key Words: Car-following, Time difference, Reaction time, Perceptual threshold, Driver's variety

1. INTRODUCTION

In recent years, the importance of Car-following models has increased significantly, with behavioral models forming the basis of the functional definitions of advanced vehicle control and Highway system (AVHS) and autonomous cruise control (ACC), etc. Systems control the accelerator and remove the human factors causing misperception and other defects. Therefore, we will take several advantages of increasing road safety and capacity.

This paper represents to identify stimuli and reactions properly and investigate problems of existent models.

Although, many models have been developed, few of these are applied to microsimulations. Because the major problem of the exist models is the difference between actual behavior and the results described by the models. The difference can be identified by goodness of fit. This paper can help models improve to their output.

In this paper, we aim to develop a microscopic car-following model to overcome the defects so that we introduce "perceptual threshold" and a "distribution of reaction times". We

combined perceptual threshold to the new model as sensitivity, and applied the distribution of reaction times.

2. LITERATURE REVIEW

In this chapter, a literature review of car-following models and estimation of reaction time is presented.

Findings from this review are summarized at the end of the chapter.

2.1 Car-Following Models

The models capturing drivers' acceleration behavior can be classified as:

- Linear car-following model
- Non-linear car-following model
- Safety distance model

2.1.1 Linear Car-Following Model

Chandler et al. (1958) developed the first car-following model that is a simple linear model. The model can be expressed as

$$a_n(t) = \alpha \Delta V_n^{front} (t - \tau_n) \quad (1)$$

Where,

- $a_n(t)$: Acceleration or deceleration at time (t)
- α : Sensitivity coefficient
- ΔV_n : Speed of vehicle
- τ_n : Reaction time

A major limitation of the above model is the assumption of a constant sensitivity for all situations.

Gazis et al. (1959) address it by incorporating the space headway between the two vehicles in the sensitivity term. Their model is as follows:

$$a_n(t) = \frac{\alpha}{\Delta X_n(t - \tau_n)} \Delta V_n^{front} (t - \tau_n) \quad (2)$$

Where,

- $a_n(t)$: Acceleration or deceleration at time (t)
- α : Sensitivity coefficient
- ΔV_n : Speed of vehicle
- τ_n : Reaction time
- ΔX_n : Headway

The model was estimated using microscopic data collected from the car-following experiments in the Holland Tunnel and the Lincoln Tunnel in New York and at the General Motors test track. The parameters were estimated for each driver of each data set using correlation analysis.

Newell (1961) suggested the following relationship between the speed and the headway. Instead of using the sensitivity-stimulus formulation as follows:

$$V_n(t) = G_n \Delta X_n(t - \tau_n) \quad (3)$$

Although, the model had the advantage of integrability to obtain different macroscopic speed-flow-density relationships, no attempt was reported to obtain a quantitative result to validate the model.

2.1.2 Non-Linear Car-Following Model

The car-following model developed by Gazis et al. (1961), known as the General Motors Nonlinear Model, is the most general one. The model is given by:

$$a_n(t) = \alpha \frac{V_n(t)^\beta}{\Delta X_n(t - \tau_n)^\gamma} \Delta V_n^{front}(t - \tau_n) \quad (4)$$

No rigorous framework for estimating the model was provided.

Gazis-Herman-Rothery (GHR) model is perhaps the most well-known model and dates from the late fifties and early sixties. Its formulation is

$$a_n(t) = cv_n^m(t) \frac{\Delta v(t - T)}{\Delta x^l(t - T)} \quad (5)$$

2.1.3 Safety Distance Model

Kometani and Sasaki (1959) specified a safe following distance model as follows:

$$\Delta x(t - T) = \alpha v_{n-1}^2(t - T) + \beta_1 v_n^2(t) + \beta v_n(t) + b_0 \quad (6)$$

If the driver of the vehicle in front were to act unpredictably a collision would be unavoidable.

Helly(1959) proposed a model that included additional terms for the adaptation of the acceleration according to whether the vehicle in front (and the vehicle two in front) was braking. The simple model is as follows:

$$a_n(t) = C_1 \Delta v(t - T) + C_2 (\Delta x(t - T) - D_n(t)), \quad D_n(t) = \alpha + \beta v(t - T) + \gamma a_n(t - T) \quad (7)$$

Where,

- $D_n(t)$: Desired following distance at time (t)

2.2 Reaction Time

In this section, we present the studies that were conducted to obtain the brake reaction time of drivers driving in real traffic.

Johansson and Rumer (1971) estimated the distribution of the brake reaction time from a sample of 321 drivers traveling in a real traffic. The subjects were instructed to apply the brake pedal as soon as they hear a sound. The brake reaction time varied from 0.4 to 2.7 seconds with a median, mean, and standard deviation of 0.89, 1.01, and 0.37 seconds respectively and a 90 percentile value of 1.5 seconds.

Lerner et al. (1995) estimated the reaction time distribution from a sample of 56 drivers driving in real traffic. The brake reaction time varied from 0.7 to 2.5 seconds with a median, mean, and standard deviation of 1.44, 1.51, and 0.39 seconds respectively.

3. DATA COLLECTION AND CORRECTION

We experimented to collect field data at several sites, mostly at urban highway. We used five vehicles equipped with Laptops and tachometers.

3.1 Data Collection

Data is collected from the tachometers by second to Laptops directly and then we handled data that we can use. Experimental conditions and equipments are as follows.

- Dates : 11,15,17,22,24,28, April,2003(6 days))
- Sites : Yangwha-Seokang, Wonhyo-Seogang, Seogang-Yanghwa Bridge segment, Road Kangbyun buk
- Period : 07:00-19:00
- Weather : Fine
- Number of used vehicle : 5
- Equipment : Laptops, tachometers

3.2 Grouping Drivers

A driver takes various reactions to the same stimulus, so that it can change traffic condition directly or indirectly. Driver's variety can divide "The Variety across Drivers" and "The Variety within a Driver".

Therefore, we employed 10 people to try to reflect driver's variety. We divided into 5 groups with driving experience under 6 months, under 1 year, under 2 years, under 5 years and over 5 years. Consequently, we assume that Driver's variety is reflected the data collection.

3.3 Data Correction

We can imagine two error types during the experiment as:

1. Road condition
2. Equipment error

We tried to match estimated vehicle trajectory to road facility and length to remove error by road condition and then remove abnormal speed by measured speed by hand. Moreover, we correct the field data using the discrete wavelet transform (DWT) in Matlab.

Wavelet transform was suggested Fourier in 1807, the discrete wavelet transform (DWT) of a signal is calculated and the resultant wavelet coefficients are passed through a threshold testing.

In this case, the coefficients that are smaller than a certain value are removed. Then the resultant coefficients are used to reconstruct the signal.

With this method, it is possible to remove noise with little loss of details. If a signal has its energy concentrated in a small number of wavelet coefficients, its coefficient values will be relatively large compared to the noise that has its energy spread over a large number of coefficients. (Filtering (Denoising) in the Wavelet Transform Domain, Yousef M. Hawwar, Ali M. Reza, Robert D. Turney, DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE, UNIVERSITY OF WISCONSIN-MILWAUKEE)

In this paper, the collected data is discrete signal per second so that we used the discrete wavelet transform (DWT) to de-noise error.

3.4 Data Estimation

Table 1. shows a example of collected data set by tachometers at Yangwha -seokang segment at Road Kangbyun buk.

Table 1. Collected Data Set

sec	Time				Vehicle 1			Vehicle 2		
	hr	min	sec	Dist.	Speed	Cum, Dist.	Dist.	Speed	Cum, Dist.	Spacing
11	8	35	19	7	25.2	116	7	25.2	87	29
12	8	35	20	5	18.0	121	7	25.2	94	27
13	8	35	21	7	25.2	128	6	21.6	100	28
14	8	35	22	6	21.6	134	5	18	105	29
15	8	35	23	4	14.4	138	4	14.4	109	29
16	8	35	24	2	7.20	140	3	10.8	112	28
17	8	35	25	3	10.8	143	2	7.2	114	29
18	8	35	26	2	7.20	145	2	7.2	116	29

We estimated accelerations, Headway, Relative speed and Spacing in Table 2 based on the field data.

Table 2. Estimated Accelerations, Headway, Relative Speed and Spacing

Vehicle 2				Vehicle 3			
Acc.	Headway	Relative speed	Spacing	Acc.	Headway	Relative speed	Spacing
0	4	0	29	0	2	1	13
-1	4	-2	27	3	2	1	14
-1	5	1	28	-2	1	-3	11
-1	6	1	29	-1	1	-2	9
-1	7	0	29	-3	1	-2	7
-1	9	-1	28	1	2	0	7
0	15	1	29	-1	1	-2	5

4. MODEL DEVELOPMENT

In this study, we developed a car-following model based on field data, measured at Yangwha-seokang Bridge, Road Kangbyun buk site, 1.127 km Road length. A car-following model generally consists of relative speed and Headway as stimuli, acceleration or deceleration as reaction and sensitivity factor.

4.1 Sensitivity

The sensitivity significantly effect to the model's behavior. It controls how far performing acceleration or deceleration. For the reason, sensitivity has to be constructed carefully and properly.

Therefore, we first construct sensitivity, and then we develop a car-following model.

4.1.1 Perceptual Threshold

In this section, we aim to improve sensitivity, so that, we introduce "perceptual threshold" which can remove unstable behavior in terms of acceleration and deceleration. The perceptual threshold, we introduced, is different from the existent models which were developed by Reiter (1994) and Evans and Rothery(1973).

When a driver drives at the real field, they do not react all the time by stimuli, especially, relative speed even though it is the major stimulus. Therefore, we performed regression analysis between relative speed (Δv) and spacing (Δx) to build sensitivity (λ). The results of regression analysis for opening and closing are in Table 3.a and Table 3.b.

- Opening: When lead vehicle accelerates, spacing (Δx) is further than following distance. Therefore, follow vehicle accelerates.
- Closing: When lead vehicle decelerates, spacing (Δx) is closer than following distance. Therefore, follow vehicle decelerates.

Table 3.a. The Results of Regression Analysis for Opening

Categories	Equation	Opening	R ²
Linear	$\Delta v = 0.0299\Delta x + 0.3426$		0.7493
Log	$\Delta v = 0.8277Ln(\Delta x) - 0.1087$		0.4918
Multinomial	$\Delta v = 0.0004\Delta x^2 - 0.0098\Delta x + 1.0837$		0.8360

Table 3.b. The Results of Regression Analysis for Closing

Categories	Equation	Closing	R ²
Linear	$\Delta v = -0.0273\Delta x - 0.7643$		0.7678
Log	$\Delta v = -0.6673Ln(\Delta x) + 0.559$		0.7959
Multinomial	$\Delta v = 0.0007\Delta x^2 - 0.0708\Delta x - 0.3104$		0.8447

From the regression analysis, we decided to determine the relation between relative speed (Δv) and spacing (Δx) as the multinomial equation. It can be generalized:

$$\Delta v = C_1\Delta x^2 + C_2\Delta x + C_3 \tag{8}$$

Now, we assumed that $C_2\Delta x + C_3$ has little contribution to the relative speed (Δv), so that we can simplify:

$$\Delta v = C_{\Delta v}\Delta x^l \tag{9}$$

We can generalize Eq. (8) to Eq. (9) having l degree. In addition, figure 1.a and figure 1.b show that which regression equation makes better fit.

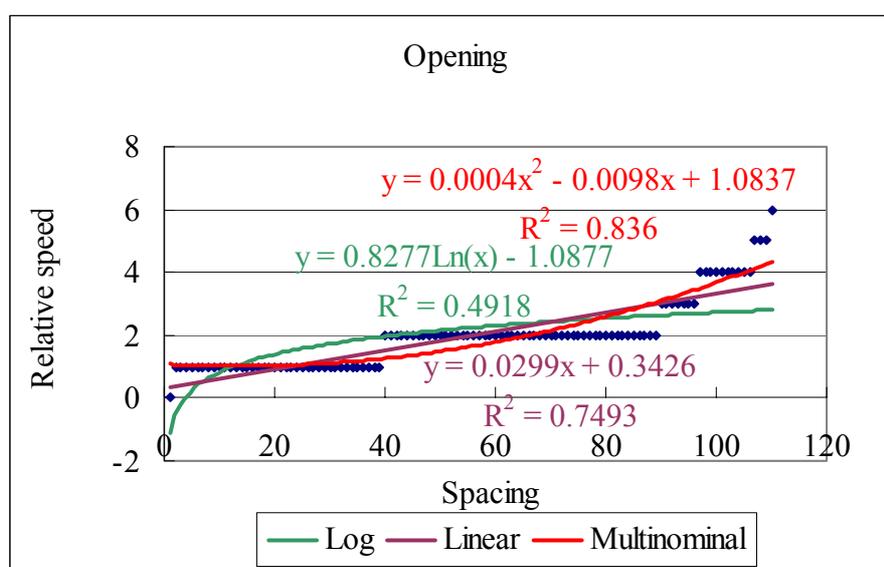


Figure 1.a. The Result of Regression Analysis for Opening

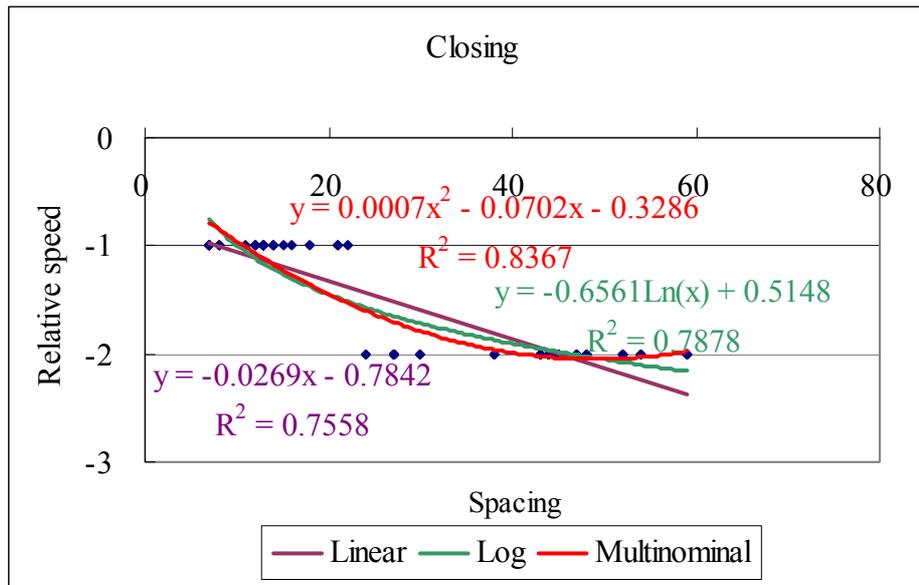


Figure 1.b. The Result of Regression Analysis for Closing

4.1.2 Sensitivity (λ) Formulation

We performed correlation analysis acceleration and deceleration with several parameters such as speed, spacing, 1/spacing and speed/spacing to construct sensitivity. Table 4. shows the results of correlation analysis for sensitivity formulation. We will use the results in Table 4 to build sensitivity (λ).

Table 4. The Results of Correlation Analysis for Sensitivity Formulation (R^2)

Categories	Both of acceleration and deceleration	Acceleration	Deceleration
Speed	0.317	0.107	0.117
Spacing	0.006	0.003	0.039
1/spacing	0.003	0.008	0.168
Speed/spacing	0.356	0.162	0.469

Apparently, we could decide to construct acceleration and deceleration separately, because the result of deceleration and speed/spacing has the top correlation coefficient ($R^2 = 0.469$), on the other hand the result of acceleration and speed/spacing has relatively low ($R^2 = 0.162$). However, when we consider both of them, we acquired comparatively high correlation coefficient ($R^2 = 0.356$). Therefore, we constructed combined model.

So, we suggest a framework of sensitivity (λ).

$$\lambda = C_{\lambda} \frac{v}{\Delta x} \tag{10}$$

Moreover, we can converse Eq. (9) to Eq. (11):

$$\Delta x = C_{\Delta x} \Delta v^l \tag{11}$$

So, we substitute Eq. (11) for Δx in Eq. (10) then,

$$\lambda = C_{\lambda} \frac{v}{C_{\Delta x} \Delta v^l} \tag{12}$$

Furthermore, we can find out correlation coefficient ($R^2 = 0.317$) between acceleration and deceleration and speed, so we assumed that the relation can be:

$$a_n = C_a v_n^m \tag{13}$$

4.1.3 Car-Following Model Formulation

Car-following model has several structures though its final output is the same as acceleration and deceleration most and it consists of several parameters. So, we performed correlation analysis to investigate the relation between parameters. The result of correlation analysis is in Table 5 and Figure 2.

Table 5. Correlation Analysis Result of Acceleration and Deceleration with Parameters (R^2)

Categories	Both of acceleration and deceleration	Acceleration	Deceleration
Speed	0.317	0.107	0.117
Relative speed	0.810	0.681	0.616
spacing	0.006	0.003	0.039
1/spacing	0.003	0.008	0.168

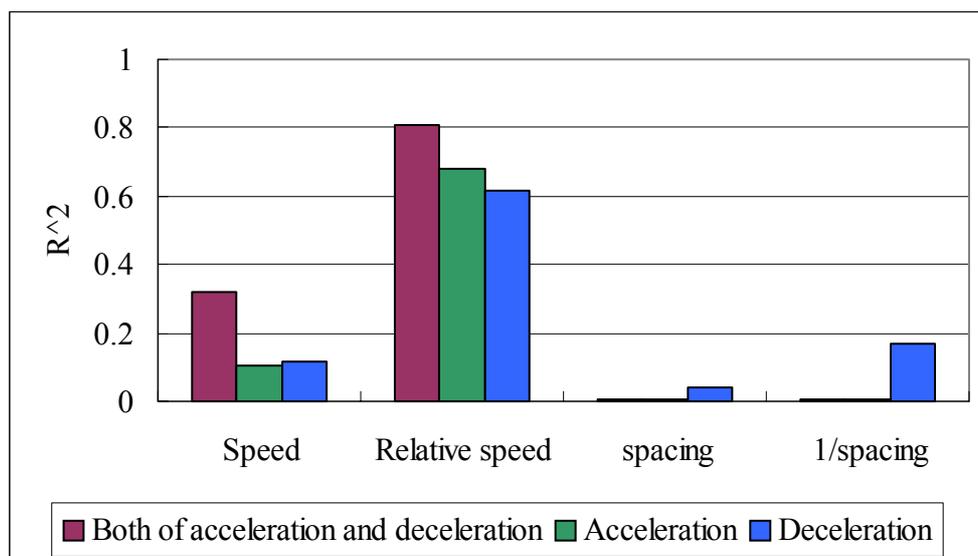


Figure 2. Correlation Analysis Result of Acceleration and Deceleration with Parameters

Figure 2 shows when we consider both acceleration and deceleration simultaneously we achieve higher correlation coefficient with relative speed ($R^2 = 0.810$) and speed contributes to acceleration and deceleration considerably ($R^2 = 0.317$). Therefore, we combined acceleration and deceleration construct car-following model.

Now, we construct a car-following model. Exist models, have been developed, have relative speed as stimuli. So, we suggest a framework of car-following:

$$a_n(t) = C_1 \lambda \Delta v(t - T) \tag{14}$$

We substitute Eq. (12) for (λ) in Eq. (14) and consider Eq. (13) and reaction time (T_n) then we construct a new car-following model.

$$a_n(t) = C_1 \frac{v_n^m(t)}{\Delta x(t - T)^l} \Delta v(t - T_n) \tag{15}$$

Where,

- $a_n(t)$: Acceleration or deceleration at time (t)
- C_1 : Sensitivity coefficient
- λ : Sensitivity
- Δv : Relative speed
- T : Reaction time
- Δx : Headway

We recognized that the model we suggest has the same formulation with GM model and GHR model. However, GM model did not support any framework to verify and GHR model is not general car-following model that GHR model was constructed by only for low speed and extreme value of acceleration and deceleration so that these models have not been considered general car-following model. Moreover, we considered a distribution of reaction time (T_n)

In this study, therefore, suggested non-linear car following model supports GM model and GHR model.

4.1.4 Reaction Time Estimation

We experimented to estimate reasonable reaction time in the field and measured the point of time when lead vehicle and follow vehicle accelerates or decelerates. We performed within this speed boundary in Table 6. (Number of measured reactions = 450).

Table 6. Analysis Boundary

Categories	Speed (km/hr)	Reaction time (sec) Measured value
Min	3.6	0.5
Max	61.2	2.5

From the estimated reaction time, we inferred a distribution operating ProModel 4, so that lognormal distribution (Rank 98.1) is obtained. Figure 3 shows lognormal distribution.

(Frequency)

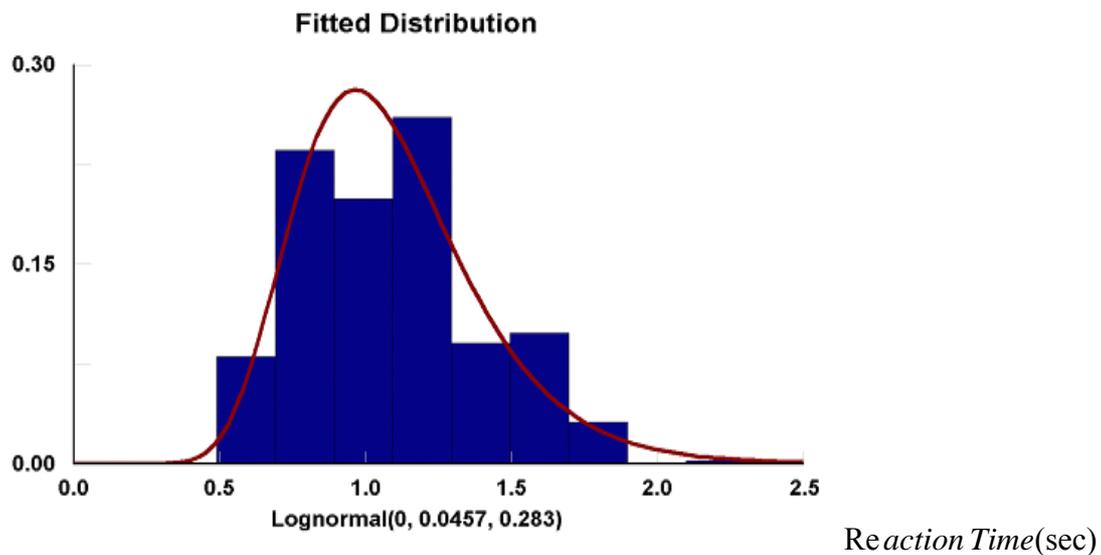


Figure 3.Fitted Distribution

$$f(x) = \frac{1.41}{x} e^{-6.25[\ln(x)-0.0457]} \quad (16)$$

- Mean : 1.09
- Variance : 0.099
- Goodness of fit : 98.1

5. CALIBRATION

We performed to verify the suggested model with acceleration and deceleration behavior against GM linear model and Helly model. Because acceleration and deceleration behavior is the core of model's fit. Therefore, we use Root Mean Squared error (RMSE) to evaluate goodness of fit.

The suggested model is non-linear so we compare it to linear model such as GM linear model and linear (Helly) model.

5.1 GM Linear Model

This model is the basic car-following model that consists of relative speed and sensitivity coefficient. It only reacts on relative speed.

We fitted as better as possible to field data with 1.1 sec of estimated mean reaction time. The result of GM model is in Table 7. It has 0.937 of RMSE

Table 7. The Result of GM Linear Model

T	Sensitivity	RMSE
1.1	0.4	0.937

The output of the model and field data are compared with acceleration and deceleration behavior in Figure 4.

From the figure 4, we recognized unstable behavior that the model makes fatal fluctuation, so the model does not perform properly with field data. Therefore, only relative speed does not describe the actual behavior precisely. Moreover, there is time difference that exists because acceleration and deceleration at time (t) are quite different.

5.2 Linear (Helly) Model

This model is the basis of GHR model that consists of relative speed and sensitivity coefficient, and added additional term of desired following spacing. Desired spacing controls whether to accelerate or decelerate and or not.

We fitted as best as possible to field data with 1.1 sec of estimated reaction time. The result of linear (Helly) model is in Table 8.

Table 8. The result of linear (Helly) model

T	C1	C2	α	β	γ	RMSE
1.1	0.5	0.3	1.1	1.8	0.0	1.614

The output of the model and field data are compared with acceleration and deceleration behavior in Figure 5.

From the figure 5, we recognized infeasible behavior that the model makes fatal fluctuation, so the model does not perform properly as field data. The model' behavior is quite different from the field data which is higher value or lower value than field data irregularly. Therefore, linear (Helly) car-following model can not be performed with relative speed and desired following spacing.

Moreover, there is time difference that exists because acceleration and deceleration at time (t) are quite different.

5.3 Suggested Model

This suggested model is non-linear model as GM non-linear model and GHR model. So, this model can support the non-linear models which has hardly ever been included any of microsimulation.

We fitted as best as possible to field data with reaction time which is truncated lognormal distribution. The result of suggested model is in Table 9.

Table 9. The result of suggested model

T	C	M	L	RMSE
Lognormal	3.0	1.4	1.7	0.727

The output of the model and field data are compared with acceleration and deceleration behavior in Figure 6.

From the figure 6, we recognized relatively feasible behavior that the model makes acceleration and deceleration behavior, and removes “time difference” so the model performs properly as field data. The model’ behavior is quite same with the field data. Therefore, non-linear car-following model has better description than linear models.

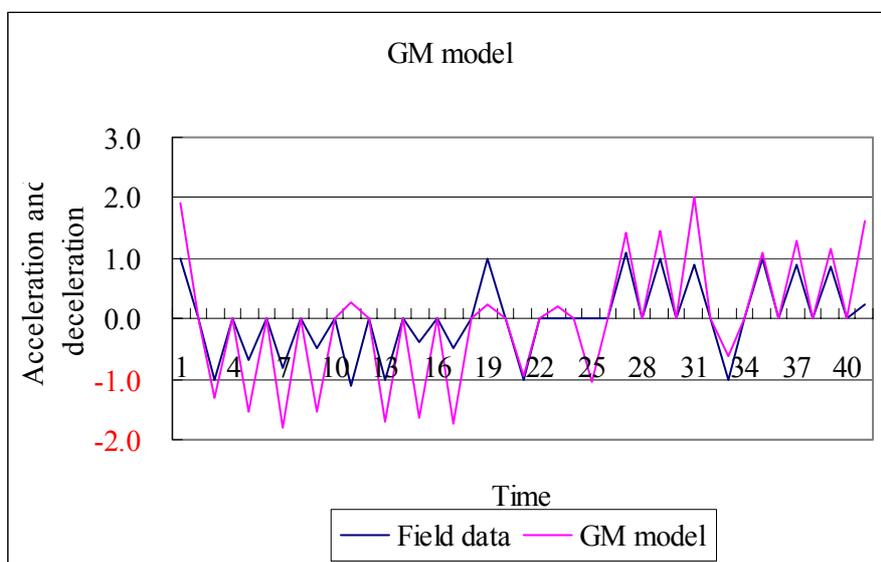


Figure 4. Comparison between field data and GM model

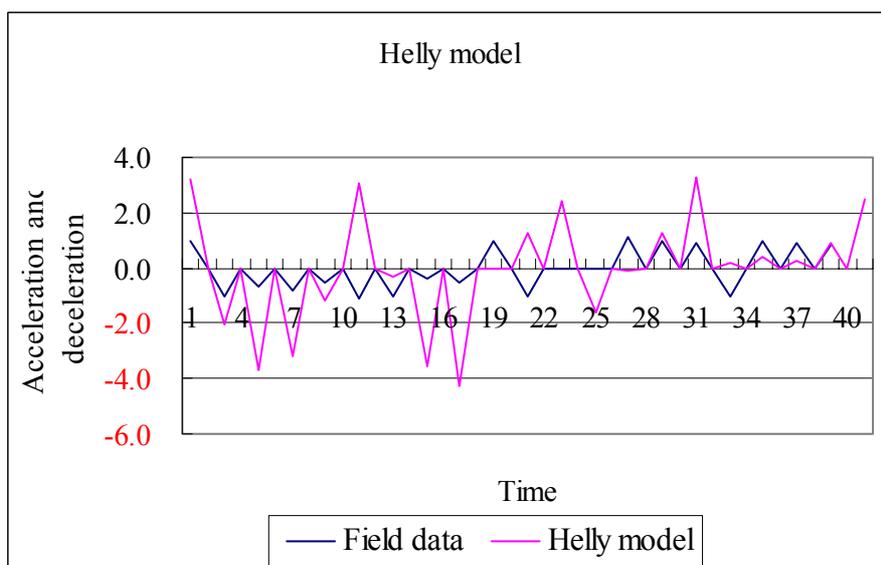


Figure 5. Comparison between field data and linear (Helly) model

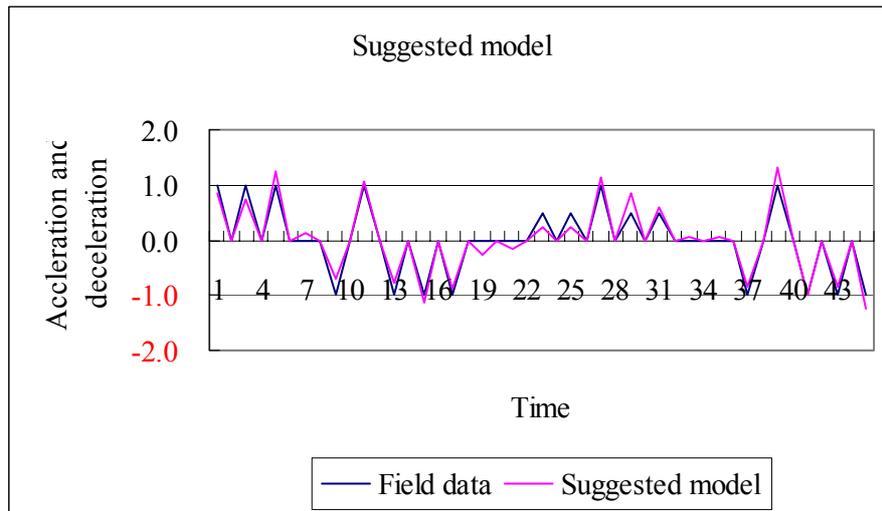


Figure 6. Comparison between field data and suggested model

6. VERIFICATION

In this chapter, we should find out the result of the model performing with the data which are collected different site and drivers. We established two scenarios that are followed.

- Mild driving scenario: Acceleration and deceleration rate ($-4.5 < a_n < 4.5 m/s^2$)
- Severe driving scenario: Acceleration and deceleration rate ($-4.5 > a_n, 4.5 < a_n m/s^2$)

6.1 Mild Driving Scenario

Figure 7 shows Mild driving scenario result at the other site(Wonhyo-Seogang Bridge segment, Road Kangbyun buk). The suggested model has 0.707(RMSE) so the model performed as real traffic condition and Times difference does not appear.

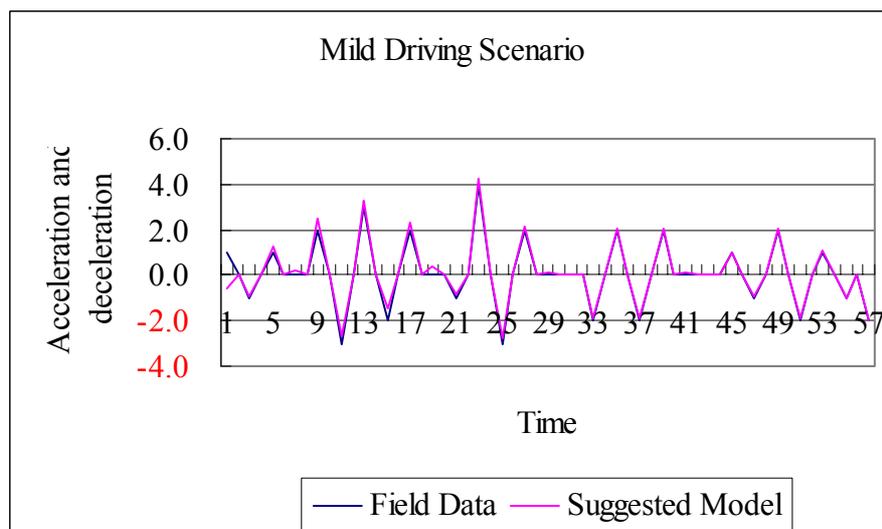


Figure 7. Comparison between field data and suggested model

6.2 Severe Driving Scenario

Figure 8 shows Severe driving scenario result at the other site(Seogang-Yanghwa Bridge segment, Road Kangbyun buk). The suggested model has 0.724(RMSE) so the model performed as real traffic condition and Times difference does not appear.

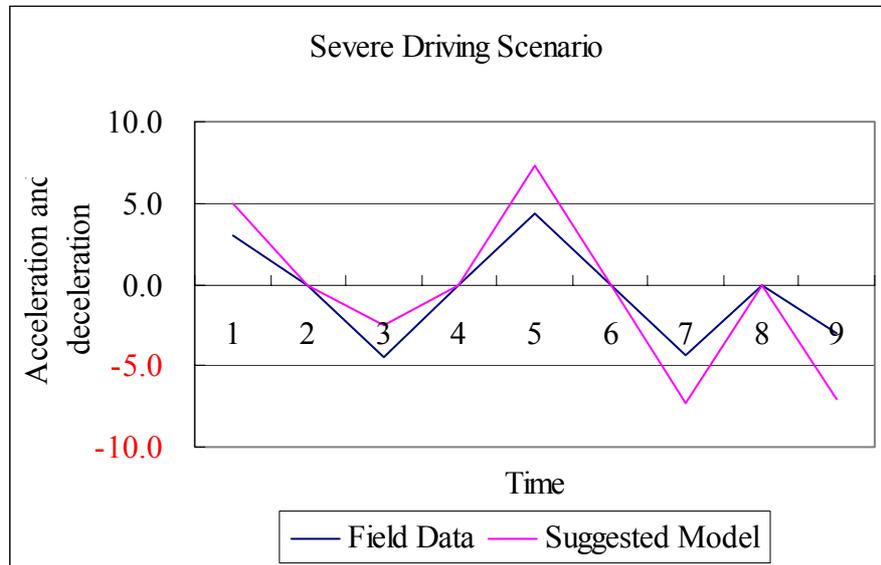


Figure 8. Comparison between field data and suggested model

7. CONCLUSIOS

In this study, we have presented non-linear car-following model. The model has been derived from microscopic foundations based on field data. Suggested model consists of sensitivity coefficient (C_1), sensitivity (λ), distribution of reaction time (T_n) and relative speed (Δv) as a stimulus. Correlation analysis performed to construct the model.

We normally use lower Root Mean Squared error (RMSE) to examine goodness of fit, so we tested models' fit with it. According to the result, suggested non-linear model has lower Root Mean Squared error (RMSE) than others, so the model performs proper behavior as the field.

We introduced "perceptual threshold" to improve sensitivity and reaction time distribution to provide reasonable reaction time that we inferred lognormal distribution. Sensitivity has been improved by perceptual threshold according to the model's behavior so, acceleration and deceleration rate are closer to real traffic condition and we applied the distribution of reaction time to the model, we recognized that the model's behavior has been improved especially acceleration and deceleration at time(t).

The model, we have developed, has the same formulation as GM non-linear model and GHR model except reaction time (T_n). So, this study can support them and also improve the non-linear model to perform as actual driver's behavior.

ACKNOWLEDGEMENTS

We would like to express our gratitude to the anonymous referees whose comments have contributed to improve both the clarity and contents of this paper. This research was supported by Engineering Research Institute and Brain KOREA 21.

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