Development of a New and Improved Driver-sensitive Car-following Model

Atif Mehmood and Said M. Easa

Address for correspondence: Said M. Easa, Department of Civil Engineering, Ryerson University, 350 Victoria Street, Toronto, ON, M5B 3K3, Canada seasa@ryerson.ca; Atif Mehmood is Transportation Planner for the Region of Waterloo, Kitchener, ON N2G 4J3 Canada.

Abstract

One of the important components of traffic simulation models is a car-following model that describes driver behaviour in a car-following situation. The existing car-following models have some limitations that may adversely affect the performance of in-vehicle rear-end collision warning systems. This paper presents a car-following model that addresses some limitations of the existing models. The proposed model considers the variations in the drivers' perception-reaction time and the effect of the front and back vehicles in the car-following situation. The proposed model explicitly considers the driver's age and gender in car-following modeling. Actual vehicle tracking data obtained from the U.S. Federal Highway Administration were used to calibrate and validate the proposed model. The results of the proposed model closely match the actual speed and spacing profiles of the following vehicle.

Keywords: car-following, human factors, simulation model, system dynamics.

Acknowledgements

This research was financially supported by a discovery grant from the Natural Sciences and Engineering Research Council of Canada, and an Ontario Graduate Scholarship.

Date of receipt of final manuscript: July 2010

1.0 Introduction

Traffic engineers and transport professionals use microscopic traffic simulation tools to evaluate traffic operational problems and intelligent transportation system (ITS) applications. The ITS systems include collision warning systems, adaptive traffic management, traveler information, and incident management systems. These systems are difficult to evaluate using analytical tools due to the complex system dynamics involved in these applications. In a traffic simulation tool, different scenarios can be generated with the roadway geometric and traffic data and traffic problems can be evaluated without disrupting traffic conditions on the road. Traffic simulation tools are composed of several driver behaviour models including car-following, lane-change, and travel path. In particular, car-following models have significant impact on the accuracy of the traffic simulation tools in replicating traffic behaviour on the road (Sakda and Hussein, 2005).

Car-following models describe how a pair of vehicles interact with each other in a traffic stream. Model performance is evaluated based on key factors that affect driver behaviour. Researchers have found a number of such factors that influence car-following behaviour. These factors are classified into two categories: individual and situational. The individual factors include age, gender, risk-taking behaviour, vehicle characteristics, and driving skill. The situational factors include time of day, day of week, weather and road conditions, and information on the lead and back vehicles such as speed and spacing.

Over the past 50 years, various car-following models were proposed that attempt to describe the driver's car-following behaviour based on the follow-the-leader concept. The existing car-following models assume that the dominant effect on driver behaviour comes from the next vehicle ahead (called the lead vehicle). However, when driving in a traffic stream, the vehicle behind the following vehicle (called the back vehicle) somehow also influences driver behaviour in a car-following situation. These car-following models were developed based on various theoretical considerations and experimental observations. These observations include driver's reaction time, speed, and spacing. Existing car-following models also assume that all drivers of different age and gender have the same reaction time. Siuhi and Kaseko (2010) proposed that the driver's response times are lower for the deceleration response than for the acceleration response. The average reaction-times for the acceleration and deceleration response were assumed to be 0.8 and 0.7 seconds, respectively. But in an earlier research, Subramanian (1996) suggested that drivers react faster under acceleration response than deceleration response. Both of these findings were quite different and were not based on a study of human factors. Mehmood and Easa conducted a comprehensive driving simulator study (Mehmood and Easa, 2009) to identify the effect of human factors and traffic kinematics on driver's reaction-time in a car-following situation. It was observed that the driver's reaction-time varies, in the both acceleration and deceleration regimes, based not only on kinematic conditions such as speed and spacing but also on individual driver's characteristics such as age and gender. There is a need to further develop existing car-following models to incorporate the effect of the back vehicle and driver characteristics on the car-following behaviour.

In this paper, the system dynamics (SD) principles were applied to address the limitations of the existing car-following models. The simulation environment in SD provides a computational platform to simulate and examine complex problems. This platform is characterized by many nonlinear relationships including heuristic and empirical with numerous feedback loops (Mehmood *et al.,* 2003). The primary objective of this paper is to develop a new car-following model, which is driver sensitive and accounts for the effects of the back vehicle, and calibrate and validate the model using actual vehicle tracking data.

The paper is organized into five sections: Literature Review which presents the review of some existing car-following models, Model Development that describes the logic of the proposed car-following model, data collection, and mathematical relationships, and Calibration and Validation which is followed by the Concluding Remarks.

2.0 Literature Review

A number of car-following models have been developed during the past several decades. These models have been grouped into five categories (Brackstone and McDonald, 1999): (a) Gazis-Herman-Rothery (GHR) model, (b) collision-avoidance (CA) models, (c) linear models, (d) psychophysical models, and (e) fuzzy logic-based models. Brief descriptions of these categories including the most recent developments are presented here.

The first car-following model was developed at the General Motors Corporation by Gazis *et al.* (1961) also known as the GM car-following model or the GHR model. This model assumes that the acceleration/deceleration rate of the following vehicle depends on the relative speed and spacing between the following and leading vehicles, and the speed of the following vehicle at time t, as follows

$$a_F(t+\Delta t) = \alpha\left[\frac{[VF(t)]^m}{[X_L(t) - X_F(t)]^l}\right][V_L(t) - V_F(t)] \tag{1}$$

where $a_F\ (t + \Delta t)$ = acceleration/deceleration rate of the following vehicle at time $(t + \Delta t)$, α, m, and l = calibration parameters, V_F = velocity of the following vehicle at time t, X_F = position of the following vehicle at time t, V_L = velocity of the lead vehicle at time t, and X_L = position of the lead vehicle at time t. Many studies were conducted for the calibration of the GHR model. Chandler *et al.* (1958) calibrated the parameters using the data sample of eight drivers which drove a test track for 20-30 minutes. Their initial work was followed by other researchers (Heyes and Ashworth, 1972; Aron, 1988; Ozaki, 1993; Wolshon and Hatipkarasulu, 2000).

The first collision avoidance (CA) model was developed by Kometani and Sasaki (1959). This model calculates the safe following distance required to avoid the collision with the lead vehicle based on the speeds of the following and leading vehicles and the reaction-time of the driver of the following vehicle. The model is expressed as

$$\Delta X\,(t-\Delta t) = \alpha\ V_L^{\,2}\ (t-\Delta t) + \beta\ VF^2(\mathrm{t}) + \beta_1\ V_F(t) + b_0 \tag{2}$$

where $\Delta X(t - \Delta t)$ = safe following distance for the following vehicle at time $(t - \Delta t)$ (m) α, β, β_1 = calibration parameters, $V_L(t - \Delta t)$ = velocity of the lead vehicle at time $(t - \Delta t)$ (km/h), and $V_F(t)$ = velocity of the following vehicle at time t (km/h). The model of Equation 2 has been improved by Gipps (1981) who introduced the performance limits of the vehicles and drivers for the calculation of the maximum and the minimum acceleration/deceleration rates. These performance limits end up with two constraints: acceleration constraint (assumed to depend on vehicle characteristics and driver comfort) and safety constraint (assumed to depend on the speed of the lead vehicle). Other CA models include the NETSIM and FRESIM models developed by the U.S. Federal Highway Administration (FHWA) and the CARSIM model developed by Benekohal and Treiterer (1988).

The linear model (Helly, 1959), which originated from the GHR model, assumes that the acceleration/deceleration rate of the following vehicle depends on the relative spacing and speed between the following and leading vehicles, desired following distance, speed of the following vehicle, and driver's reaction time. The model is given by

$$a_n(t) = C_1 \Delta v\,(t - T) + C_2[\Delta x(t - T) - D_n(t)] \tag{3}$$

$$D_n(t) = \alpha + \beta\,v(t - T) + \gamma\,a_n\,(t - T) \tag{4}$$

where $a_n(t)$ = the acceleration of vehicle n at time t, $D_n(t)$ = desired following distance at time t, v = speed of vehicle n, Δx = relative distance between the vehicles n and (n-1), Δv = relative speed between the vehicles n and (n-1), T = driver's reaction time, α, β, γ, C_1, and C_2 = calibration parameters. The main difficulty with this model is its calibration (Hanken and Rockwell, 1967; Rockwell *et al.,* 1968; Aycin and Benekohal, 1998).

The psychophysical or action-point (AP) models were developed based on the assumption that a driver will perform an action when a threshold of his/her perception-reaction is reached. Michaels (1963) proposed certain thresholds of the relative speed and spacing between the following and the leading vehicles. For example, based on the threshold of the relative speeds a driver will decelerate until the relative speed between the following and the lead vehicles becomes zero. In a situation when the spacing between the following and leading vehicles is greater than a certain threshold then the driver of the following vehicle will not react to the actions of the leading vehicle. The first AP model (Wiedemann, 1974), incorporated a traffic simulation program, VISSIM, and described the acceleration/deceleration rate of the following vehicle in four different situations: un-influenced driving, closing process, following process, and braking situation. There are certain thresholds and acceleration/deceleration models for each driving situation. Other examples of action point models include those developed by Mehmood *et al.* (2003) and Zhang *et al.* (1998). Mehmood *et al.* (2003) developed the AP model using the SD approach. The model incorporates the information of the second leading vehicle and has some alertness levels based on the onset of the brake light of the lead vehicle. The thresholds used in AP models vary widely among drivers and hence there is a need to incorporate individual driver characteristics when including driver behaviour in a car-following model. The model presented in this paper is regarded as a psychophysical model that accounts for individual driver behaviour in a car-following situation.

The first fuzzy-logic model was presented by Kikuchi and Chakroborty (1992). Other models include those by Yikai *et al.* (1993). The fuzzy logic-based models were developed based on fuzzy-set theory that describes how adequately a variable fits the description of a term. In these models, driver decisions are determined based on a set of commonsense driving rules developed through experience. The driving rules were presented in IF-THEN format and govern the driver's decision for a given driving condition. For example, if the vehicle separation is 'Close' AND 'Closing' THEN brake.

Based on this review, the limitations of existing car-following models can be summarized as follows:

1. The existing car-following models do not explain the variation of model parameters in different car-following situations. The model parameters are assumed to represent driver behaviour of the car-following vehicle in all driving scenarios, such as acceleration and deceleration regimes.
2. The existing models assume a constant driver reaction-time, and therefore do not consider individual driver characteristics, such as age and gender.
3. Some existing car-following models assume shorter reaction-time for the deceleration regime and others assume shorter reaction-time for the acceleration regime. The reaction-time values were just assumed values and were not based on any empirical evidence.
4. The fuzzy logic-based car-following models are difficult to calibrate and this contributes to their lack of credibility and reliability in practical applications.
5. The existing car-following models assume that the driver of the following vehicle responds only to the actions of the lead vehicle and ignore the conditions of the back vehicle.

3.0 Model Development

This section describes the development of a driver sensitive car-following model. The assumptions and logical framework of the proposed model are first presented, followed by the equations of the proposed model and the data collection.

3.1 Logic of Proposed Model

The car-following situation considered in the proposed model assumes a string of three vehicles: lead vehicle, following vehicle, and back vehicle, all traveling along a single lane (Figure 1). It is assumed that the driver of the following vehicle perceives information either from both the lead and the back vehicles or only the lead vehicle depending on their kinematic conditions such as speed and spacing. The spacing is defined as the longitudinal distance measured from the back bumper of the lead vehicle to the front bumper of the following vehicle.

The three vehicles are assumed to be passenger cars (since data related to other vehicle classes were not available). The driver of the following vehicle is assumed to drive in three regimes: coasting, accelerating, and decelerating. Based on a previous study by Mehmood and Easa (Mehmood and Easa, 2009), the driver reaction-time in these regimes is considered to be different and depends on the vehicle spacing, speed, and driver characteristics such as age and gender. The reaction time is also different for the cases of acceleration and deceleration.

The proposed model predicts the acceleration/deceleration rate based on the information of the lead and the back vehicles and the desired speed and the reaction-time of the driver of the following vehicle. The desired speed is affected by the acceleration and deceleration parameters. It is assumed that the back vehicle only contributes to the acceleration regime when it is approaching a following vehicle with higher speed. The following vehicle can also accelerate based on the desired speed, if it is more than the current speed. The desired speed is defined as the maximum speed at which the driver of the following vehicle would travel based on the given kinematic conditions. The logic of the proposed car-following model is shown in Figure 2 and is highlighted in the following steps:

Figure 1
Car-following vehicle dynamics

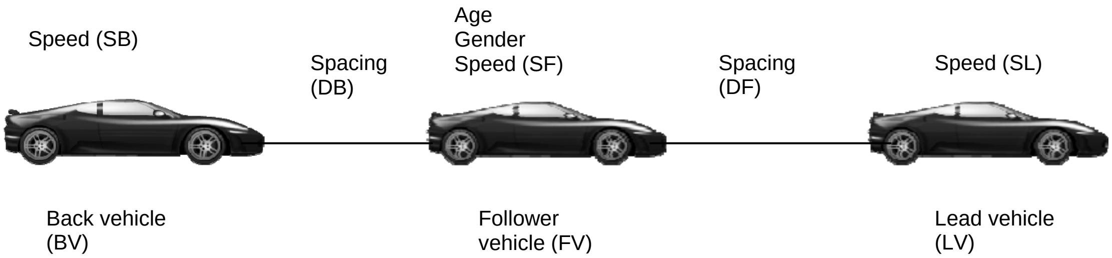
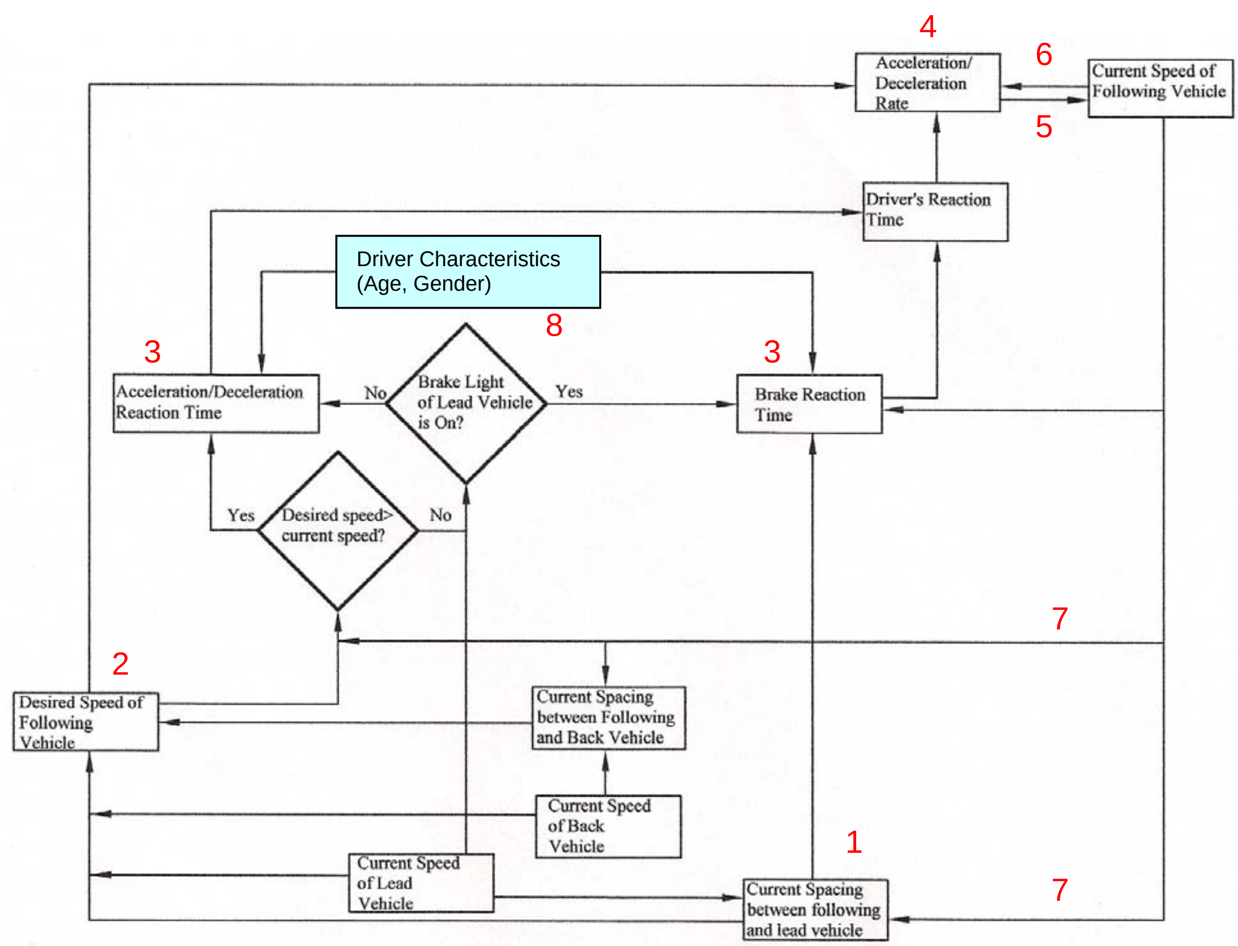


Figure 2
Logic of the proposed car-following model



1. Initially at time t_0, the current speed of the following vehicle and spacing between the following and the lead vehicles can be inputted to the proposed model.
2. The desired speed of the following vehicle is calculated at any time t (Equation 6, shown later).
3. The following vehicle can accelerate or decelerate based on the desired speed at any time t. For the deceleration regime, brake reaction time (Equation 11) is used when the brake

of the lead vehicle is ON; otherwise deceleration reaction-time (Equation 10) with throttle input is used. For the acceleration regime, the acceleration reaction-time (Equation 10) with throttle input is used.

4. The acceleration/deceleration rate of the following vehicle is calculated based on the desired speed, the current speed, and the reaction-time values at time t (Equation 5).
5. The acceleration/deceleration rate calculated at time t_0 is used to calculate the current speed of the following vehicle at time ($t_0 + \Delta t$).
6. The acceleration/deceleration rate at time ($t_0 + \Delta t$) is calculated based on the desired speed, the current speed, and the reaction-time values at time ($t_0 + \Delta t$).
7. The speed of the lead and back vehicles are input into the model which is used to calculate the calibration parameters and spacing among the lead, the following, and the back vehicles.
8. The calibration parameters for the reaction time used in the calibration process in this study are based on the data for the driver's population.

More details on the model logic are presented later in the mathematical relationships. The desired speed was calibrated based on the spacing between the following and the lead vehicles. The acceleration and deceleration parameters were calibrated based on the inverse-time-to-collision (*INVT*) associated with the lead and the back vehicles. The *INVT* depend on the relative speed and spacing between the following and the lead and the back vehicles, respectively.

3.2 Data Collection

The vehicle trajectory data used for calibration and validation of the proposed car-following model were collected by the Federal Highway Administration as part of the Next Generation Simulation (NGSIM) program (Hranac *et al.,* 2005). The data were collected on June 15, 2005, using video cameras mounted on a 36-storey building which is located adjacent to the U.S. Highway 101 and Lankershim Boulevard interchange in the Universal City neighbourhood.

Vehicle trajectory data for a sample of 80 following vehicles were extracted from the NGSIM database. As mentioned earlier, each sample consisted of a string of three vehicles, the following, the lead, and the back vehicles. The Highway Capacity Manual (HCM, 2000) suggests a time headway of 3 s as the critical headway to identify whether a vehicle is in a car-following situation or not. Therefore, the time headway for the pair of vehicles was constrained to be 3 s or less. Motorcycles and trucks were excluded from the data in order to work with more homogeneous vehicle characteristics. These vehicle types represented less than 2% of the total vehicle population. Vehicles that appeared in more than one lane were not considered for the car-following analysis. The right-most lanes near the on and off-ramps were also excluded from the analysis since the vehicles entering and existing the freeway continually disturb the car-following behaviour of other vehicles in this lane.

The variables collected for each subject vehicle include observation time, following vehicle ID, lane number, vehicle speed, vehicle class, vehicle acceleration/deceleration rate, longitudinal position, the lead and back vehicle ID, and vehicle length. The data were further processed to filter the speed of the lead and back vehicles. In addition to the speeds, the spacing among the following, the lead, and the back vehicles were determined for each representative sample. The spacing between the vehicles from the front bumper of the following vehicle to the rear bumper of the lead vehicle was calculated using vehicle lengths.

3.3 Mathematical Relationships

Following the underlying assumptions of the proposed car-following model, a stock flow diagram was developed using the VENSIM DSS program. This program provides a user friendly and flexible environment to define/code, calibrate, and validate the mathematical relationships (Ventana Systems, 2007). Additionally, the program has a wide range of built-in mathematical functions and optimization procedures that could facilitate the calibration and validation.

Like many existing car-following models, the proposed model predicts the acceleration/deceleration rate of the following vehicle at each simulation time step during a continuous traffic flow. This rate is defined as follows,

$$ADF(t) = \left[\frac{DSF(t) - SF(t)}{PRTF(t)} \right] \tag{5}$$

where $ADF(t)$ = acceleration/deceleration rate of the following vehicle at time t (m/s^2), $DSF(t)$ = desired speed of the following vehicle at time t in both steady and non-steady state conditions (m/s), $SF(t)$ = current speed of the following vehicle at time t (m/s), and $PRTF(t)$ = reaction-time of the following vehicle driver at time t (s). The desired speed is the maximum speed that a driver would like to travel for the given kinematic conditions.

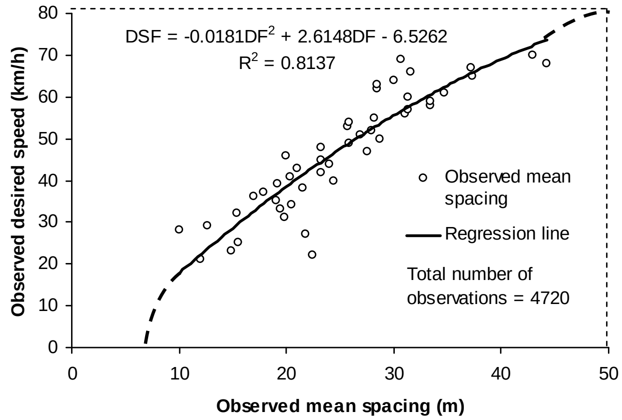
As previously mentioned, the following vehicle driver travels in three regimes: coasting, accelerating, and decelerating. At each simulation time interval (say dt = 0.1 s) the driver of the following vehicle adjusts the speed difference, if any, between his/her current speed and the desired speed. The steady state condition emulates the situation when the relative speed between the following and the lead vehicles is zero, and in the non-steady condition this relative speed is not zero. The desired speed in a steady state condition at simulation time t is assumed to depend on the spacing between the following and the lead vehicles (*DF*). The relationship between the desired speed and the spacing between the following vehicle and the lead vehicle was calibrated using the NGSIM individual vehicle tracking data.

For each pair of vehicles, the speed of the following vehicle and its corresponding distance headway were extracted. For each observed speed, the mean distance headway from all the vehicles observed to travel at this speed was computed. The developed relationship between the desired speed in the steady state conditions and the observed mean spacing is illustrated in Figure 3.

Based on field data observations obtained from the NGSIM database, it is assumed that for the *DF* of 50 m the *DSF* is 80 km/h and for *DF* of 6 m the *DSF* is 0 (Figure 3). These constraint values imply a jam density of 110 vehicles/km and pairs of vehicles do not interact in a car- following situation at a spacing of 50 m or more.

Figure 3

Calibrated desired speed relationship



Thus, the desired speed of the following vehicle is defined as follows,

$$DSF(t) = \begin{cases} 80 \text{ km/hr} & DF(t) \geq 50 \text{ m} \\ 0.278\, [-0.0181 DF^2(t) + 2.6148 DF(t) - 6.5262] & 6\text{m} < DF(t) < 50 \text{ m} \\ 0 & DF(t) \leq 6 \text{ m} \end{cases} \quad (6)$$

where $DSF(t)$ = desired speed of the following vehicle (km/h) at time t, and $DF(t)$ = spacing between the following and the lead vehicle at time t (m), and 0.278 = unit conversion factor, for converting speed from km/h to m/s.

The variable $DF(t)$ is determined as follows,

$$DF(t) = DF(t - dt) + [SL(t) - SF(t)]\, dt \quad (7)$$

where $DF(t - dt)$ = current spacing between the following and the lead vehicle at time $(t - dt)$. Initially it is externally defined at time $t = 0$ (m), dt = assumed simulation interval = 0.1 s, $SL(t)$ = speed of the lead vehicle at time t (m/s), and $SF(t)$ = speed of the following vehicle at time t (m/s).

The current speed of the following vehicle, $SF(t)$, is determined as follows,

$$SF(t) = SF(t - dt) + ADF(t - dt)\, dt \quad (8)$$

where $SF(t - dt)$ = speed of the following vehicle at time $(t - dt)$, which is externally defined at $t = 0$ (m/s) and $ADF(t - dt)$ = acceleration/deceleration rate of the following vehicle at time $(t - dt)$, calculated using Equation 5 at time $(t - dt)$ (m/s^2).

The desired speed relationship illustrated in Figure 4, and defined in Equation 6, is consistent with the SAVE database (Ervin *et al.,* 2001). As mentioned earlier, the proposed model assumed that the following vehicle driver travels in three regimes, coasting, accelerating, and decelerating. The following vehicle drivers accelerate or decelerate in response to the actions of the lead and the back vehicles. The lead vehicle actions are dominant during the deceleration regime of the following vehicle. However, while driving in a traffic stream the back vehicle is also pushing the lead vehicle if the back vehicle approaches the lead vehicle with an increasing rate of change of spacing. Therefore, it is assumed that the back vehicle dynamics will only affect the acceleration regime of the following vehicle.

The proposed model also assumes that the reaction times during the acceleration and deceleration regimes are different. In a previous study (Mehmood and Easa, 2009), the authors conducted a simulator experiment to evaluate the effect of human factors on driver reaction time in car-following scenarios. The car-following driver reacts to adjust speed by using the gas pedal only or by using the brake pedal in the case whenthe lead vehicle is braking and its brake light is ON. The term acceleration/deceleration reaction time (*ADRT*) is used when the driver reacts to adjust his/her speed by only using the gas pedal. The term brake-reaction time (*BRT*) is used when the driver reacts by braking in response to the lead vehicle braking. Reaction time models were developed for both *ADRT* and *BRT*. The deceleration regime is classified into two states: when the lead vehicle is braking or not braking. The brake light status of the lead vehicle is determined using the relationship suggested by Ozaki (1993), which is given by

$$\text{Brake light of the lead vehicle} = \begin{cases} \text{ON} & ADL(t) < -0.013\ SL(t) \\ \text{OFF} & \text{Otherwise} \end{cases} \tag{9}$$

where $ADL(t)$ = acceleration/deceleration rate of the lead vehicle at time t (m/s^2) and $SL(t)$ = speed of the lead vehicle at time t (m/s).

The reaction-time models for *ADRT* and *BRT* have been developed as (Mehmood and Easa, 2009), as:

$$ADRT(t) = 0.017\ Age + 0.159\ Gender \tag{10}$$

$$BRT(t) = 0.078\ Gender - 0.002\ SF(t) + 0.049\ DF(t) \tag{11}$$

where $BRT(t)$ = brake-reaction time at time t (s), $ADRT(t)$ = acceleration/deceleration reaction time at time t (s), *Age* = age of the driver of the following vehicle (years), and *Gender* = gender of the driver of the following vehicle (0 for males and 1 for females). The preceding reaction time models depend on both vehicle dynamics and driver characteristics. It is evident that driver reaction time increases with the age and that the females are slower than the males.

The acceleration and deceleration regimes correspond to two non-steady sate conditions: one for acceleration and the other for deceleration. Therefore, for the non-steady state conditions three calibration parameters are introduced and for each non-steady sate condition, Equation 5 is modified as follows,

$$ADF(t) = \left[\frac{DSF(t)b_1 - SF(t)}{ADRT(t)}\right] \quad \text{(non-braking scenario, deceleration regime)} \tag{12}$$

$$ADF(t) = \left[\frac{DSF(t)b_2 - SF(t)}{BRT(t)}\right] \quad \text{(braking scenario, deceleration regime)} \tag{13}$$

$$ADF(t) = \left[\frac{DSF(t)b_3 - SF(t)}{ADRT(t)}\right] \text{(non-braking back-lead vehicle scenario, acceleration regime)} \tag{14}$$

where b_1 = parameter for the lead vehicle non-braking scenario (deceleration regime), b_2 = parameter for the lead vehicle braking scenario (deceleration regime), and b_3 = parameter for the non-braking back vehicle scenario (acceleration regime).

4.0 Calibration and Validation

The calibration of the proposed car-following model was accomplished using 45 samples extracted earlier from the NGSIM database. The calibration parameters include b_1, b_2, b_3, *Age*, and *Gender* of the driver of the following vehicle. When a model is structurally complete and properly simulates the process, the calibration of the model can proceed. The calibration involves finding the values of model parameters that make the model generate behaviour curves that best fit actual data. The behaviour curves of the proposed model are the speed and spacing profiles. In VENSIM there are two ways to calibrate the model: (1) changing the values manually and performing simulation to achieve a better fit between simulated and actual data and (2) using optimization. In optimization, the program automatically changes the parameters of choice and looks for the best fit between the simulation output and actual data. The model parameters along with their lower and upper bounds are defined in the optimizer before a simulation run. Once the optimum parameters are determined the respective inverse time-to-collision (*INVT*) values are accumulated in each sample. The *INVT* was found to be a significant variable in the calibration. The data points for all samples are then accumulated to calibrate the relationship for the parameters (b_1, b_2, and b_3). These relationships are shown in Figures 4-6.

The samples used for the calibration represent the vehicle dynamics on freeways. The calibration parameters suggest that in case of deceleration regimes the rate of change of speed is higher when the following vehicle is braking compared to when it is not braking and decelerating with only the throttle input. The parameters also suggest that drivers use the throttle input for the deceleration regime when they intend to reduce their desired speeds by 20% (Figure 4). It is also observed that the lead vehicle has a dominant influence on the actions of the driver of the following vehicle, but the back vehicle can also contribute to the acceleration regime when it is approaching the following vehicle with higher speeds. In usual practice, drivers either change their lane to avoid a conflict with the back vehicle or increase their speeds to remain in a continuous traffic flow. This study is limited to the car-following modeling and the contribution of the back vehicle in a lane-change manoeuvre can further be studied in lane-change modeling.

For validation, 15 random samples of the three vehicle platoons were extracted from the NGSIM database. The samples used for the validation were different from the samples used for calibration of the proposed car-following model. The trajectory of the lead and back vehicles, and the initial position and the speed of the following vehicle were provided as input to the proposed car-following model.

Figure 4

Calibrated non-braking parameter relationship

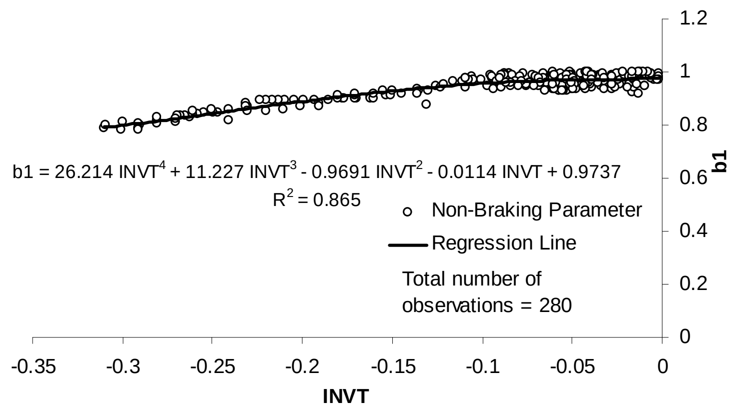


Figure 5

Calibrated braking parameter relationship

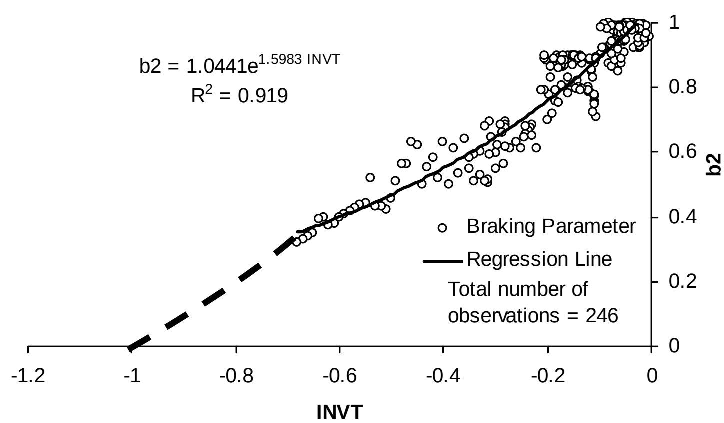
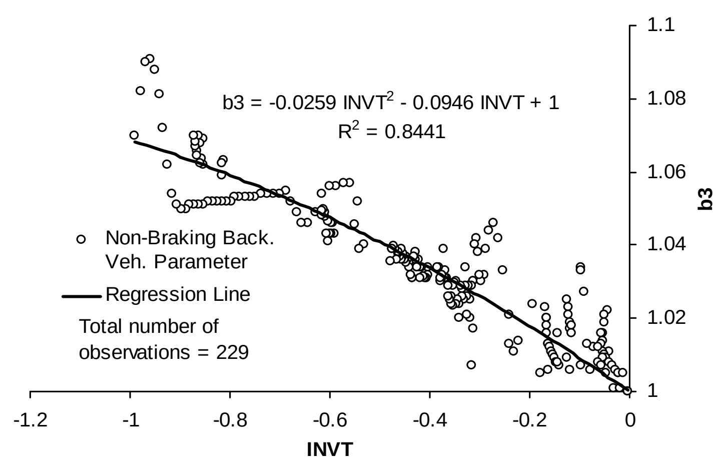


Figure 6

Calibrated non-braking back vehicle parameter relationship



The age and gender of the following vehicle's driver were generated based on their statistical distributions in the driver population. These values were also input to the proposed model. Validation of the proposed car-following model was conducted by comparing the model estimates of the speed and spacing of the following vehicle with those observed in the NGSIM database. Figure 7 shows the observed and predicted results associated with the following vehicle. It is evident that the speed and spacing profiles predicted by the proposed model closely follow those of the observed field data. Note that the observed curve has a slight shift to the left compared with the predicted curve. There are several factors that may contribute to the difference between the two curves, including weather conditions, pavement surface conditions, roadway geometric features, and driver inattention. Since information on these factors was not available for the observed data, it is difficult to identify the specific factors that contribute to that difference.

Figure 8 shows the simulation results of a representative sample in which different driver characteristics were tested to check how the age and gender of the driver affect the speed profile of the following vehicle. It is observed that the average speeds of the females are less than the average speeds of the males. The results also show that older drivers tend to drive at lower speeds than the young drivers under same traffic conditions.

Figure 7

Observed and predicted speed and spacing profiles (a) speed profiles, (b) spacing profiles

(a)

(b)

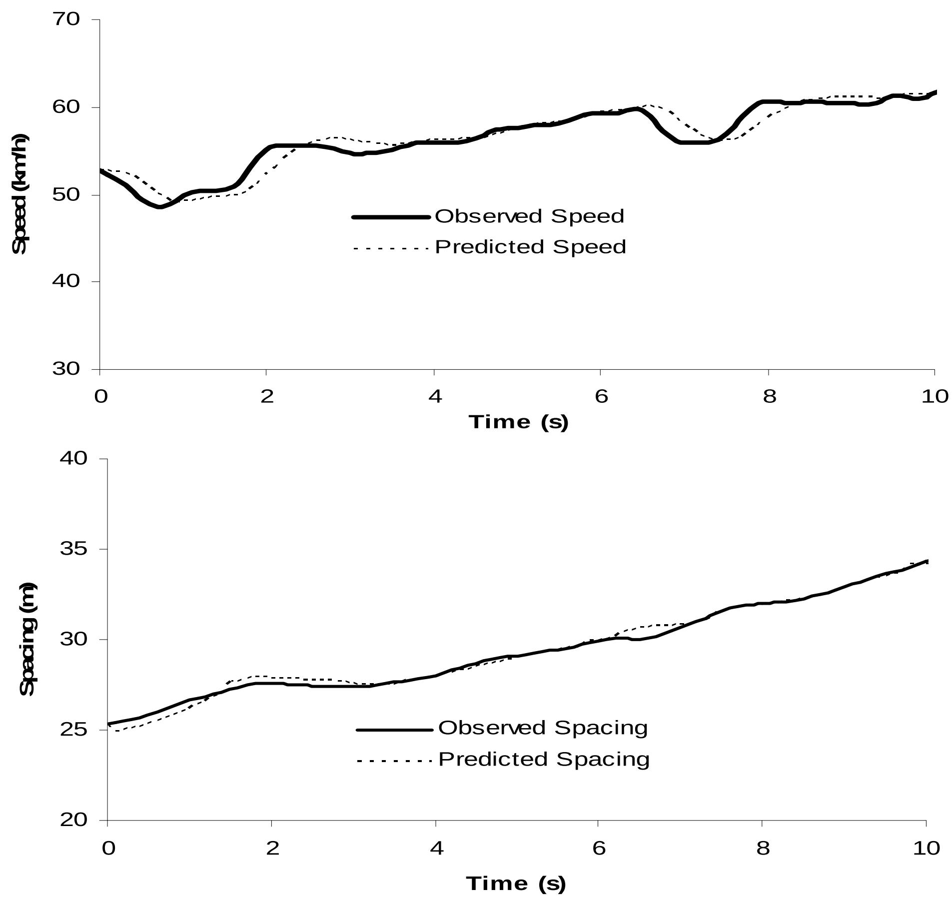


Figure 8
Effect of age and gender on speed profile

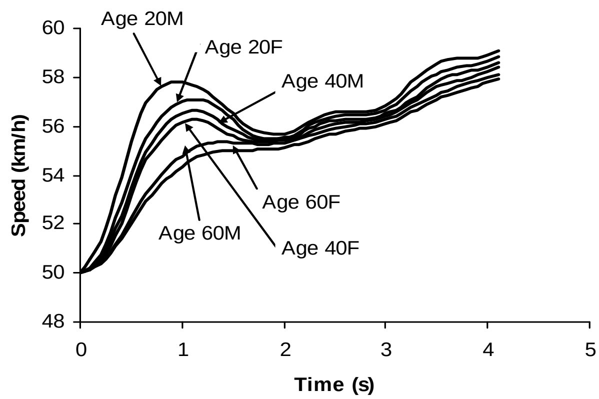


Table 1
RMS associated with speed and spacing of the following vehicle (10 samples)

Sample	Ave. Observed Speed	RMS (Speed)	Ave. Observed Spacing	RMS (Spacing)	Number of Observations
1	44.5	1.34	18.51	0.19	151
2	47.0	2.17	15.18	0.32	145
3	58.9	1.11	30.32	0.24	123
4	51.4	5.01	8.33	0.45	60
5	48.5	1.27	13.44	0.29	64
6	45.3	1.65	16.45	0.56	159
7	44.2	1.86	16.98	0.50	162
8	53.4	0.76	16.02	0.28	205
9	55.0	1.29	23.67	0.38	207
10	46.3	1.26	15.45	0.32	185
Average	50.0	1.77	17.43	0.35	108

The root-mean-square (*RMS*) error associated with the prediction of the speed and spacing profiles of the following vehicle was estimated for each sample (Table 1). The average *RMS* values for the speed and spacing for the 10 samples were 1.77 and 0.35, respectively.

5.0 Concluding Remarks

This paper has presented a new and improved car-following model based on system dynamics principles that has addressed some limitations of existing car-following models. The existing models do not consider driver's characteristics in modeling driver behavior in a car-following situation. Besides, they only use the information associated with the lead vehicle such as the speed and the spacing between the following and the lead vehicles. The proposed model explicitly considers driver characteristics (age and gender) and accounts for the information about the back vehicle in modeling driver behaviour. These improvements in car-following modeling represent the key contributions of the present study. Based on this research, the following comments are offered:

1. The proposed car-following model is driver-sensitive and accounts for the information of the back vehicle while following a lead vehicle. The model assumes that drivers travel in three regimes: coasting, accelerating, and decelerating. The deceleration regime is further classified into two regimes based on the lead vehicle braking and non-braking scenarios. The reaction-time used in the acceleration and deceleration regimes is assumed to depend on vehicle dynamics and driver characteristics. Unique parameters are developed for the acceleration and deceleration regimes. The results show that the rate of change of speed is higher for the braking deceleration regime than that for the non-braking deceleration regime. The back vehicle can only contribute to the acceleration regime if it is approaching the following vehicle with a higher speed.
2. The calibration of the parameters was performed using the NGSIM vehicle trajectory data collected on freeways. Therefore, the observations for the calibration parameters may vary for other classes of roadways. The calibration process resulted in a sample of driver population that represented the NGSIM data. For validation purposes, the statistical distributions of that sample were used to generate the age and gender values. This was a fair assumption as it is similar to other calibration parameters that were assumed to represent the NGSIM data.
3. This paper is the first attempt of car-following modeling in which driver characteristics were considered explicitly in determining the acceleration/deceleration rate of the following vehicle. It was found that males and young drivers travel at higher speeds than females and older drivers, respectively. The model estimates of the spacing and speed profiles of the following vehicle were compared with actual field data and the model showed excellent correspondence.
4. Traffic operational models normally include elements involving driver behaviour, such as lane-change, route choice, lane-choice, and intersection maneuvers. It is recommended that future research should explore human factors in other drivers' operational elements. This research initiative will be useful to further extend the proposed driver-sensitive car-following model to other elements such as lane-change behaviour and to other classes of vehicles.
5. It is also recommended that the proposed model should be applied for a macroscopic traffic analysis to study the impact of individual driver characteristics on traffic operations. A suitable method for incorporating driver age and gender when implementing the proposed car-following model is needed. The selection of such a method would depend on the type of operational analysis for which the context simulation modeling is conducted, such as an intersection, a corridor, or a network. A survey of the age and gender of the drivers expected to use the proposed network or corridor can be conducted and considered for a macroscopic traffic analysis. The survey data will help to develop the statistical distributions that can be used to generate driver characteristics for a macroscopic traffic analysis in a municipality or a region.
6. The proposed car-following model has potential for being implemented in an in-vehicle rear-end collision warning system. Such a system would include an algorithm that involves a decision rule to trigger the warning. The decision rule requires the

kinematics of the lead and the following vehicles and the reaction-time of the driver of the following vehicle. For future research, the proposed car-following model can be integrated with the decision rule of the collision warning algorithm to check its functionality. The calibration parameters based on driver population developed in this study would be useful at the early stage of using such a warning system. As the system is used for some time, the system can accumulate such data for the specific user(s) of the vehicle and use them to calibrate driver-specific parameters using such techniques as neural networks.

References

Aron, M. (1988). Car-following in an urban network: simulation and experiments. *Proceedings* of *Seminar D, 16th PTRC (Planning and Transport, Research and Computation) Meeting,* Barth, U.K., 29-39.

Aycin, M.F., and R.F. Benekohal,,(1998). Linear acceleration car-following model development and validation. *Transportation Research Record* 1644, Transportation Research Board, Washington, D.C., 10-19.

Benekohal, R. and J. Treiterer, (1988). CARSIM: Car-following model for simulation of traffic in normal and stop-and-go conditions. *Transportation Research Record* 1194, Transportation Research Board, Washington, D.C., 99-111.

Brackstone, M. and M. McDonald, (1999). Car-following: a historical review. *Transortation Research.*, *Part F: Traffic Psychological. Behavior*, 2(4), 181–196.

Chandler, R.E., R. Herman, and E.W. Montrol, (1958). Traffic dynamics: studies in car-following. *Operations Research*, 1(2),165-184.

Ervin, R., C. MacAdam, A. Vayda and E. Anderson, (2001). Applying the SAVME database on inter-vehicle kinematics to explore the natural driving environment. Presented at the 80th Annual Meeting of the Transportation Research Board, Washington, D.C.

Gazis, D.C., R. Herman, and R.W. Rothery, (1961). Nonlinear follow-the-leader models of traffic flow. *Operations Research,* 9(4), 545-567.

Gipps, P.G. (1981). A Behavioural car following model for computer simulation. *Transportation Research B*, 15B, 105-111.

Hanken, A. and T.H. Rockwell, (1967). A model of car following derived empirically by piece-wise regression analysis. *Proceedings of the 3rd International Symposium on the Theory of Traffic Flow*, New York, 40-41.

Helly, W. (1959). Simulation of bottlenecks in single lane traffic flow. *Proceedings of the Symposium on Theory of Traffic Flow*, Research Laboratories, General Motors, Elsevier, New York, 207-238.

Heyes, M.P. and R. Ashworth, (1972). Further research on car-following models. *Transportation Research*, 6, 287-291.

Highway Capacity Manual (2000). Transportation Research Board, National Research Council, Washington, D.C.

Hranac, R., R. Margiotta and V. Alexiadis, (2005). *Next generation simulation (NGSIM) high-level data plan*, Report to Federal Highway Administration, FHWA-HOP-06-011.

Kikuchi, S. and P. Chakroborty, (1992). Car-following model based on fuzzy inference system. *Transportation Research Record 1365*, Transportation Research Board, Washington, D.C., 82-91.

Kometani, E. and T. Sasaki, (1959). Dynamic behaviour of traffic with a non-linear spacing-speed relationship. *Proceedings of the Symposium on Theory of Traffic Flow*, Research Laboratories, General Motors, 105-119.

Mehmood, A., F. Saccomanno and B. Hellinga, (2003). Application of system dynamics in car-following models. *Journal of Transportation Engineering*, ASCE, 129(6), 625-634.

Mehmood, A. and S. M. Easa, (2009). Modeling reaction time in car-following behaviour based on human factors. *International Journal of Applied Science, Engineering and Technology*, 5(14), 93-101.

Michaels, R.M. (1963). Perceptual factors in car-following. *Proceedings of 2nd International Symposium on Theory of Traffic Flow*, OECD, Paris, 44-59.

Ozaki, H. (1993). Reaction and anticipation in the car-following behaviour. *Proceedings of the 13th International Symposium on Traffic and Transportation Theory,* 349-366.

Rockwell, T.H., R.L Ernst and A. Hanken, (1968). A sensitivity analysis of empirically derived car following models. *Transportation Research*, 2, 363-373.

Sakda, P. and D. Hussein, (2005). Comparative evaluation of microscopic car-following behavior. *IEEE Transactions on Intelligent Transportation Systems*, 6(3), 314-324.

Siuhi, S. and M. Kaseko, (2010). Parametric study of stimulus-response behavior for car-following models. *Proceedings of Annual Meeting of the Transportation Research Board*, Paper 10-1779, Washington, D.C.

Subramanian, H. (1996). *Estimation of car-following models*. M.Sc. Thesis, Massachusetts Institute of Technology, MA.

Ventana Systems (2007). *VENSIM Ventana simulation environment*: User's guide. Version 5, Ventana Systems Inc., 149 Waverley Street, Belmont, MA, 02178,

Wiedemann, R. (1974). *Simulation of road traffic flow*. Reports of the Institute for Transport and Communication, University of Karlsruhe.

Wolshon, B. and Y. Hatipkarasulu, (2000). Results of car-following analyses using global positioning system. *Journal of Transportation Engineering*, American Society of Civil Engineering, 126(4), 324-331.

Yikai, K., J.I. Satoh, N. Itakura, N. Honda and A. Satoh, (1993). A fuzzy model for behaviour of vehicles to analyze traffic congestion. *Proceedings of the International Congress on Modelling and Simulation*, University of Western Australia, Perth, Australia.

Zhang, Y., L.E. Owen J.E. and Clark, (1998). Multi-regime approach for microscopic traffic simulation. *Transportation Research Record* 1644, Transportation Research Board, Washington, D.C., 103-115.