

Evaluation of a car-following model using systems dynamics

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Abstract

Models that describe the processes by which drivers follow each other in the traffic stream are generally referred to as car-following models. During the past 50 years, driver behavior within the traffic stream has been studied and models that attempt to describe this behavior have been proposed.

Car-following models have frequently been developed for the purpose of incorporation with microscopic simulation models. These models have then been used to evaluate a wide range of potential geometric options, operational strategies, and/or policies.

In this paper we formulate a car-following model using the systems dynamic (SD) approach. We compare the behavior of the proposed SD model to the GM model, a classic car-following model that has been extensively described in the literature. These comparisons illustrate that the proposed SD car-following model avoids several unrealistic characteristics of the GM model. The ultimate objective is to use the proposed model to investigate the mechanisms leading to rear-end crashes and to quantify the impact that different technologies or policies (e.g. driver vision enhancement systems) may have on rear-end crash potential.

Keywords: Car-following, Driver behaviour, Systems Dynamics, Microscopic traffic simulation

1.0 Introduction

Rear-end crashes involving two or more vehicles currently represent about one-fourth of all road crashes in Canada as well as in U.S. General Estimates Systems (GES) reported that in 1998 rear-end crashes constitute approximately 28% of all crashes in the U.S. In Ontario rear-end crashes represent about 23% of all crashes reported in any given year during 1993 to 1997 (Ontario Road Safety Annual report, 1993-1997). While many injuries and fatalities are caused by rear-end crashes, rear-end crashes also cause approximately 157 million vehicle-hours of delay annually in U.S., which is about one-third of all road crash-caused delays (McGehee et al., 1992).

Several factors may contribute to rear-end crashes, such as driver perception/reaction time, driver inattention, high speed and following too closely, and limitations in visibility. According to National Safety Council (Accident Facts, 1996) about 90% of rear-end crashes result from driver inattention and/or following a lead vehicle too closely. The study of driver behaviour

under car-following situations is essential in developing advanced vehicle control and safety systems (AVCSS). Such systems seek to replicate human driving behaviour through partial control of the accelerator, while removing potential hazards that may occur through driver misperception and action. The development of effective safety systems for reducing rear-end crashes requires a thorough understanding of factors that contribute to rear-end crashes. Driving an automobile is a continuous complex task. It requires the driver to constantly scan the environment and to respond properly in order to maintain control, avoid obstacles, and interact safely with other vehicles. To build and integrate the technologies that might avert rear-end crashes, it is important to first fully understand driver behaviour in the car-following situations at a given location for a range of transportation conditions.

Driver behaviour in the car-following situation has been studied extensively since the 1950s. Over the years various models that reflect the car-following behaviour of drivers for different traffic assumptions and conditions have been developed (see for example, the work by Chandler et al., 1958; Forbes et al., 1958; Forbes, 1963; Gazis et al., 1961; Herman and Potts, 1959; Herman and Rothery, 1969; May, 1967, Gipps, 1981; Van Aerde, 1995; Hogema, 1998; and Zhang et al., 1998). By far the most significant contribution to the development of car-following theory was made by the General Motors (GM) researchers (Chandler et al, Herman et al, Gazis).

This paper reviews the existing car-following models from the theoretical and practical standpoint. These models have a number of shortcomings depending on their formulation, including failure to consider the longer view of the traffic stream (i.e. several lead vehicles interacting to effect the behaviour of a following vehicle), failure to consider a situation when relative speed is zero at a small spacing, and failure to distinguish between risk critical situations and other situations for similar initial speeds and spacing. The paper then proposes a System Dynamics (SD) model that extends the features of these existing car-following models by introducing a concept of driver comfort zones effecting speed and spacing at different points of time. The proposed SD model is evaluated by comparing its results with those suggested by the car-following models like the GM model for a given set of transportation conditions. Comparison between the performance of the two models shows that the proposed SD model can overcome many shortcomings of the existing car-following models.

2.0 Existing car-following models

Models that describe the processes by which drivers follow each other in the traffic stream are generally referred to as car-following models. Car-following models have been studied extensively since as early as the 1950s. The earliest work focused on the principle that vehicle separation is governed by safety considerations in which distance or time headway between vehicles are a function of speed. Pipes (1953) developed a car-following model on the assumption that drivers maintain a constant distance headway. His work was followed by Forbes (1958) who assumed that drivers maintain a constant time headway. Follow-up research incorporated factors such as spacing between vehicles, speed differential, and driver sensitivity into car-following models. These models are summarized in Table 1.

In Table 1, the car-following models by Chandler et al., 1958; Gazis et al., 1959, 1961; Edie, 1961; Newell, 1961; Herman and Rothery, 1963 and Bierley, 1963 assumed that in car-following situation the Following Vehicle driver observes only the vehicle immediately ahead in determining his or her speed. Fox and Lehman (1967), and Bexelius (1968) suggested that instead of following only the immediately vehicle ahead, drivers in a car-following situation also observe the vehicles ahead of the lead vehicle. They incorporated the effect of a second lead car in their car-following models.

Table 1: Car-following models

| Source: | Corresponding Car-following Model |
|----------------------------|--|
| Chandler et al. (1958) | $a_F(t + \Delta t) = \mathbf{a} [V_L(t) - V_F(t)]$ |
| Gazis et al. (1959, 1961) | $a_F(t + \Delta t) = \mathbf{a} \left[\frac{V_L(t) - V_F(t)}{X_L(t) - X_F(t)} \right]$ |
| Edie (1961) | $a_F(t + \Delta t) = \mathbf{a} \left[\frac{V_F(t)}{[X_L(t) - X_F(t)]^2} [V_L(t) - V_F(t)] \right]$ |
| Newell (1961) | $a_F(t + \Delta t) = G_n [X_L(t) - X_F(t)]$ |
| Herman and Rothery, (1963) | $a_F(t + \Delta t) = \mathbf{a} \left[\frac{[V_F(t)]^m}{[X_L(t) - X_F(t)]^l} [V_L(t) - V_F(t)] \right]$ |
| Bierley (1963) | $a_F(t + \Delta t) = \mathbf{a} [V_L(t) - V_F(t)] + \mathbf{b} [X_T(t) - X_F(t)]$ |
| Fox and Lehman (1967) | $a_F(t + \Delta t) = \mathbf{a} V_F(t) \left[\frac{W_1[V_L(t) - V_F(t)]}{[X_L(t) - X_F(t)]^2} + \frac{W_2[V_T(t) - V_F(t)]}{[X_L(t) - X_F(t)]^2} \right]$ |
| Bexelius (1968) | $a_F(t + \Delta t) = \mathbf{a} [V_L(t) - V_F(t)] + \mathbf{b} [V_T(t) - V_F(t)]$ |
| Rockwell et al. (1968) | $a_F(t + \Delta t) = \mathbf{a} [V_L(t) - V_F(t)] + \mathbf{b} a_L(t)$ |

Where

- $a_F(t + \Delta t)$ = Acceleration/deceleration rate of Following Vehicle driver at time $t + \Delta t$
 $a_L(t)$ = Acceleration/deceleration rate of Lead Vehicle driver at time t
 $V_F(t)$ = Following Vehicle speed at time t
 $V_L(t)$ = Lead Vehicle speed at time t
 $V_T(t)$ = Target (2nd Lead Vehicle) speed at time t
 $X_F(t)$ = Following Vehicle distance at time t
 $X_L(t)$ = Lead Vehicle distance at time t
 t = Simulation time (sec)
 Δt = Perception-reaction time (sec) or simulation interval
 G_n = Empirical relationship between velocity and headway for acceleration/deceleration
 $\hat{a}, \hat{a}, m,$
 l, W_1, W_2 = Model parameters

In this paper, we will be using the GM model (equation 1) as a basis of comparison for car-following models in general because of the comprehensive field experiments conducted to validate its underlying assumptions (May, 1990).

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

A common feature of the above GM model is the assumption that driver behaviour can be represented as a stimulus-response system. System response is the driver's decision to accelerate or decelerate. The rate of acceleration (or deceleration) is a function of driver sensitivity and the stimulus. Stimulus is assumed to be the difference in speed between the Lead and the Following Vehicle. Driver sensitivity is a function of the spacing between the Lead and the Following Vehicle, the speed of the Following Vehicle, and a calibrated coefficient.

Notwithstanding considerable work carried out on car-following models following the initial work by GM, the GM model structure has remained as the basis of car-following behaviour. However, in order to calibrate and subsequently evaluate the GM model many researchers have attempted to estimate the best combination of parameters (c , m , and l). Among these the most notable examples of this work are: May and Keller, 1967; Heyes and Ashworth, 1972; Ceder et al., 1976; Aron, 1988; Ozaki, 1993). A summary of optimal parameter combinations to emerge is given in Table 1.

Table 1: Most reliable estimates of parameter combinations for the GM model

| Source | C | m | l |
|---------------------------|-------------------------|---------------------|--------------------|
| May and Keller (1967) | 1.33 x 10 ⁻³ | 0.8 | 2.8 |
| Heyes and Ashworth (1972) | 0.8 | -0.8 | 1.2 |
| Ceder et al. (1976) | | 0.6 | 2.4 |
| Aron (1988) | 2.45 / 2.67 / 2.46 | 0.655 / 0.26 / 0.14 | 0.676 / 0.5 / 0.18 |
| Ozaki (1993) | 1.1 / 1.1 | 0.9 / -0.2 | 1 / 0.2 |

2.1 Limitations of existing GM car-following model

Despite the dominance of the GM model (and its variants) in the research literature, this model exhibits several undesirable characteristics. Many of these undesirable characteristics are common to car-following models in general and include (Chakroborty and Kikuchi, 1999):

1. The response of the Following Vehicle driver is based on only one stimulus (relative speed). When the Lead and Following vehicles are travelling at the same speed, the acceleration/deceleration response dictated by the GM model is zero, regardless of the current spacing between vehicles. Owing to the single stimulus nature of the model, it fails to illustrate the behaviour of the Following Vehicle driver at zero relative speed. For example, consider the situation when the relative speed between two successive vehicles is zero and the spacing is too short. For such a situation we expect the Following Vehicle

driver will initially decelerate to increase the spacing until a comfortable spacing is achieved to desirable and then accelerate to reduce the speed difference between the two vehicles. This would occur if the Lead Vehicle is not travelling at a speed that exceeds desired speed of the Following Vehicle driver.

2. The GM model assumes a symmetrical behaviour for the Following Vehicle driver. For example, consider two cases: one with a positive relative speed with a certain magnitude and the other with a negative relative speed with the same magnitude, and all other factors are identical. In the interest of safety, we expect the acceleration in first case to be lower than the deceleration (in absolute terms) in second case. It has been observed that drivers act differently depending on whether spacing between vehicles is increasing or decreasing (more risk critical). Drivers "pay closer attention to spacing decreases than to spacing increases" (Leutzbach, 1988).
3. Another drawback of GM model is that it assumes that the Following Vehicle driver observes only the Lead Vehicle in determining his or her speed. In reality, it has been observed that drivers respond in relation to the behaviour of several downstream vehicles, not just the vehicle immediately ahead (Fox and Lehman 1967, Bexelius, 1968).

In order to evaluate the properties of GM model, we have translated it into stock flow diagram in this paper. In a stock-flow diagram the logic of programming code is more readily demonstrated and visualized. This approach was adopted for the proposed model, which we are comparing to the GM model.

Figure 1 illustrates the basic features and assumptions underlying the stock-flow diagram for the car-following situation considered in this paper. The Target, the Lead and the Following vehicle are moving in the same lane with the same initial speed and initial spacing. The speed limit of roadway is assumed 100 ft/sec. The Lead Vehicle encounters some obstruction (refer to as Target) along its path causing the driver to decelerate in order to avoid a crash with the Target. It has been assumed for this paper that all vehicles travel in the same lane and only speed changes are allowed.

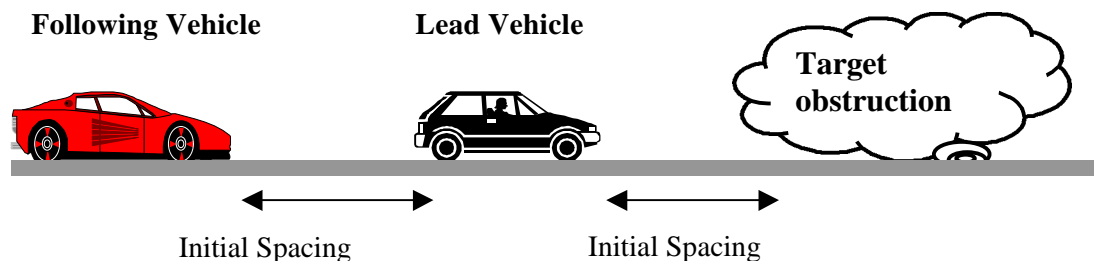


Figure1: Car-following situation considered in this paper

3.0 Stock-flow diagram of GM model

Figure 2 illustrates the stock-flow diagram of GM model. The GM model equations are given in Appendix-A to this paper.

The GM model is considered into four sectors: 1) the Target, 2) the Lead Vehicle, 3) the Following Vehicle, and 4) the Spacing. Each sector performs certain functions and interacts with the other sectors through feedback links. The details of each sector are described below.

3.1 Target Sector

In Figure 2, the Target Obstruction Sector is an exogenous sector, whose function is to describe the Target in terms of required speed, and spacing for the Lead Vehicle. The speed of the Target is set exogenously by the user, while the speed and spacings of the Lead and Following Vehicles is determined endogenously subject to the GM model described in section 2 of this paper.

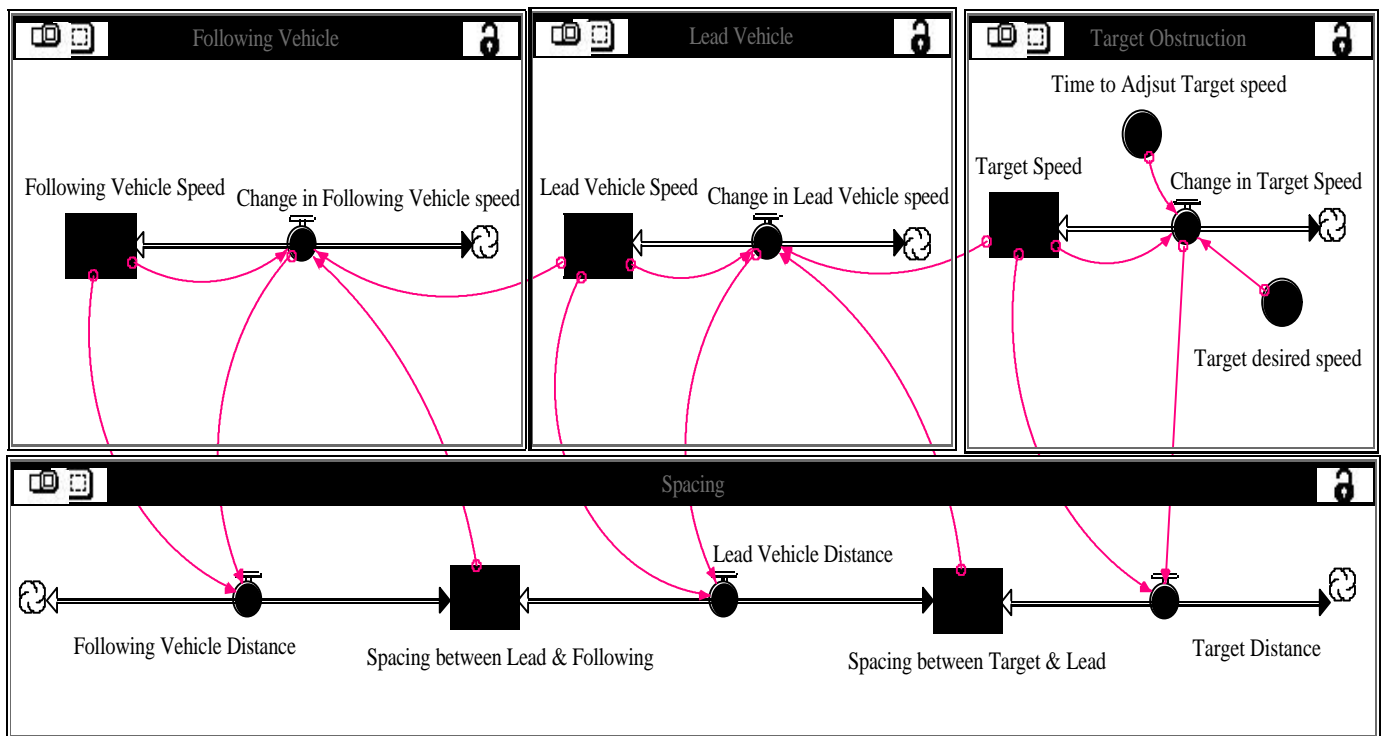


Figure 2: Stock-flow diagram of GM model

In this sector the stock variable Target Speed represents the speed of the Target. The rate of change in the speed of the Target is determined by the speed of the Target and desired speed of the Target for an assumed interval of time over which this change takes place. Any change in the speed of the Target will change its relative position with respect to the Lead Vehicle. The spacing between the Target and the Lead Vehicle is calculated in the Spacing Sector.

3.2 Lead and Following Vehicle Sector

The process describing the Lead and the Following Vehicle Sector is similar. The only difference between the Lead and Following Vehicle Sector is that the Lead Vehicle driver considers the Target while adjusting his or her speed and the Following Vehicle driver considers the Lead Vehicle while adjusting his or her speed. The acceleration/deceleration rate for both the Lead and the Following Vehicle driver is determined by the GM model (equation 1). The values of parameters in equation 1 are taken from Chakroborty and Kikuchi (1999). These values are: $c = 69$, $l = 2$, $m = 1$. Chakroborty and Kikuchi estimated the value of c for a given l and m by fitting the corresponding speed-density relation to an observed speed-density data set obtained from the Queen Elizabeth Way freeway in Canada.

3.3 Spacing Sector

As shown in Figure 2, in this sector there are two stocks, one determines the current spacing between the Target and the Lead Vehicle, while the other determines the current spacing between the Lead Vehicle and the Following Vehicle. The distance travelled during the simulation interval by the Target, the Lead Vehicle, and the Following Vehicle is determined by their respective speeds, acceleration/deceleration rates and the simulation time interval. This distance is determined by the equation of motion given below.

$$S = V * dt + 0.5 * a * dt^2 \quad (2)$$

Where S is the distance travelled during the simulation interval dt , ' a ' is the acceleration/deceleration rate during dt and V is the beginning of dt .

The next section describes the stock-flow diagram of a revised car-following model as proposed in this paper.

4.0 A more realistic car-following model

To alleviate the shortcomings of existing GM models discussed earlier in this paper, a more realistic car-following model is presented to replicate the behaviour of following vehicle drivers. Thus proposed model considers endogenously the speed, acceleration/deceleration of the Following vehicles, and spacing between the Lead and Following vehicles. Road geometry, pavement conditions, and weather conditions are controlled externally. The basic difference between this model and the existing car-following models is that existing car-following models consider each vehicle pair separately whereas the revised model considers several vehicles at a time. Furthermore, the revised model is unique in car-following theory in that it introduces a concept of "desired safe spacing or operating speed" into the formulation. The desired speed and spacing is subjective standard that reflects "feeling of safety" on the part of an individual driver faced with a given traffic situation.

The stock-flow diagram of proposed model is given in Figure 3. In the proposed model only the Lead and the Following Vehicle sectors are different from the GM model while the Target and

the Spacing sectors both are same as described for GM model. The Lead and the Following Vehicle sectors of proposed model are described below.

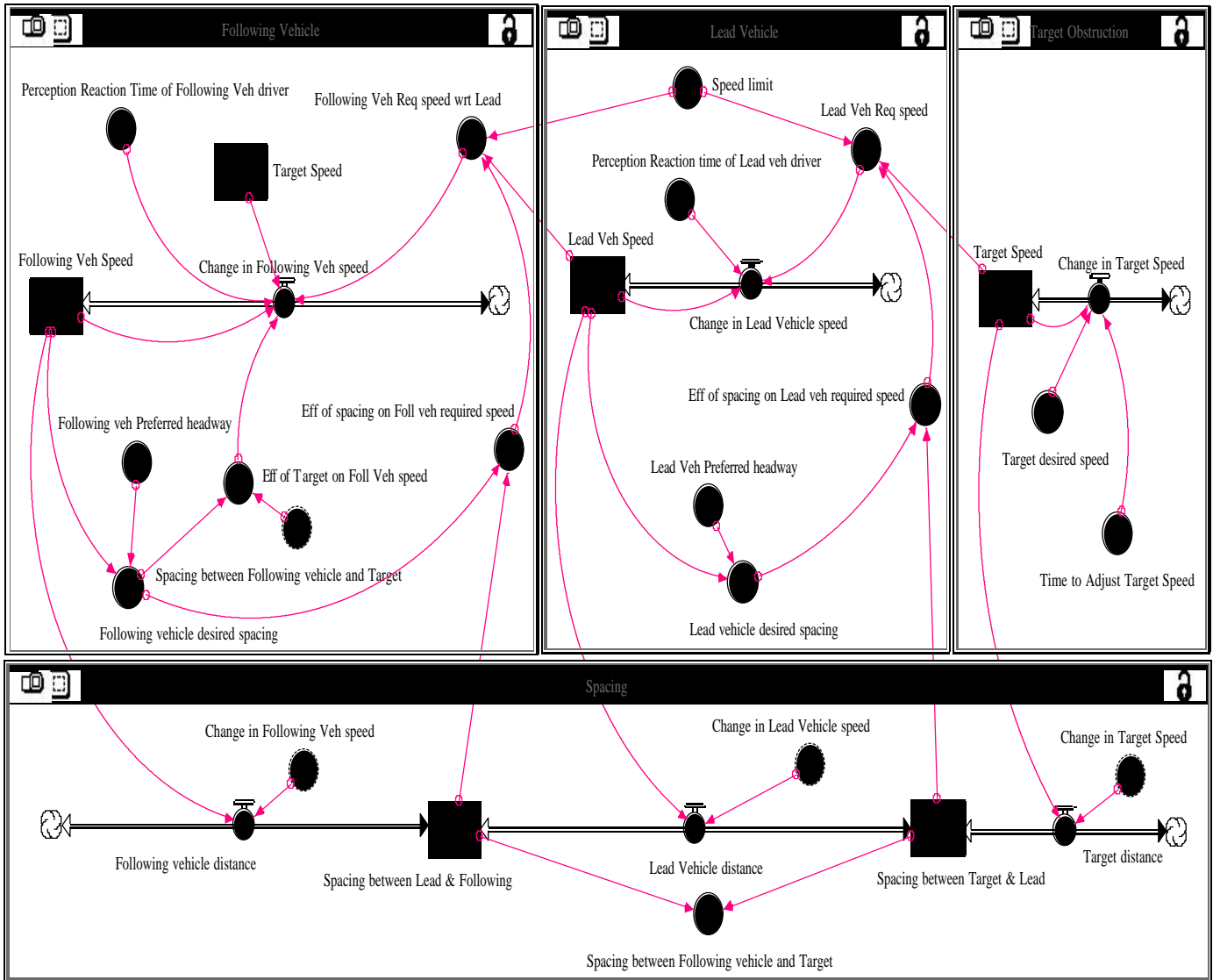


Figure 3: Stock-flow diagram of proposed model

The process describing the Lead Vehicle sector is similar to the Following Vehicle Sector as described in the next paragraph. The only difference between the Lead and Following Vehicle Sector is that the driver of the Following Vehicle considers both the spacing between the Target and the Lead Vehicle, and the spacing between the Lead and the Following Vehicle when adjusting his or her speed. While adjusting his or her speed, the Lead Vehicle driver considers only the spacing between the Target and itself.

In the Following Vehicle sector, the stock variable Following Vehicle Speed represents the current speed of the Following Vehicle. The acceleration/deceleration rate of the Following

Vehicle driver is assumed to depend on his required safe speed with respect to the Lead Vehicle, his own current speed, and his perception reaction time. We have assumed for this initial application that the perception reaction time is 2.5 sec (Olson, 1986). The required safe speed for the Following Vehicle is established based on the current speed of the Lead Vehicle, speed limit of roadway (assumed 100 ft/sec), desired and current spacing of the Lead and Following Vehicles. The desired spacing of a driver at a particular speed is the distance that he or she considers is safe and attempts to maintain it. The desired spacing for the Following Vehicle is assumed the product of its current speed and a constant preferred time headway of the Following Vehicle driver (Winsum, 1999 and Aycin, 1997). The preferred time headway is defined as a headway the driver wants to maintain under car-following situation. Winsim (1999) has reported that there are substantial differences in the value of preferred headway between drivers. For example, drivers who are less skilled generally choose to drive at a larger time headway. In this paper we have assumed the preferred time headway of the Following Vehicle driver is 1.5 sec. The current spacing is the actual spacing between vehicles calculated in the spacing sector. The factors such as pavement conditions, pavement friction, road geometry, and traffic conditions can affect the required safe speed for the Following or the Lead Vehicle. For our initial analysis in this paper, we have assumed ideal conditions and these other relationships have not been incorporated into the model.

5.0 Discussion of comparative results between GM and proposed model

In this section a comparison is made between the GM model enumerated earlier in this paper and the proposed model. Both GM and proposed model are tested for assumed range of transportation conditions. In this paper we will discuss only four experiments. These experiments are discussed below.

Experiment 1

In this experiment simulation run starts for both GM and proposed model where all variables are parameterised to reflect equilibrium in all stocks. Initially, we assume that the speeds of the Target, Lead, and Following Vehicles are the same at 80 ft/sec. Furthermore, the current spacing between the Target and the Lead Vehicle, and between the Lead and Following Vehicle is assumed initially to be equal to their desired spacing (120 ft).

We now assume that the speed of the Target is decreased 25% from an initial value of 80 ft/sec at time $t = 10.0$ sec to final value of 60 ft/sec at time $t = 20.0$. This reduction in the speed of the Target could be in response to the on-set of congestion or the presence of some debris along the path of the Target. Figure 4 illustrates the speed profiles of the Target, Lead Vehicle and Following Vehicle over 40.0 sec of simulation interval obtained using the GM and the proposed model (PM) based on the same adjusted Target speed. Figure 5 illustrates the spacing between the Lead Vehicle and the Target, and the Lead Vehicle and the Following Vehicle over this same simulation interval obtained using the GM and the proposed model.

As shown in Figure 4 and 5, the reduction in the speed of the Target results in a corresponding reduction in the current spacing between the Target and the Lead Vehicle. The Lead Vehicle

driver perceives the reduction in the Target speed and the spacing between the Target and Lead Vehicle, and reduces his speed accordingly to match that of the Target. So also the reduction in the speed of the Lead Vehicle results in a corresponding reduction in the current spacing between the Lead and the Following Vehicle. The driver of the Following Vehicle also reacts in a similar fashion to reduce his or her speed to match that of the Lead Vehicle. In Figure 4, the Target, Lead, and Following Vehicle speeds are adjusted accordingly until a new equilibrium speed profile is established. This occurs when the vehicle and Target speeds are equal to each other. In Figure 5, the current spacing between the Target and the Lead Vehicle is reduced as a result of a reduction in the speed of the Target. However, when the Lead Vehicle speed and Target speed become equal, the current spacing between the Target and the Lead Vehicle stabilizes at its new equilibrium value. Similarly the spacing between the Lead Vehicle and the Following Vehicle is reduced and until it reaches at equilibrium where all speeds are equal.

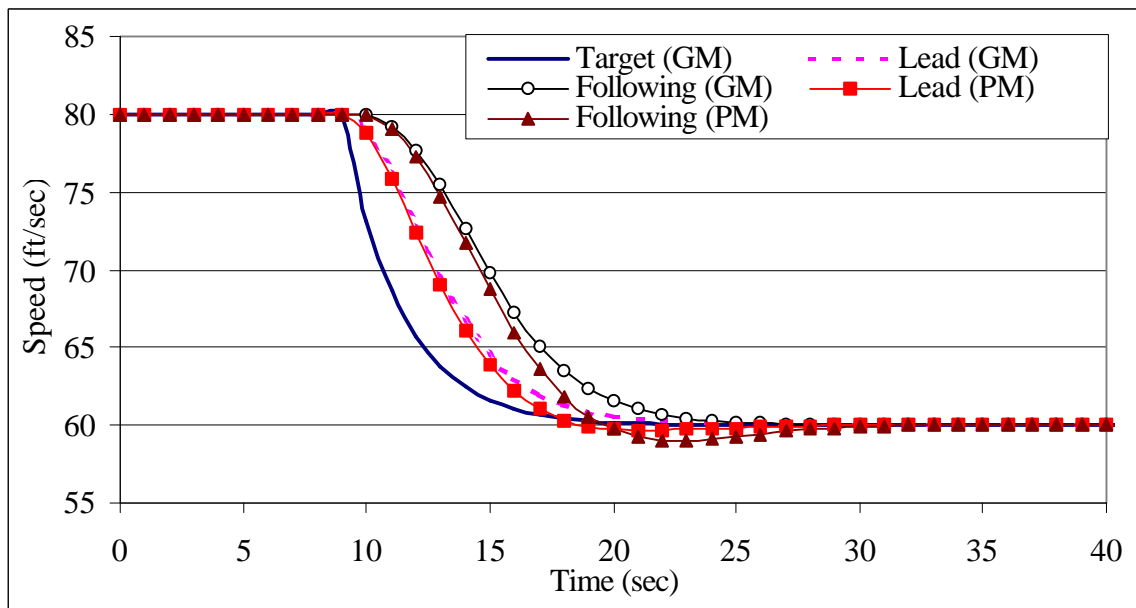


Figure 4: Speed profiles of the Target, Lead and Following vehicle obtained using GM and proposed model (PM) in experiment 1.

There are no dramatic difference in the results obtained from the GM model and the proposed model for this experiment. Both models reflect similar speed and spacing profiles. We note that for the proposed model the equilibrium spacing between the Target and the Lead Vehicle, and between the Lead and the Following Vehicle is higher than suggested by the GM car-following model. All vehicles are spaced at 90 ft for the former and 80 ft for the latter. The difference between 90 ft and 80 ft spacing reflects our assumption in the proposed model concerning driver preference as assumed in this application.

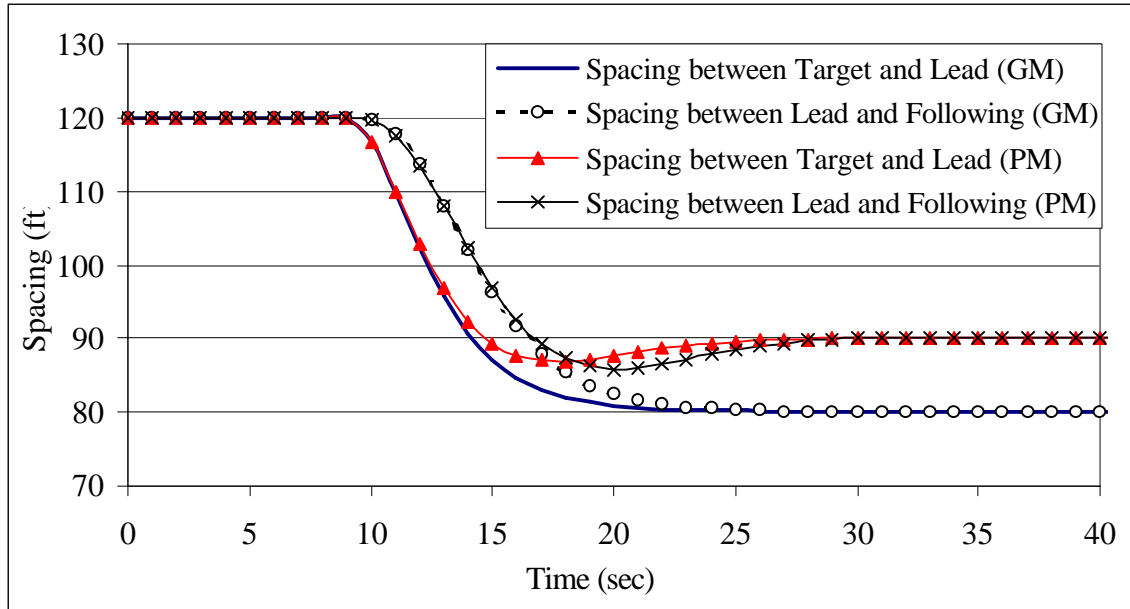


Figure 5: Spacing profiles obtained using GM and proposed model (PM) in experiment 1

Experiment 2:

In experiment 2, we assumed that the Target, the Lead, and the Following vehicle all are moving at a constant speed of 80 ft/sec with a spacing of 20 ft apart. Figure 6 and 7 shows the speed and spacing profiles obtained using the GM and PM model.

As shown in Figure 6, there is no variation in the speed profiles obtained using GM model. This is because GM model assumes that for zero relative speed the acceleration/deceleration response is zero regardless of the spacing between vehicles. However, according to the proposed model, when spacing at a particular speed is lower than desired spacing for that speed, the driver decelerates first and then accelerates to adjust the spacing to match with his or her desired spacing. This is shown in Figure 6, the Lead and the Following vehicles decelerates first to increase the spacing and then accelerate to match their spacing with their desired spacing. The variations in spacing profiles obtained using proposed model is shown in Figure 7, while spacing profiles obtained using GM model show no variation because speed of the Lead and the Following vehicle is unchanged.

These results reflect a type of "harmonic" relationship in drivers behaviour as they adjust their speeds and spacing to an equilibrium position in response to the Target position and speed. Drivers of the Lead and the Following Vehicles initially reduce their speeds dramatically to avoid a collision at the minimum spacing and then increase their speeds to a desired level, with the corresponding desired spacing. For this experiment the desired spacing is 120 ft between the Target and the Lead Vehicle, and between the Lead Vehicle and the Following Vehicle. This corresponds to desired spacing that we assumed in the model for a speed of 80 ft/sec. Under the GM car-following model the suggested spacing is 20 ft, which remains unchanged from our initial assumptions.

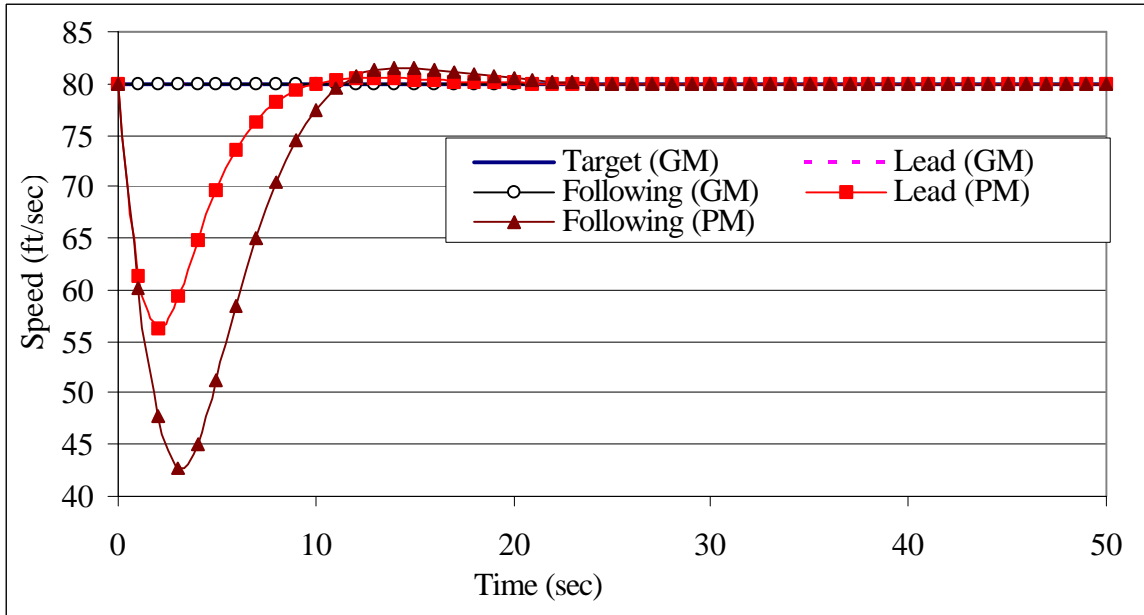


Figure 6: Speed profiles of the Target, Lead and Following vehicle obtained using GM and proposed model (PM) in experiment 2.

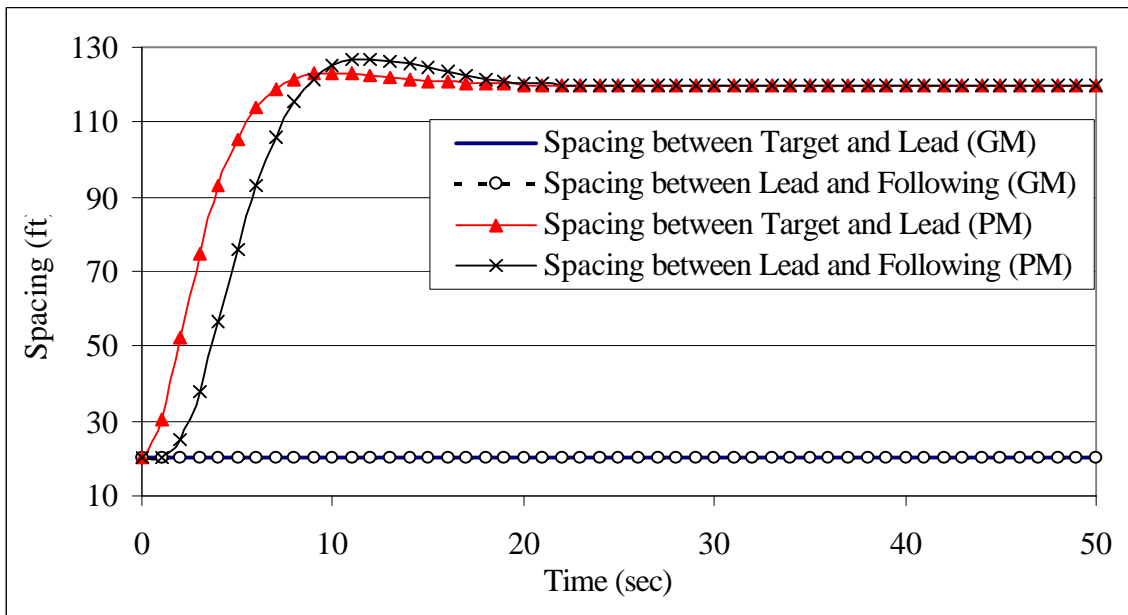


Figure 7: Spacing profiles obtained using GM and proposed model (PM) in experiment 2.

Experiment 3

In experiment 3, we assumed that the Target, the Lead, and the Following vehicle all are moving at a constant speed of 80 ft/sec with a spacing of 200 ft apart. Figure 8 and 9 shows the speed and spacing profiles obtained using the GM and proposed model.

As shown in Figure 8, there is no variation in the speed profiles obtained using GM model since relative speed is zero. However, according to the proposed model, when spacing is large, the driver accelerates first and then decelerates to reduce spacing to match with his or her desired spacing. This is shown in Figure 8, the Lead and the Following vehicles accelerates first to decrease the spacing and then accelerate to match their spacing with their desired spacing. The variations in spacing profiles obtained using proposed model is shown in Figure 9, while spacing profiles obtained using GM model show no variation because speed of the Lead and the Following vehicle is unchanged.

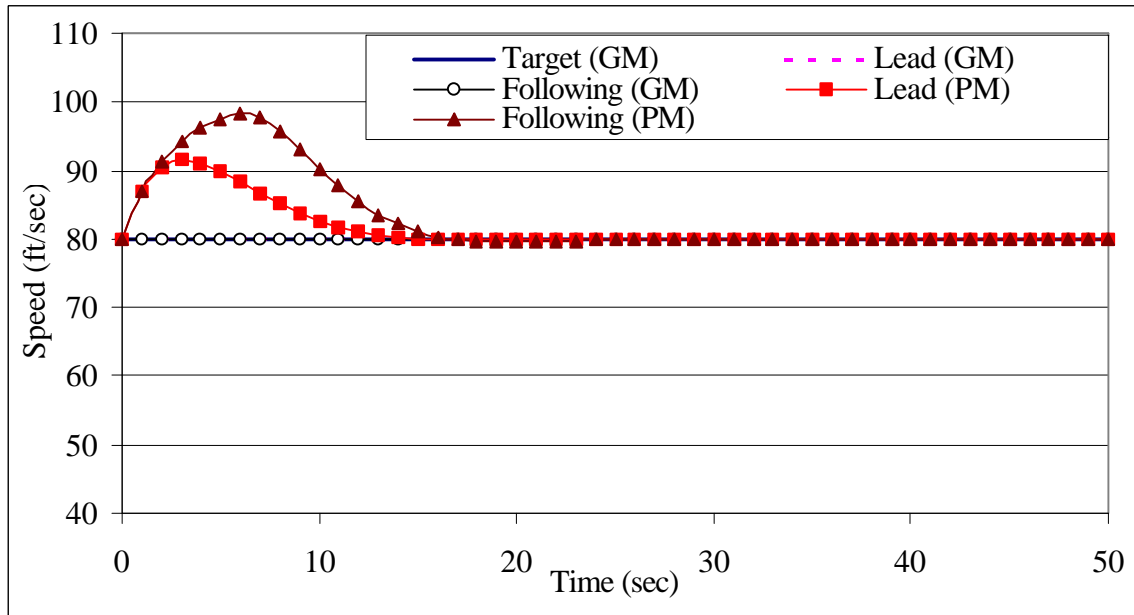


Figure 8: Speed profiles of the Target, Lead and Following vehicle obtained using GM and proposed model (PM) in experiment 3.

The results of experiment 4 also reflect a type of "harmonic" relationship in drivers behaviour as they adjust their speeds and spacing to an equilibrium position in response to the Target position and speed. Drivers of the Lead and the Following Vehicles initially increase their speeds at a given large spacing of 200 ft and then decrease their speeds to a desired level, with the corresponding desired spacing. In this experiment the desired spacing is also 120 ft between the Target and the Lead Vehicle, and between the Lead Vehicle and the Following Vehicle. This corresponds to desired spacing that we assumed in the model for a speed of 80 ft/sec. Under the GM car-following model the suggested spacing is 200 ft, which remains unchanged from our initial assumptions.

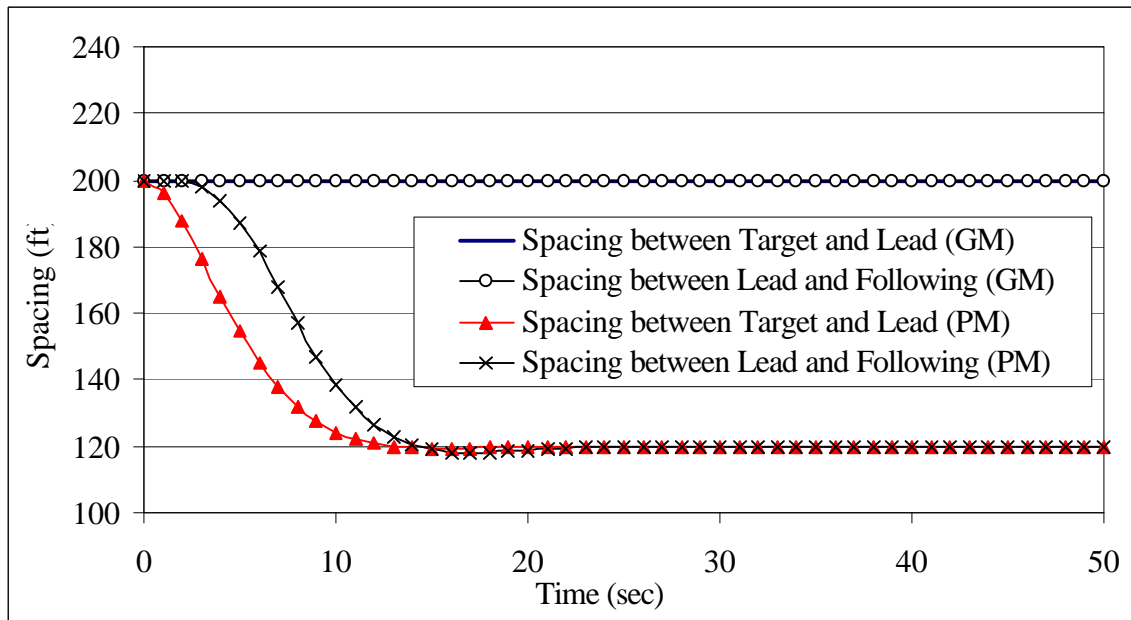


Figure 9: Spacing profiles obtained using GM and proposed model (PM) in experiment 3.

Experiment 4

In this experiment we assumed that initially the Target, the Lead, and the Following vehicle all are moving at a speed of 110 ft/sec with a spacing of 120 ft apart. Figure 10 and 11 shows the speed and spacing profiles obtained using the GM and proposed model.

As shown in Figure 10 and 11, there is no variation in the speed and spacing profiles obtained using the GM model since relative speed is zero. However, according to the proposed model, the Lead and the Following Vehicle driver adjust their speeds and spacing to their assumed desired levels. The desired speed in this experiment for both the Lead and the Following Vehicle is equal to the assumed speed limit (100 ft/sec) while the corresponding desired spacing for both the Lead and the Following Vehicle is 150 ft. In Figure 11, spacing between the Target and the Lead Vehicle is constantly increasing because speed of the Target is higher than the speed of the Lead Vehicle.

The results of experiment 4 reflect our assumption that drivers will not follow their Target if the speed of the Target is more than the speed limit. They will adjust their speeds and spacing according their desired levels. The GM car-following model suggests that drivers always follow their Target even if the speed of the Target is more than the speed limit.

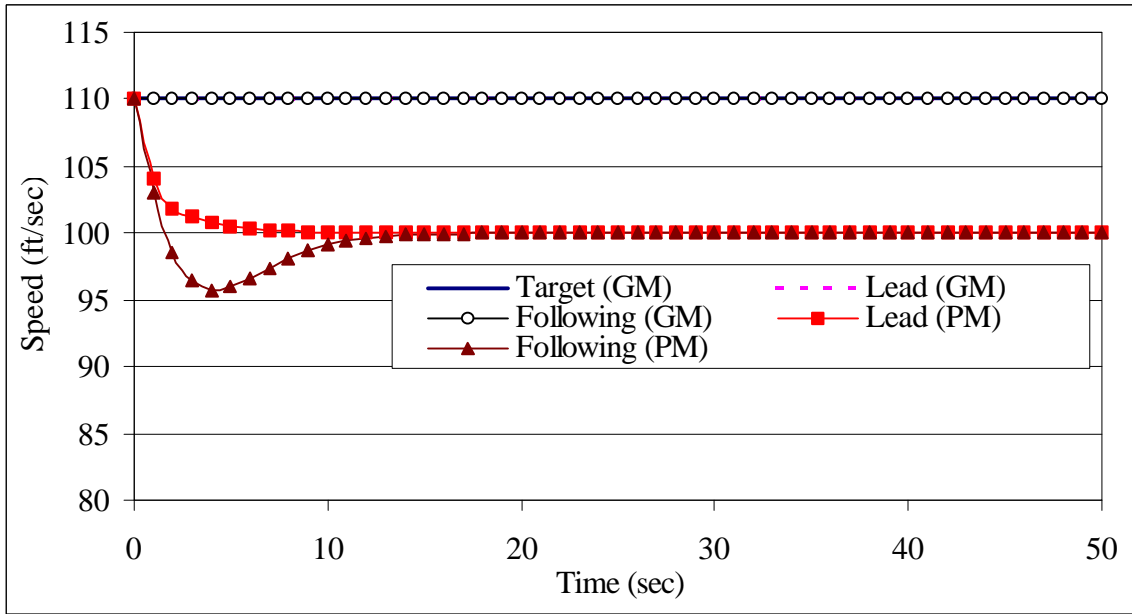


Figure 10: Speed profiles of the Target, Lead and Following vehicle obtained using GM and proposed model (PM) in experiment 4

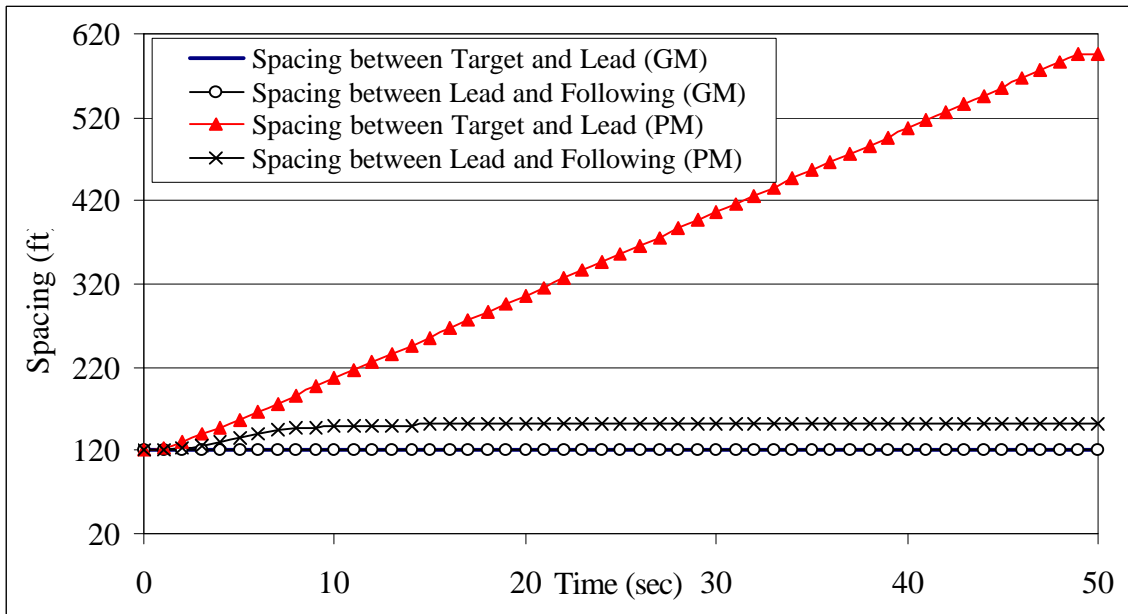


Figure 11: Spacing profiles obtained using GM and proposed model (PM) in experiment 4.

6.0 Conclusions

In this paper we have discussed a number of existing car-following models and have identified their several shortcomings. We have presented a revised car-following model based on System

Dynamics principles, which attempts to address many of these shortcomings. The proposed model assumes that drivers consider a longer view of the road ahead, rather than just the behaviour of vehicle immediately in front. The model also takes into account the driver's desired speed and spacing in relation to increased risk of collisions. In this paper we compared the speed and spacing profiles of different vehicles with respect to the speed and position of the Target. We conducted four experiments concerning speed and spacing of the Lead and Following Vehicle for different initial assumptions. For these experiments the speed and position of a Target Vehicle is given over the simulation period.

These experiments suggest that the proposed car-following model yields more realistic results than suggested by the existing GM car-following model. In the proposed model drivers seek to maintain the speed and spacing that is consistent with their understanding of the risks involved for any traffic situation. Obviously the experiments conducted in this exercise have been simplified for the purpose of demonstrating the proposed model.

In future we intend to carry out a thorough validation of the proposed car-following model with respect to observed micro-level vehicle tracking data.

Appendix-A: GM model equations:

Target Obstruction:

$$\text{Target_Speed}(t) = \text{Target_Speed}(t - dt) + (\text{Change_in_Target_Speed}) * dt$$

$$\text{INIT Target_Speed} = \text{Target_desired_speed}$$

INFLOWS:

$$\text{Change_in_Target_Speed} = (\text{Target_desired_speed} - \text{Target_Speed}) / \text{Time_to_Adjsut_Target_speed}$$

$$\text{Target_desired_speed} = 80 - \text{step}(20, 10)$$

$$\text{Time_to_Adjsut_Target_speed} = 2.5$$

Lead Vehicle:

$$\text{Lead_Vehicle_Speed}(t) = \text{Lead_Vehicle_Speed}(t - dt) + (\text{Change_in_Lead_Vehicle_speed}) * dt$$

$$\text{INIT Lead_Vehicle_Speed} = \text{Target_desired_speed}$$

INFLOWS:

$$\text{Change_in_Lead_Vehicle_speed} = (69 * \text{Lead_Vehicle_Speed} * (\text{Target_Speed} - \text{Lead_Vehicle_Speed})) / (\text{Spacing_between_Target_ \& _Lead})^2$$

Following Vehicle:

$$\text{Following_Vehicle_Speed}(t) = \text{Following_Vehicle_Speed}(t - dt) +$$

$$(\text{Change_in_Following_Vehicle_speed}) * dt$$

$$\text{INIT Following_Vehicle_Speed} = \text{Target_desired_speed}$$

INFLOWS:

$$\text{Change_in_Following_Vehicle_speed} = (69 * \text{Following_Vehicle_Speed} * (\text{Lead_Vehicle_Speed} - \text{Following_Vehicle_Speed})) / (\text{Spacing_between_Lead_ \& _Following})^2$$

Spacing sector:

$$\text{Spacing_between_Lead_ \& _Following}(t) = \text{Spacing_between_Lead_ \& _Following}(t - dt) +$$

$$(\text{Lead_Vehicle_Distance} - \text{Following_Vehicle_Distance}) * dt$$

$$\text{INIT Spacing_between_Lead_ \& _Following} = 120$$

INFLOWS:

$$\text{Lead_Vehicle_Distance} = \text{Lead_Vehicle_Speed} + 0.5 * \text{Change_in_Lead_Vehicle_speed} * dt$$

OUTFLOWS:

$$\text{Following_Vehicle_Distance} =$$

$$\text{Following_Vehicle_Speed} + 0.5 * \text{Change_in_Following_Vehicle_speed} * dt$$

$$\text{Spacing_between_Target_ \& _Lead}(t) = \text{Spacing_between_Target_ \& _Lead}(t - dt) +$$

$$(\text{Target_Distance} - \text{Lead_Vehicle_Distance}) * dt$$

$$\text{INIT Spacing_between_Target_ \& _Lead} = 120$$

INFLOWS:

$\text{Target_Distance} = \text{Target_Speed} + 0.5 * \text{Change_in_Target_Speed} * dt$

OUTFLOWS:

$\text{Lead_Vehicle_Distance} = \text{Lead_Vehicle_Speed} + 0.5 * \text{Change_in_Lead_Vehicle_speed} * dt$

Appendix-B Proposed model equations:

Target Obstruction:

$$\text{Target_Speed}(t) = \text{Target_Speed}(t - dt) + (\text{Change_in_Target_Speed}) * dt$$

$$\text{INIT Target_Speed} = \text{Target_desired_speed}$$

INFLOWS:

$$\text{Change_in_Target_Speed} = (\text{Target_desired_speed} -$$

$$\text{Target_Speed}) / \text{Time_to_Adjust_Target_Speed}$$

$$\text{Target_desired_speed} = 80 - \text{step}(20, 10)$$

$$\text{Time_to_Adjust_Target_Speed} = 2.5$$

Following Vehicle:

$$\text{Following_Veh_Speed}(t) = \text{Following_Veh_Speed}(t - dt) + (\text{Change_in_Following_Veh_speed}) * dt$$

$$\text{INIT Following_Veh_Speed} = \text{Target_desired_speed}$$

INFLOWS:

$$\text{Change_in_Following_Veh_speed} = (\text{Following_Veh_Req_speed_wrt_Lead} - \text{Following_Veh_Speed}) / \text{Perception_Reaction_Time_of_Following_Veh_driver} + ((\text{Target_Speed} - \text{Following_Veh_Speed}) / \text{Perception_Reaction_Time_of_Following_Veh_driver}) * \text{Eff_of_Target_on_Foll_Veh_speed}$$

$$\text{Following_vehicle_desired_spacing} =$$

$$\text{Following_Veh_Speed} * \text{Following_veh_Preferred_headway}$$

$$\text{Following_veh_Preferred_headway} = 1.5$$

$$\text{Following_Veh_Req_speed_wrt_Lead} =$$

$$\text{if}(\text{Lead_Veh_Speed} * \text{Eff_of_spacing_on_Foll_veh_required_speed}) > \text{Speed_limit} \text{ then}$$

$$\text{Speed_limit} \text{ else } (\text{Lead_Veh_Speed} * \text{Eff_of_spacing_on_Foll_veh_required_speed})$$

$$\text{Perception_Reaction_Time_of_Following_Veh_driver} = 2.5$$

$$\text{Eff_of_spacing_on_Foll_veh_required_speed} =$$

$$\text{GRAPH}(\text{Spacing_between_Lead_ \& _Following} / \text{Following_vehicle_desired_spacing})$$

$$(0.00, 0.00), (0.167, 0.26), (0.333, 0.47), (0.5, 0.64), (0.667, 0.78), (0.833, 0.9), (1, 1.00), (1.17,$$

$$1.09), (1.33, 1.17), (1.50, 1.23), (1.67, 1.28), (1.83, 1.31), (2.00, 1.33)$$

$$\text{Eff_of_Target_on_Foll_Veh_speed} =$$

$$\text{GRAPH}(\text{Spacing_between_Following_vehicle_and_Target} / \text{Following_vehicle_desired_spacing})$$

$$(0.00, 1.00), (0.0833, 0.72), (0.167, 0.52), (0.25, 0.385), (0.333, 0.295), (0.417, 0.22), (0.5,$$

$$0.165), (0.583, 0.125), (0.667, 0.09), (0.75, 0.065), (0.833, 0.04), (0.917, 0.02), (1.00, 0.00)$$

Lead Vehicle:

Lead_Veh_Speed(t) = Lead_Veh_Speed(t - dt) + (Change_in_Lead_Vehicle_speed) * dt
INIT Lead_Veh_Speed = Target_desired_speed
INFLOWS:
Change_in_Lead_Vehicle_speed = (Lead_Veh_Req_speed - Lead_Veh_Speed) / Perception_Reaction_time_of_Lead_veh_driver
Lead_vehicle_desired_spacing = Lead_Veh_Speed * Lead_Veh_Preferred_headway
Lead_Veh_Preferred_headway = 1.5
Lead_Veh_Req_speed =
if((Target_Speed * Eff_of_spacing_on_Lead_veh_required_speed) > Speed_limit) then
Speed_limit else (Target_Speed * Eff_of_spacing_on_Lead_veh_required_speed)
Perception_Reaction_time_of_Lead_veh_driver = 2.5
Speed_limit = 100
Eff_of_spacing_on_Lead_veh_required_speed =
GRAPH(Spacing_between_Target_&_Lead / Lead_vehicle_desired_spacing)
(0.00, 0.00), (0.167, 0.26), (0.333, 0.47), (0.5, 0.64), (0.667, 0.78), (0.833, 0.9), (1, 1.00), (1.17,
1.09), (1.33, 1.17), (1.50, 1.23), (1.67, 1.28), (1.83, 1.31), (2.00, 1.33)

Spacing sector:

Spacing_between_Lead_&_Following(t) = Spacing_between_Lead_&_Following(t - dt) +
(Lead_Vehicle_distance - Following_vehicle_distance) * dt
INIT Spacing_between_Lead_&_Following = Following_vehicle_desired_spacing
INFLOWS:
Lead_Vehicle_distance = Lead_Veh_Speed + 0.5 * Change_in_Lead_Vehicle_speed * dt
OUTFLOWS:
Following_vehicle_distance =
Following_Veh_Speed + 0.5 * Change_in_Following_Veh_speed * dt
Spacing_between_Target_&_Lead(t) = Spacing_between_Target_&_Lead(t - dt) +
(Target_distance - Lead_Vehicle_distance) * dt
INIT Spacing_between_Target_&_Lead = Lead_vehicle_desired_spacing
INFLOWS:
Target_distance = Target_Speed + 0.5 * Change_in_Target_Speed * dt
OUTFLOWS:
Lead_Vehicle_distance = Lead_Veh_Speed + 0.5 * Change_in_Lead_Vehicle_speed * dt
Spacing_between_Following_vehicle_and_Target =
Spacing_between_Lead_&_Following + Spacing_between_Target_&_Lead

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