A CAR FOLLOWING MODEL INCORPORATING EXCESS CRITICAL SPEED CONCEPT

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Abstract: Car following models based on stimulus-response concept use a variable reaction time, which is difficult to determine. Due to the difficulty of estimating the reaction time and the inability of setting up a functional form to represent the driving conditions, conventional estimating methods do not yield realistic model parameters. Following a graphical procedure used to determine reaction time and to give pairs of stimulus-response data, a new car following model has been developed, which includes a variable, Excess Critical Speed (E C S). It is the difference between the safe speed and the speed of the following vehicle. Regression of thus obtained response against stimulus gives more stable parameters. The model was calibrated using the graphically processed stimulus and response data and gives a better regression fit than the conventional model. A relationship for variable reaction time also has been developed from the graphical data analysis.

Key Words: car following, reaction time, model parameters

1. INTRODUCTION

A model describing the movement of vehicles in a platoon following each other is an essential part of microscopic simulation of traffic flow. Many car following models have been used in microscopic simulation programs. The earliest development of car following relationship was by Pipes(1953) and Forbes et al.(1958) from the minimum safety distance viewpoint. Subsequently, more realistic car following models were proposed, which can be classified as speed-spacing models and stimulus-response models. In the speed-spacing models the speed of a vehicle is governed by the space between successive vehicles (Leutzbach,1972, May,1990, Hermann et al., 1959).The models assume that the drivers adjust the speed such that the space at any instant between two vehicles in a traffic stream moving at a uniform speed is a quadratic function of the mean speed. The stimulus-response models have the basic relationship of the form,

$$Response = (Sensitivity) * Stimulus \quad (1)$$

A general form of the stimulus-response model was developed by Gazis et. al.(1961) as

$$\ddot{x}_2(t+T) = \left(\frac{\alpha[\dot{x}_2(t+T)]^m}{[x_1(t)-x_2(t)]^\ell}\right) * [\dot{x}_1(t)-\dot{x}_2(t)] \tag{2}$$

where subscripts 1 and 2 denote leading and following vehicles, respectively. x, $\dot{x}$ and $\ddot{x}$ are position, speed and acceleration of vehicles, respectively. t is time of stimulus, while T is reaction time i.e., the time between stimulus (relative speed to the leader) and response (acceleration of the follower), and α, ℓ and m are parameters.

Speed and space in the sensitivity term govern the magnitude of the response. It states that high speed at smaller space gives high response and low speed at larger space gives low response for the same condition of stimulus. However, Eq.(2) sometimes gives unreasonable responses: following vehicles should be decelerated, regardless of the speeds of both vehicles, if the speed of the following vehicle is too high and the available space is not enough. But Eq.(2) always gives acceleration, irrespective of the speed, if the lead vehicle is faster than the following vehicle. On the contrary, the following vehicle should be accelerated if its speed is small enough and the available space is large enough. But, Eq.(2) gives deceleration if the lead vehicle is slower than the following vehicle. Also, Eq.(2) states that if there is no difference in speed, there should be no acceleration or deceleration. This prevents a follower coming closer to a leader moving at the same speed even if there is a large space between them or moving away from a leader if the speed of the following vehicle is too high.

The other inherent deficiency in the stimulus–response model is its inability to address the different traffic conditions (Hidas,1998, Gipps,1981, Sinha et al.,1970, Hsu,1974, Ozaki, 1993, Newell, 1963) hypothesized that there are two space-speed relationships; one for acceleration and the other for deceleration conditions. Dijker et al.(1998) proved this hypothesis by establishing different space-speed relationship parameters for types of vehicles with different acceleration and deceleration. Sinha et.al.,(1970) derived a car following relationship by mathematical analysis for three different driving conditions. But none of these models takes the importance of reaction time into account. Hsu(1974) developed a stimulus-response car following model which separately considers the drivers who use either a speed detecting mode or a distance detecting mode. This model was verified by comparing performance with proven models and no attempt has been made to verify it using car following experimental data. However, Ozaki(1993) resolved the problem of the general model, not responding to driving conditions, by determining two sets of parameters α, ℓ and m, one in acceleration and the other in deceleration conditions, respectively.

The response of a following vehicle is governed by the reaction time, which is difficult to estimate. It heavily affects the accuracy of the model. Many model developers assumed that the reaction time remains constant during the driving process. Gazis et al.(1961) gave a method of determining this constant reaction time using a correlation technique. Hermann et. al.(1977) found that the reaction time increases with increasing space between the vehicles. Ozaki(1993) showed, using car following experiments, that the reaction time varies during a driving process and that it depends on the space and the acceleration of the leader at the time of stimulus. Hidas(1998) developed a car following model specifically for urban interrupted traffic situations. With coarse approximations, the model calculates the reaction time from speed and deceleration information.

There is very few literature found on a method of determining the reaction time and the parameters directly from car following experiment data. Gazis et.al.(1961) suggested that the correct reaction time is the one which gives the highest correlation coefficient between the relative speed and the follower's acceleration. Ozaki(1993) detected reaction time for each acceleration and deceleration action from a plot of acceleration and relative speed over time. The procedure assumes that the reaction time remains constant within each acceleration or deceleration action. However, as will be discussed later, during any action of acceleration or deceleration there are profound changes in relative speed and acceleration rates where the reaction time may vary during each driving action.

An indirect method of estimating parameters α, ℓ and m using a macroscopic model, which is a transformation of the general car following microscopic model and Greenberg(1959) model, is given by Cedar et.al.(1976). Based on this method, nomographs have been developed by Easa et al.(1980), which can be referred to obtain the microscopic parameters. There are no means of determining the reaction time in this procedure. The method requires macroscopic traffic flow data and hence cannot give the parameters α, ℓ and m from car following experiment data. Therefore the method is beyond the scope of this study.

The objectives of this study are: (1) to identify the deficiencies of the conventional stimulus-response car following model through the empirical data of a single car following experiment, (2) to present a graphical method to show that the reaction time is variable and that it depends on driving situation, speed and space, (3) obtain by graphical means the data necessary for the identification of car following model parameters, (4) to propose a new car following model that takes the excess critical speed into account and (5) to evaluate the excess critical speed model comparing it with the conventional model.

A single car following experiment was conducted to obtain data necessary for the analysis. The paper discusses the method of acquisition and processing of data. Erroneous sets of data resulting from measurement errors were discarded. Using the selected data sets, the reaction time for each set was determined from correlation analysis of follower's acceleration and the leader's speed relative to that of the follower. Employing the values of fixed reaction times, sets of values of space, speed, relative speed and the corresponding acceleration values were tabulated and used in a regression with constraints. A discussion of the distribution of reaction time and the model parameters resulting from the regression analysis is presented.

A method of determining variable reaction time by a graphical procedure and the use of the data obtained from the graphical method to obtain reliable car following model parameters was developed. Graphs of relative speed and acceleration were plotted against a common base of time. By visual inspection, the graphs were divided into sections of stimulus and response. The reaction times were determined as the time distance between the corresponding stimulus and response points. The sets of values of space, speed, relative speed and the corresponding acceleration values were tabulated for the pairs of stimulus and response. The data sets were grouped according to the driving conditions of acceleration or deceleration.

A regression of the conventional model was carried out using the results of the graphical procedure separately in accelerating and in decelerating conditions. The results of the regression analysis are presented in tables giving 't' statistics of parameters and the R^2 values of the regressions, for seven sets of data. A relationship for the reaction time in terms of space, speed and leader acceleration has been developed and presented separately for accelerating and decelerating conditions.

A new model which incorporates the excess critical speed (ECS) as an explanatory variable was developed. A regression of the new model was carried out using the same data sets obtained from the graphical procedure. The results of the regression are presented in a table, which gives 't' statistics of the parameters and the R^2 values of the regressions. Finally, comparison of the new model and the conventional car following model with reference to 't' statistics and R^2 values is discussed.

2. CAR FOLLOWING EXPERIMENTS

Data collection

A single test car, following vehicles in a stretch of a road in the Takasago City of Japan, was used to collect the necessary data. The test car was equipped with an electromagnetic distance measuring (E D M) equipment to monitor the distance between itself and a vehicle in front. A fifth wheel recorded the distance travelled by the test car. The acceleration in m/s^2 of the test car was obtained from readings of an accelerometer. The data were recorded continuously at the time interval of 0.05 seconds. The car was driven in the southbound and the northbound directions of the road generating 20 data sets in each direction, as shown later in Table 1.

Data processing

The speed in m/s of the test car was calculated as the rate of change of distance recorded by the fifth wheel. The relative speed in m/s was calculated from the E D M readings as the rate of change of spacing. The E D M readings were at times found to be erratic when the rays had failed to impinge on the leading vehicle. It was not difficult to trace such occurrences, as abnormal sudden change of space was indicative of the fault. There were occasions when some data sets showed acceleration while speed recorded was decreasing. The initial data processing involved removal of these faulty data lines. The data were arranged in tables of five columns containing time of observation, space, speed, relative speed, and acceleration, respectively. A total of seven data sets with large expanse of continuous data were selected. Deletion of lines of erroneous data caused discontinuity of data. Continuity of data is important especially when used in the direct regression analysis.

3. PRELIMINARY NUMERICAL ANALYSIS

In this section all the problems encountered in the identification of the conventional car following model parameters are studied. First, the reaction time is determined according to correlation between the stimulus and response. Using the reaction time, the acceleration corresponding to the respective relative speed is determined. The parameters α, ℓ and m of the car following model are found by a regression analysis and are shown to give a large variation. Then, the data are graphically analyzed to examine more carefully the relationship between the stimulus and the response. In the graphical method, the variable reaction times are determined by comparing the acceleration curve with the relative speed curve plotted on a common base of time. The reaction times thus obtained are used to determine the parameters α, ℓ and m by a regression model. The parameters thus obtained are shown to be more stable but the regression fit is still not acceptable. A mathematical relationship for the reaction time was attempted by a linear regression using space, follower's speed and leader's acceleration as explanatory variables.

Direct correlation method

The correlation analysis of acceleration against relative speed was carried out with a reaction time, T= 0.0, 0.5, 1.0, 1.5 and 2.0 secs. The reaction time was increased in steps of 0.5 seconds in accordance with Gazis (1961) to reduce the number of correlation operations. The value of T, which gave the highest correlation coefficient, was selected as the correct reaction time for each data set. Figure 1 shows the distribution of the T values for all the data sets analyzed. The analysis gave a variation of T with a mean value of T=1.12 seconds and a variance of 0.40 sec^2. Figure 1 clearly shows that the reaction time T is quite variable for every car following experiment. It also suggests that the reaction time changes during every driving process. One single reaction time T cannot be fixed for all data sets.

Using the reaction time identified for each data set, the observed acceleration and the corresponding space, speed and relative speed were traced from the tables of data. The square of the difference between the observed acceleration and the acceleration calculated employing Eq (2) using the observed space speed and relative speed values was used as the objective function subject to the constraints ($0 < \alpha \leq 1$), ($0 \leq l \leq 4$) and ($0 \leq m \leq 2$.). The Box Complex algorithm (Deb, 1995) was used to minimize the objective function,

$$Z = \sum_t (a_{Cal}(t) - a_{Obs}(t))^2 \tag{3}$$

where a_{Cal} is the calculated acceleration and a_{Obs} is the observed acceleration, respectively.

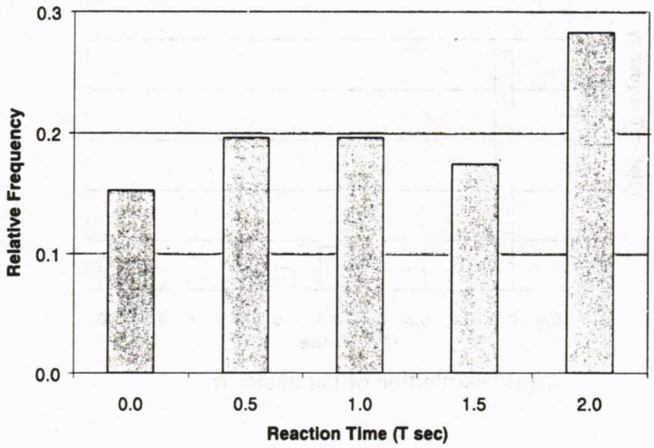


Figure 1. Distribution of Reaction Time from Correlation Analysis.

Figures 2(a) to 2(c) show that the parameters α, ℓ and m thus obtained by this method have large variations. High values occur for all the parameters at the extreme low limits followed by a spread of the values in the range between the limits. In the case of m a high value occurs at the upper extreme too. The Figures 2(a) to 2(c) show that the regression analysis with constraints does not yield stable parameters.

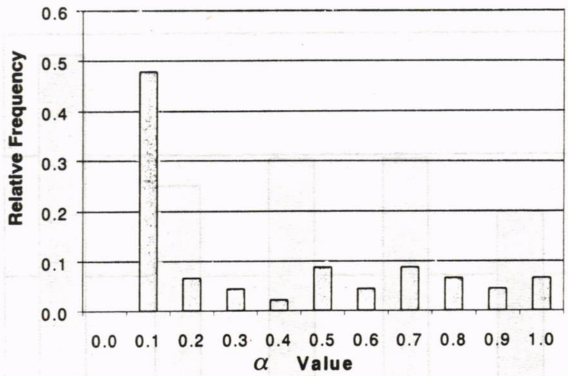
The calculated mean values of α, l and m are 0.30, 1.30 and 0.87 with variance 0.34, 1.17, and 0.70, respectively. The unstable values of parameters may be due to either the reaction time being not accurate or the conventional car following model itself being not applicable to the driving conditions. Therefore, the reaction time was determined graphically to select the acceleration values corresponding to the space, speed and relative speed values.

Graphical method

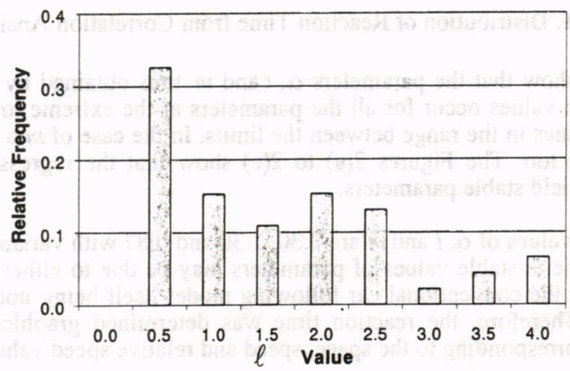
As indicated above, the reaction time may differ from data set to data set. Therefore, the reaction time was estimated for each data set using a graphical method. The basis of the graphical method is the selection of significant points of stimulus and the detection of their corresponding points of response. The procedure adopted for the estimation of reaction time by the graphical method is as follows:

- Produce graphs of acceleration and relative speed on a common base of time
- From inspection of the graphs, pick the points of stimulus defined as change in rate of relative speed and .corresponding response, which is defined as change in rate of acceleration.
- Record the reaction times for each set of stimulus and response, which is defined as the time lag between the change in stimulus and change in response.

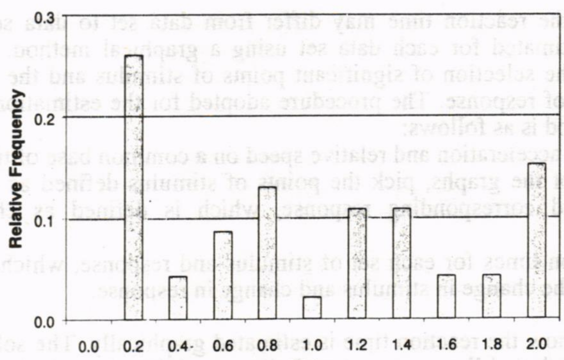
The Figure 3 depicts how the reaction time is estimated graphically. The solid line represents acceleration while the dotted line represents relative speed. The base is time in seconds. For example, the point RS1 in the relative speed curve is a minimum point. By visual inspection, the nearest corresponding minimum point in the acceleration curve can be found at A1. Similarly, RS2 is a maximum point on the relative speed curve and A2 is the corresponding point on the acceleration curve.



(a) Distribution of Parameter α



(b) Distribution of Parameter ℓ



(c) Distribution of Parameter m

Figure 2. Distribution of Parameters α, ℓ and m of Conventional Model Obtained Using Box Complex Optimization Method.

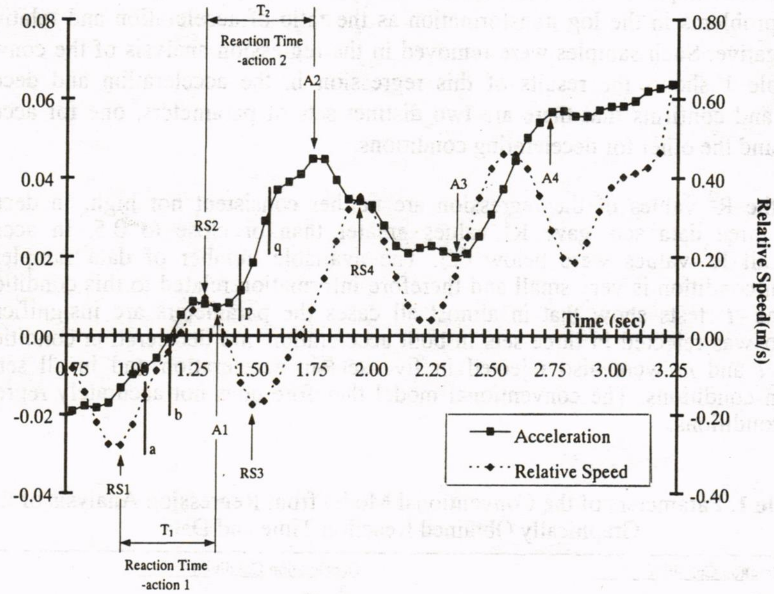


FIGURE 3. Graphical Analysis of Stimulus and Response.

Thus, the section of the curve RS1 to RS2 constitutes a section of stimulus action and A1 to A2 represents the corresponding section of response. The points RS3-A3 and RS4-A4 are similar pairs of stimulus and response resulting in sections (RS2-RS3), (RS3-RS4), (A2-A3) and (A3-A4) on the curves of Figure 3. Since the duration of RS1 to RS2 is different from that of A1 to A2 it can be seen that the reaction time T_1 at the beginning of the course of action is different from T_2 at the end of the action. Similarly, different reaction times exist from RS3 to A3 and from RS4 to A4. This illustrates that the reaction time can be a variable within a data set and also within individual sections of stimulus and response. If the duration of the section RS1-RS2 is equal to that of A1-A2 there will be equal number of stimulus points and response points and matching the pairs of stimulus and response is simple. However, in this example there are 6 stimulus points on RS1-RS2 and 7 response points on A1-A2 and direct matching is not possible. In order to circumvent this problem, the sections were subdivided into equal parts. These subdivisions are shown by two solid vertical lines **a** and **b** on the section RS1-RS2 and by the lines **p** and **q** on the section A1-A2. The reaction times of the subdivisions are taken as the difference of time between the beginning of corresponding subdivisions. The reaction times were obtained by noting the times of stimulus and response on the tables of data. It was not necessary to measure the reaction times on the graphs.

The space, speed and relative speed values were averaged within each subdivision of stimulus section and the acceleration was averaged on the corresponding subdivision of the response section. This operation gives matching pairs of stimulus and response data in the corresponding sections Similar process was carried out on sections of unequal stimulus and response, covering all data points of the set. The process of manual selection of stimulus response pairs was painstaking. Noise was present in some regions of the data sets. Therefore the development of a simple computer program which detects points of gradual change of rate of stimulus and response covering all the data was not successful.

The mean values of space, speed, relative speed and acceleration were tabulated for acceleration and deceleration conditions separately. There were no acceptable data available in deceleration condition in the South 9 and South12 data sets. The tabulated data were used in a linear regression analysis according to the log transformed form of Eq.(2). In some data sets there were samples where acceleration and relative speed did not have the same sign. This gave problems in the log transformation as the ratio of acceleration and relative speed became negative. Such samples were removed in the regression analysis of the conventional model. Table 1 shows the results of this regression in the acceleration and deceleration conditions and confirms that there are two distinct sets of parameters, one for acceleration conditions and the other for decelerating conditions.

However, the R^2 values of the regression are neither consistent nor high. In deceleration conditions three data sets gave R^2 values greater than or close to 0.5. In acceleration conditions all R^2 values were below 0.5. The available number of data samples in the deceleration condition is very small and therefore information related to this condition is not reliable. The '*t*' tests show that in almost all cases the parameters are insignificant. The parameter α was rejected in three sets in both acceleration and deceleration conditions. The parameters l and m were also rejected in five sets in acceleration and in all sets in the deceleration conditions. The conventional model therefore does not accurately represent car following conditions.

Table 1. Parameters of the Conventional Model from Regression Analysis of the Graphically Obtained Reaction Time and Data

	Acceleration Condition						Deceleration Condition					
Run	No. of samples	Item	α	ℓ	m	R^2	No. of samples	Item	α	ℓ	m	R^2
North 3	28	Value	0.110	-0.095	0.167	0.10	31	Value	0.163	0.864	0.678	0.01
		t Statistic	-2.182	0.134	0.536			*t Statistic*	-3.271	-1.179	1.157	
		95%Critical Range		**-2.060**	**2.060**			95%Critical Range		**-2.048**	**2.048**	
South 5	36	Value	0.061	-4.668	-6.146	0.35	7	Value	11.999	20.136	20.754	0.66
		t Statistic	-0.086	4.152	-3.041			*t Statistic*	0.623	-1.942	1.639	
		95%Critical Range		**-2.036**	**2.036**			95%Critical Range		**-2.776**	**2.776**	
South 6	33	Value	9.149	1.874	-0.763	0.18	6	Value	0.000	7.460	34.240	0.60
		t Statistic	0.982	-2.307	-0.970			*t Statistic*	-2.045	-2.096	1.996	
		95%Critical Range		**-2.042**	**2.042**			95%Critical Range		**-3.182**	**3.182**	
South 9	40	Value	1.319	0.043	0.046	0.10						
		t Statistic	3.394	-1.717	1.498							
		95%Critical Range		**-2.027**	**2.027**							
South 10	9	Value	>1000	5.938	-0.103	0.21	34	Value	0.000	0.017	2.477	0.10
		t Statistic	0.536	-1.078	-0.022			*t Statistic*	-3.339	-0.045	1.810	
		95%Critical Range		**-2.447**	**2.447**			95%Critical Range		**-2.040**	**2.040**	
South 11	48	Value	0.000	-9.018	-7.593	0.31	19	Value	928.713	7.823	3.893	0.48
		t Statistic	-4.000	4.261	-4.427			*t Statistic*	1.530	-3.442	1.411	
		95%Critical Range		**-2.010**	**2.010**			95%Critical Range		**-2.120**	**2.120**	
South 12	23	Value	>1000	21.844	9.191	0.38						
		t Statistic	3.089	-2.980	0.571							
		95%Critical Range		**-2.086**	**2.086**							

Regression for reaction time

The graphical analysis showed that the reaction time varied during the course of driving between –0.30 secs and 2.45 secs with a mean at 1.35secs The negative values indicate anticipated stimulus. To determine this variable reaction time there should be a mathematical relationship between the reaction time and the variables like space, speed, relative speed and acceleration. Therefore, equipped with the data available from the graphical analysis of the reaction time, a regression was carried out between the reaction time T and space, speed and leader acceleration in order to find a relationship for T in terms of these three variables. A relationship of the form,

$$T = \beta_0 + \beta_1\big(x_1(t) - x_2(t)\big) + \beta_2\big(\dot{x}_2(t)\big) + \beta_3\big(\ddot{x}_1(t)\big) \tag{4}$$

was assumed with the addition of the follower's speed as an explanatory variable to the model developed by of Ozaki(1993), considering the fact that the follower's speed also has a reasonable correlation with the reaction time.

Table 2 presents the results of regression analysis for both acceleration and deceleration conditions. The R^2 values for the acceleration condition are generally lower than 0.5. In deceleration condition they are always above 0.5. The '*t*' test results show that the coefficients of space should be rejected in three data sets and the coefficients of speed should be rejected in four data sets at 95% confidence levels, whereas the coefficients of leader acceleration are rejected in all the sets in accelerating condition.

Table 2. Regression Analysis of Reaction Time Vs Space, Speed and Leader Acceleration

	Acceleration Condition							Deceleration Condition						
Run	No. of samples	Item	β_0	β_1	β_2	β_3	R^2	No. of samples	Item	β_0	β_1	β_2	β_3	R^2
North 3	28	Value	0.833	0.073	-0.097	-0.037	0.27	31	Value	0.998	-0.122	0.179	0.002	0.60
		t Statistic	5.312	1.624	-2.204	-1.377			*t Statistic*	12.624	-2.201	2.703	0.237	
		95%Critical Range		**-2.064**	**2.064**				95%Critical Range		**-2.048**	**2.048**		
South 5	41	Value	1.727	-0.039	-0.083	-0.061	0.30	9	Value	-1.683	-1.462	2.459	-0.235	0.90
		t Statistic	5.416	-1.656	-1.522	-1.822			*t Statistic*	-2.029	-4.494	4.274	-2.601	
		95%Critical Range		**-2.027**	**2.027**				95%Critical Range		**-2.447**	**2.447**		
South 6	33	Value	0.728	0.060	-0.067	-0.106	0.39	6	Value	22.370	0.349	-3.434	-0.719	0.86
		t Statistic	2.480	4.147	-1.517	-1.040			*t Statistic*	3.720	2.992	-3.485	-2.427	
		95%Critical Range		**-2.045**	**2.045**				95%Critical		**-3.182**	**3.182**		
South 9	52	Value	1.292	-0.275	0.340	0.003	0.69							
		t Statistic	11.176	-9.726	10.190	0.159								
		95%Critical Range		**-2.030**	**2.030**									
South 10	31	Value	-4.876	0.065	0.329	-0.001	0.72	34	Value	-2.251	0.018	0.210	-0.019	0.54
		t Statistic	-7.839	5.902	7.511	-0.303			*t Statistic*	-3.931	2.360	3.696	-2.299	
		95%Critical Range		**-2.052**	**2.052**				95%Critical Range		**-2.044**	**2.044**		
South 11	64	Value	0.179	0.034	-0.025	-0.003	0.14	22	Value	-0.205	0.180	-0.175	-0.014	0.85
		t Statistic	1.712	2.478	-1.305	-0.247			*t Statistic*	-0.785	9.252	-4.686	-0.825	
		95%Critical Range		**-2.000**	**2.000**				95%Critical Range		**-2.101**	**2.101**		
South 12	23	Value	-0.302	0.066	-0.031	0.011	0.06	31						
		t Statistic	-0.633	0.823	-0.419	0.752								
		95%Critical Range		**-2.093**	**2.093**									

In deceleration condition, the coefficient of space is rejected in one set, the coefficients of speed in none and that of leader acceleration should be rejected in three sets. However, eliminating leader acceleration lowered the R^2 value further. Therefore, it was decided to keep the leader acceleration in the regression model. Unlike the findings of Ozaki(1993) the follower's speed significantly contributed to the reaction time. It is also seen that coefficients in acceleration conditions differ from those in deceleration conditions. This agrees with the results of Ozaki (1993). The low R^2 values in the regression suggests that the model for reaction time needs further improvement. Attempts to improve it using other combinations of state variables could not yield better results.

4. A NEW CAR FOLLOWING MODEL

Figures 2(a) to 2(c) show that the parameters estimated by the conventional method have large variations over all the data sets. Also Table 1 shows that the regression is still poor even though more stable parameters were given by the data obtained from rigorous graphical analysis. Hsu (1974) stated that a driver's behavior of maintaining space appropriate to own speed should be addressed in the model. It can be assumed that the drivers sense safe speed with respect to the available space in making driving decisions. Therefore, these two variables should be part of the stimulus in the model. They can be combined to give a single variable called Excess Critical Speed (E C S) which is the difference between the maximum safe speed at which the follower can drive and the current speed of the follower. E C S forms a second stimulus in addition to the relative speed. This inclusion of the E C S concept can also accommodate the state where the acceleration rate and the relative speed have opposite algebraic signs.

Excess Critical Speed

Suppose a critical situation when a leading vehicle comes to an urgent instantaneous halt while a vehicle is following behind at a distance $[x_1(t) - x_2(t)]$ in m. It can be shown from the equation of motion that the critical speed v_{CR}, which the follower can achieve without causing collision, is given by,

$$v_{CR} = \sqrt{2 * f[x_1(t) - x_2(t)]} \tag{5}$$

where f in m/s^2 is the maximum deceleration rate of the following vehicle, which depends mainly on the vehicle and road conditions. Then, Excess Critical Speed (E C S) is defined as the difference between v_{CR} and the current speed $\dot{x}_2(t)$:

$$E\ C\ S = v_{CR} - \dot{x}_2(t) \tag{6}$$

If the E C S is positive, the follower has the freedom to increase the speed up to the critical speed even if the relative speed is negative. If the E C S is negative, speed should be reducted to keep safe space between them. The introduction of E C S concept makes it possible for a follower to move closer to a leader moving almost at the same speed if the space is enough for the speed or to move away regardless of the speed of lead vehicle if the space is not sufficient. This facility is not realized in the conventional car following model. If the relative speed is zero, the acceleration estimated by the conventional model reduces to zero while the new model allows acceleration or deceleration according to the sign of the E C S.

Car following model incorporating ECS concept

It can be assumed that the follower perceives E C S as well as the relative speed as a stimulus. Since the E C S will not be correlated with the relative speed, a new car following model, in which they are treated as independent variables, is given by

$$\begin{aligned} \ddot{x}_2(t+T) &= \alpha_0 + \alpha_1[E\ C\ S] + \alpha_2[\dot{x}_1(t) - \dot{x}_2(t)] \\ &= \alpha_0 + \alpha_1\left[\sqrt{2 * f(x_1(t) - x_2(t))} - (\dot{x}_2(t))\right] + \alpha_2[\dot{x}_1(t) - \dot{x}_2(t)] \end{aligned} \tag{7}$$

where α_0, α_1, α_2 are model parameters. Ideally α_0 should be zero since acceleration or deceleration reduces to zero if both E C S and the relative speed are zero. But, in this study it is left in the equation in order to verify in a regression analysis.

Regression analysis of the new model

The maximum deceleration rate f should be known to compute the E C S. A value for f was determined by correlating acceleration and E C S computed using different values of f ranging from 3 m/s^2 to 6 m/s^2 in one data set. The acceleration values were taken from the same tables of data prepared for the graphical analysis. The corresponding space and speed values were used to calculate the E C S values. The value of $f = 5$ m/s^2 which gave the best correlation between acceleration and the E C S was used in the calculation of E C S in the other data sets.

This value is very close to the value of –0.55g suggested in the Highway Capacity Manual for mean unexpected deceleration in steady state.

A regression of E C S and relative speed against acceleration was carried out on the basis of Eq. (7). Table 3 shows that the R^2 values given by the new model are much higher than those shown in Table 1 of the conventional car following model. Table 3 also shows that R^2 values are high and consistent in the accelerating conditions. In decelerating conditions, these values are lower and inconsistent. The results of '*t*' tests show that the parameters are generally significant at 95% confidence level and suggest that the new model is superior to the conventional model. Regression analysis for acceleration using other combinations of state variables were tried but did not improve the results. Replacing ECS with space improved in two runs but were low in the others and the significance of the parameters as shown by '*t*' statistic was very much lower.

Table 3. Regression Analysis of the New Car Following Model

	Acceleration Condition						Deceleration Condition					
Run	No. of samples	Item	α_0	α_1	α_2	R^2	No. of samples	Item	α_0	α_1	α_2	R^2
North 3	28	Value	0.032	0.014	0.030	0.69	31	Value	-0.038	0.002	0.065	0.47
		t Statistic	1.869	2.143	2.341			*t Statistic*	-1.527	0.544	4.740	
		95%Critical Range		**-2.060**	**2.060**			95%Critical Range		**-2.048**	**2.048**	
South 5	41	Value	-0.093	0.039	0.000	0.73	9	Value	-0.045	0.014	0.010	0.16
		t Statistic	-5.966	7.300	-0.073			*t Statistic*	-0.302	0.280	0.441	
		95%Critical Range		**-2.025**	**2.025**			95%Critical Range		**-2.447**	**2.447**	
South 6	33	Value	-0.010	0.010	0.030	0.89	6	Value	0.028	-0.010	0.026	0.73
		t Statistic	-1.071	2.854	6.309			*t Statistic*	0.885	-0.957	1.518	
		95%Critical Range		**-2.042**	**2.042**			95%Critical Range		**-3.182**	**3.182**	
South 9	52	Value	-0.068	0.048	0.013	0.95						
		t Statistic	-7.950	10.994	2.265							
		95%Critical Range		**-2.070**	**2.070**							
South 10	31	Value	-0.068	-0.003	-0.003	0.46	34	Value	-0.070	0.003	0.000	0.14
		t Statistic	3.658	-2.851	3.682			*t Statistic*	-3.526	2.201	-0.221	
		95%Critical Range		**-2.048**	**2.048**			95%Critical Range		**-2.044**	**2.044**	
South 11	64	Value	-0.043	0.027	0.023	0.82	22	Value	-0.003	-0.007	0.011	0.26
		t Statistic	-3.755	6.329	5.459			*t Statistic*	-0.323	-0.495	1.087	
		95%Critical Range		**-2.000**	**2.000**			95%Critical Range		**-2.093**	**2.093**	
South 12	23	Value	0.075	0.089	-0.063	0.74						
		t Statistic	8.145	7.557	-4.427							
		95%Critical Range		**-2.086**	**2.086**							

The α_0 value should ideally be zero, since the acceleration should be zero if both stimuli are zero. However, except in three cases in deceleration and two cases in acceleration the '*t*' test does not reject α_0 meaning that it is not zero. But the mean value of α_0 is very low at 0.025 in accelerating conditions and 0.009 in decelerating conditions. Except in the cases of the data sets South5, South10 and South12 the coefficients $\alpha_1$and α_2 are positive in accelerating conditions. In decelerating conditions α_1 is negative in South6 and South11 data sets. Generally α_1 values are larger in the acceleration condition and α_2 values are larger in the decelerating condition. This shows that during acceleration when there is safe distance between the vehicles the follower is more concerned about the space than about the relative speed. On the other hand deceleration takes place when the vehicles are close to one another and the follower is more concerned about the relative speed than the space between them.

Therefore it can be inferred that the E C S is the larger contributing factor in the accelerating condition while relative speed is the larger contributor in the decelerating condition.

Mean parameters of the model

The mean values of the regression coefficients were obtained as weighted averages for the new model described by Eq(7). R^2 was considered the best measure for weighting where the data sets with low regression fit had lower effect on the mean than the data sets with higher regression fit. On the other hand arithmetic mean or weighting the coefficients by the number of samples gave large variance about the mean. The new model formed, using the mean parameters is given by Eq. (8) and (9) for acceleration and deceleration conditions, respectively.

$$\ddot{x}_2(t+T) = -0.025 + 0.034\left[\sqrt{2*5(x_1(t)-x_2(t))} - (\dot{x}_2(t))\right] + 0.006\left[\dot{x}_1(t)-\dot{x}_2(t)\right] \quad (8)$$

$$\ddot{x}_2(t+T) = -0.009 - 0.003\left[\sqrt{2*5(x_1(t)-x_2(t))} - (\dot{x}_2(t))\right] + 0.031\left[\dot{x}_1(t)-\dot{x}_2(t)\right] \quad (9)$$

Having determined the acceleration it is necessary to find the time at which the acceleration is effected. This is derived from the regression coefficients of Table 2. The mean coefficients were obtained as averages weighted by R^2. The Eq.(10) and (11) give the relationships for T in acceleration and in deceleration conditions respectively.

$$T = -0.617 - 0.040(x_1(t)-x_2(t)) + 0.151(\dot{x}_2(t)) - 0.026(\ddot{x}_1(t))_1 \quad (10)$$

$$T = 4.515 - 0.247(x_1(t)-x_2(t)) - 0.178(\dot{x}_2(t)) - 0.227(\ddot{x}_1(t)) \quad (11)$$

5. CONCLUSIONS

The reaction time of car following models is difficult to estimate, but the accuracy of the models heavily depends on the reaction time. The car following experimental data showed that the reaction time obtained using direct analysis suggested by Gazis et.al.(1961) varied during the driving process. The direct regression of car following experimental data did not yield the correct parameters of car following models.

By closely examining the time series data of acceleration and relative speed, it is possible to select the respective stimulus-response pairs and determine the variable reaction times. By using these response pairs in regression analysis it was possible to obtain more stable parameters of general car following model.

A model giving realistic car following behavior has been developed for acceleration and deceleration modes separately using relative speed and E C S as explanatory variables. The new model can represent different driving conditions. The concept of E C S allows it to accommodate combinations of acceleration, space and speed conditions not allowed in the conventional model. It proved to be the most accurate model with good regression fit of empirical data. The parameters of E C S models also show that during acceleration a driver is more concerned about the space than the relative speed while the relative speed is more important than the space during deceleration.

The relationships obtained are for a single driver only. Since the parameters are driver and driving condition dependent it is necessary to calibrate the model using data obtained for different drivers and in different driving conditions. The model has to be used in a traffic simulation program to test its validity. The manual extraction of information from stimulus-response graphs for regression analysis from the data is very tedious. It is necessary to seek the assistance of a computer program to carry out this task.

A relationship for reaction time in terms of space, speed and leader acceleration has been developed for use in traffic simulation models. It can predict the reaction time using the available variables. It is a linear relationship obtained from regression analysis of data processed graphically from car following experimental data.

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