Microscopic Modeling of Driver Behavior in Uninterrupted Traffic Flow

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Abstract: In this paper a comprehensive microscopic model of driver behavior in uninterrupted traffic flow is developed. The model aims to explain or predict the actions of a driver in a variety of driving scenarios ranging from free flow conditions on wide roads to forced flow conditions on narrow two-way roads. The salient features of the proposed theory are (1) a single model (or framework) is used to describe driver behavior in different driving scenarios and (2) the response of drivers through both steering control and speed control are modeled. Driver behavior is simulated in 19 different driving scenarios. Results from these simulations show the efficacy of the proposed model in explaining/predicting driver behavior.


CE Database subject headings: Driver behavior; Traffic models; Traffic flow.

Introduction

A microscopic theory of traffic flow attempts to model driver behavior with the purpose of predicting the actions of a driver in a given scenario. In the past, various theories on driver behavior have been proposed; most of them relate to driver behavior in car-following situations where the driver is forced to follow a slow moving vehicle (for example, see Pipes 1953, 1967; Chandler et al. 1958; Forbes et al. 1958; Gazis et al. 1959, 1961; Herman et al. 1959; Herman and Potts 1959; Forbes 1963; Rockwell et al. 1968; Kikuchi and Chakroborty 1992; Fritzschke 1994; Aycin and Benekohal 1998; Chakroborty and Kikuchi 1999). Some work has also been done on how drivers react to obstacles on their path (for example, see Michaels and Gozan 1963; Taragin 1955). Recently, some work is being carried out in the area of cellular automata based traffic simulation (Nagel and Schreckenberg 1992; Wahle et al. 2001); however, their validity as realistic microscopic models of driver behavior is questionable. Nonetheless, to date, no theory exists that can model driver behavior in a comprehensive manner. That is, in a manner by which the same model can predict a driver’s behavior in a variety of driving scenarios ranging from free flow conditions to forced flow conditions in two-way traffic.

In this paper, an attempt is made to develop such a comprehensive microscopic model of driver behavior. Results on the lateral positions and speeds of a vehicle (as obtained from the proposed model) in 19 different driving scenarios are presented. The results show that the proposed model can, with a single description of driver behavior, predict the actions of a driver in a variety of driving scenarios.

The paper is divided into six sections, of which this is the first. The next section describes the behavior of humans while driving and relates it to the properties which any comprehensive microscopic model of driver behavior should possess. The section “Existing Models of Driver Behavior” briefly describes and critically reviews some of the important existing models of driver behavior. The section “Proposed Model” describes in detail the development of the proposed comprehensive model. This is followed by the section “Results.” The last section concludes with a summary of the findings of this work.

Desirable Features of a Comprehensive Microscopic Model of Driver Behavior

This section discusses various aspects of driver behavior. Based on this discussion as the backdrop, this section also identifies the features desirable in a comprehensive microscopic model of driver behavior.

Driver Behavior

While driving, humans constantly perceive their immediate driving scenario and react accordingly. It is hypothesized that a driver’s actions in a given scenario are motivated by two factors: (1) the driver’s concern for safety and (2) the driver’s urge to reach his or her destination as soon as possible. One’s concern for one’s own safety is a basic human trait and hence the first assumption does not require any justification. The second assumption of urgency comes from the idea that nobody wants to spend extra time in reaching their destination. This is not a new paradigm in transportation and is ingrained in many accepted principles of transportation, most notably the Wardrop’s principle. One may argue, perhaps rightly, that the second assumption is more applicable to commuting drivers on work trips. Nonetheless, it is felt that these two factors (assumptions) together with the existing traffic rules largely determine the perception-reaction mechanism of every driver in all driving scenarios.
The problem at hand, therefore, is to develop a model which uses these factors to predict the observed behavior of drivers in different driving situations. In the following some of the “standard” observed behaviors of drivers are identified. It is felt that any comprehensive microscopic model of driver behavior should be able to predict/explain these behaviors. In other words, these “standard” behaviors form the desirable features of a comprehensive microscopic model of driver behavior.

**Desirable Features of a Comprehensive Model**

In this section, some of the standard behaviors of drivers (or alternatively, the desirable features of any comprehensive microscopic model of driver behavior) are identified. The description of the behaviors given here are based on number of observations in India and in the United States and can be easily verified by observing any traffic stream.

**Driver Behavior in Free Flow Conditions**

In free flow conditions drivers do not face any constraints from other vehicles. The only features of the driving environment that affect the driver’s behavior are the road edges (alternatively the road width which defines how far are the road edges), curves, lane markings, potholes (especially in developing countries), and other static obstacles like parked vehicles, lane barriers, etc. The fact that these driving environment features affect driver behavior are well known and documented (for example, see Highway Capacity Manual 1998).

The way in which these driving environment features affect the driver behavior are summarized below. Any microscopic model of driver behavior should exhibit these properties.

1. On a road without lane markings a driver tends to stay on one side of a road (the preferred side depends on the practice of the country (traffic rules)—for example, drivers in the United Kingdom and India use the left side whereas drivers in the United States use the right side of the road). However, as the road width reduces drivers tend to veer toward the center of the road. Further, the speeds of the vehicles reduce as the road narrows;

2. Like road edges, lane markings are generally visualized as delineation of a space in which the vehicle should drive. They however differ from road edges in the sense that transgressing a lane marking does not pose as much threat to safety as transgressing a road edge does. Thus, it is seen that drivers tend to be closer to the lane marking if the other side is a road edge; and

3. When static obstacles (like parked vehicles, potholes, etc.) are present, vehicles tend to avoid them by moving either to the left or to the right. The extent and direction of the lateral movement depend on the size of the obstacle and its location with respect to the path of the vehicle. Further, the vehicle sometimes slows down while avoiding the obstacle, depending on the road width and other factors.

**Driver Behavior in Car-Following Situations**

Car-following is a driving situation where a driver is forced to follow another vehicle (the leading vehicle, LV) at speeds lower than the desired speed of the driver. The behavior exhibited by a driver in such situations has been studied amply in the past. A good discussion on car-following behavior of drivers may be found in Chakroborty and Kikuchi (1999). Few of the more important aspects of this behavior are mentioned here.

1. Stability: There exists a stable condition—a condition in which the following vehicle (FV) travels at the same speed as that of the LV and maintains a distance headway considered “safe” for the speed at which the vehicles are traveling;

   • Local Stability: The actions of the driver of FV in response to the actions of LV are such that, once the LV starts maintaining a constant speed (after varying the speed for some time), the distance headway and relative speed eventually converge to the “safe” distance headway and zero, respectively, and

   • Asymptotic Stability: The actions of the drivers of successive FVs, in a platoon of vehicles, in response to the actions of the vehicle ahead are such that the perturbations to the stable condition introduced by the actions of the leader of the platoon get damped (or reduce) as the perturbations are transmitted upstream in the platoon.

2. Closing-In and Shying-Away: Irrespective of the actions of the LV, the driver of FV makes appropriate changes in speed if he/she finds the distance headway between the vehicles (LV and FV) to be larger or smaller than the “safe” distance headway. If the headway is larger than the “safe” distance headway then the FV closes in, or if the headway is smaller than the “safe” distance headway then the FV shies away.

**Driver Behavior in Passing (Overtaking) Situations**

Driver behavior in passing situations, referred to as passing or overtaking behavior, is a behavior exhibited by the driver of a FV when the driver gets an opportunity to go past a slow moving LV. The behavior assumes importance as an area of study, when in order to pass (overtake) the LV, the driver of the FV has to move into the opposing lane.

**Driver Behavior in the Presence of On-Coming Vehicles**

Drivers behave differently when they are on narrow two-way roads. Drivers tend to drive closer to the center line of the road when there are no on-coming or opposing vehicles. However, when there is an on-coming vehicle, both the drivers move toward their respective road edges as the vehicles close in and then back toward the center line once they have crossed each other. This behavior also has an effect on the speed of the vehicles, which generally reduce as the vehicles approach and cross each other.

**Existing Models of Driver Behavior**

The existing literature in traffic flow theory is devoid of any comprehensive model of driver behavior. That is, there are no models which can, within a single framework, explain all the behaviors described in the previous section. There are, however, models of driver behavior which try to describe or explain only a particular aspect of driving. For example, in the last five decades a lot of models of driver behavior in car-following situations have been developed; these were referred to in the Introduction. A good review of the car-following models may be found in Brackstone and McDonald (1999). Taragin (1955) and Michaels and Gozan (1963) also did some work on driver’s behavior with respect to lateral displacement in the presence of obstacles.

None of the above models are, as stated earlier, comprehensive models of driver behavior. This lack of a single framework to model driver behavior in different driving situations motivated the writers to explore the possibility of developing a single model capable of describing driver responses in a variety of driving scenarios.
Proposed Model

Any comprehensive microscopic model of traffic flow can only be based on the most basic and general assumptions on driver behavior. As suggested earlier, it is felt that the response of drivers in all situations are motivated by two basic factors—safety and urgency (i.e., one’s urge to reach one’s destination as soon as possible). These are the two factors which then give rise to the “single” behavioral pattern of drivers, the ramifications of which can be observed in different forms in different driving situations.

In the following sections, a theory or model of this “single” behavioral pattern of drivers is developed. The section on results show how this model can predict the behavior of drivers in different driving situations.

General Framework

In this section, a framework which can formalize the concepts of “safety” and “urgency” as factors determining a driver’s responses in different driving situations is constructed step-by-step. The framework erected here is in part motivated by the concepts of potential field theory based robot path planning. An excellent discussion on this topic may be found in Latombe (1991).

Step-by-Step Construction of the Proposed Framework

1. It is assumed that the behavior of a driver in any driving situation can be completely described by specifying over a period of time the lateral positions and the speeds of the vehicle being driven by the driver. The driver whose behavior is being studied is referred to as the test driver (TD); and the vehicle driven by the TD is referred to as the test vehicle (TV);

2. A driving situation or driving environment is generally characterized by different roadway and traffic features in the vicinity of the TD. The term “roadway features” include features such as road width, curvature of road, road surface conditions, shoulder width, etc. The term “traffic features” include features such as parked vehicles and other moving vehicles. In addition to the roadway and traffic features, a driving environment may in certain conditions (such as when a driver wants to turn at an intersection) include an immediate goal—a point on the road which is preferred by the TD due to a variety of reasons;

3. All roadway and traffic features are viewed as obstacles, either dynamic or static;

4. Each obstacle poses a threat to the safety of the TD. Hence, each obstacle is assumed to emanate, around it, a positive potential field (repulsive force field) which repels the TD. A goal is assumed to emanate, around it, a negative potential field (attractive force field) which attracts the TD. The potential field emanated by an object i (an object is either an obstacle or a goal) is denoted by $U_i(x,y)$, where, $x$ is the lateral distance of a point (on the road) from the left edge (with respect to the direction of TVs motion) of the road and $y$ is the longitudinal distance of the point from an arbitrary upstream (with respect to the direction of TVs motion) location on the road;

5. The shape and strength of the potential field emanated by an obstacle depend on the properties of the obstacle. For example, the potential field due to a parked vehicle may be less pronounced than the potential field emanated by a truck coming in the opposing direction;

6. The potential at any point on the road, $U(x,y)$ is the algebraic sum of the potentials at that point on the road due to all the obstacles and goal present in the driving environment. That is

$$U(x,y) = \sum U_i(x,y) \quad (1)$$

7. The potential at a point may be viewed as the resistance posed by that point to the motion of TV (or the threat to safety as perceived by the TD). It is also known that a driver reduces one’s speed as the threat to one’s safety increases.

Hence, it is assumed that an inverse relation exists between the sustainable speed, $V_s(x,y)$ at a point on the road and the potential at that point. The term sustainable speed of a point means the speed at which a driver feels comfortable at that point given his/her immediate driving scenario;

8. A road is divided into many transverse cross-sections; the distance $h$ between two contiguous cross-sections could be arbitrarily small. The TV is assumed to move from one cross-section to the next; and

9. Given the lateral position of a vehicle, its orientation, and the maximum steering angle of a vehicle, only certain points of the next cross-section are accessible by the vehicle. These points of the next cross-section are referred to as the accessible points.

The foregoing discussion proposes a framework which formalizes the concepts of “safety” and “urgency” and based on which the comprehensive model of driver behavior is developed. It is apparent from the above discussion as to how the proposed framework formalizes the concept of “safety”—recall, the potential at any point on the road indicates how “unsafe” that point is. However, the formalization of “urgency” is hidden in the concept of sustainable speed and its relation with the potential. This formalization becomes apparent in the forthcoming discussions on the model.

In the next section two submodels, termed as response models are presented. These models predict the response of the drivers through (1) steering control and (2) choice of acceleration or deceleration rate in a given driving situation. The response models are developed on the basis of the general framework presented here.

Response Models

As stated before, two response models are presented here. The first model is named the Steering Response Model (SRM) as it predicts the choice of steering angles (over time) by a driver in a given driving situation. The second model is referred to as the Acceleration Response Model (ARM) as it predicts the acceleration/deceleration rates (over time) of a driver in a given driving situation.

Steering Response Model

The purpose of the SRM is to predict the responses of the driver achieved through steering control. In other words, the SRM aims at predicting the lateral positions of the TV on the road over time. That is, the final outcome of the SRM should be the position profile of the TV in a given driving situation.

The proposed SRM predicts the position of the TV in the next cross-section (say the $n$th cross-section) based on following information:

1. The position of the TV in the present cross-section [say the $(n-1)$-th cross-section];

2. The orientation of the TV in the present cross-section (the
angle \( \theta_{n-1} \), which indicates orientation, is measured from a line parallel to the longitudinal axis of symmetry for the road section being looked at) and;

3. The maximum steering angle of the TV, \( \theta_{\text{max}} \) (which need not always be a constant and could very well be a function of the speed of TV).

The proposed model is best explained with the help of the schematic shown in Fig. 1. The figure shows the current orientation of TV, \( \theta_{n-1} \), and its current location; \( (x_{n-1}, y_{n-1}) \). Note that the subscripts are added to the coordinates in order to remind the readers as to which cross-section the TV is currently in. The figure also shows the set of accessible points \( A_n \) in the next cross-section. As can be seen from the figure, the set \( A_n \) can be obtained using the following equation:

\[
A_n = \{(x_n, y_n) | x_{n-1} - h \tan(\theta_{\text{max}} - \theta_{n-1}) \leq x_n \leq x_{n-1} + h \tan(\theta_{\text{max}} + \theta_{n-1}), y_n = y_{n-1} + h \}
\]

The predicted location of TV in the next cross-section, \( (x_n^*, y_n^*) \), can be deduced from the concept of “urgency” and the assumption that sustainable speed at a point is inversely related to the potential at that point. From this it can be directly stated that drivers will choose that point of the next cross-section which is accessible and offers the least potential among all accessible points. That is, \( (x_n^*, y_n^*) \) is a point which satisfies the following property:

\[
U(x_n^*, y_n^*) = \min_{(x_n, y_n) \in A_n} U(x_n, y_n)
\]

**Acceleration Response Model**

The purpose of the ARM is to predict the acceleration/deceleration rates of TV over time in different driving situations. It is assumed that TVs acceleration/deceleration rate at time \( t + \Delta t \) (where \( \Delta t \) is the perception/reaction time of the TD and can be a function of various factors like driver type, fatigue, etc.), \( \dot{\chi}(t + \Delta t) \), is determined by the following two factors: (1) the rate of change of potential being faced by the TD at time \( t \), \( \dot{\chi}(t) \), and (2) the difference between the sustainable speed \( V_s(t) \) and the actual speed \( V_a(t) \), of the TV at time \( t \).

Before going into the rationale for the assumptions, it may be pointed out that the notation used here is with respect to time (this is done since the model deals with derivatives of quantities with respect to time). This, however, poses no special problems since, at any particular time, the TV occupies a particular position on the road and hence there exists a one-to-one correspondence between \( U(t) \) and \( U(x,y) \), and \( V_s(t) \) and \( V_a(t) \). That is, \( U(t) = U(x^*, y^*) \) and \( V_s(t) = V_a(x^*, y^*) \), where \( (x^*, y^*) \) is the position of the TV at time \( t \).

The rationale for choosing \( \dot{\chi}(t) \) and \( V_s(t) - V_a(t) \) as the factors which affect \( \dot{\chi}(t + \Delta t) \) comes from the basic understanding of how drivers control their speed while driving. It is well understood that the extent to which a driver reacts (by accelerating or decelerating) depends on how quickly the vehicle is approaching (or receding from) an obstacle or, more generally, a more constrained driving environment. The reason \( V_s(t) - V_a(t) \) affects the actions of the TD is because it gives the driver a sense of whether the driver is going too fast or too slow for the conditions in which the driver is driving. If \( V_s(t) \) (i.e., the speed at which the TD is driving) is less than \( V_a(t) \) (the sustainable or safe speed) then the TD can go faster (thereby reducing the travel time) without sacrificing on safety and hence TD will accelerate; on the other hand, if \( V_a(t) - V_s(t) \) then the TD will feel unsafe and will reduce the speed.

Mathematically, the model proposed here is as follows:
In the equation, the term $\alpha$ is a parameter which indicates whether or not the TV is driving in a condition constrained by other dynamic obstacles (which, it is felt, drivers view differently than static obstacles). The value of $\alpha$ varies from 0 to 1; $\alpha=0$ if the driver is in a “free flow” like situation (i.e., with few or no dynamic obstacle), $\alpha=1$ if the driver is in a complete “constrained flow” situation (i.e., with dynamic obstacles in its vicinity), $\alpha$ is between 0 and 1 if the driving scenario is between free flow and constrained flow situations.

The parameter $\beta(t)$ is a sensitivity parameter for the first term in brackets. It is assumed that the TD is more sensitive in situations where the TD feels unsafe, i.e., $\beta(t)$ is higher if the TD faces a potential (at time $t$) which is higher than the potential for which the actual speed (at time $t$) is the sustainable speed. Keeping this in mind the following expression is proposed for the determination of $\beta(t)$:

$$\beta(t) = 1 + \frac{U(t) - f^{-1}[V_a(t)]}{d}$$

The function $f(\cdot)$ is a function relating the potential at a point to the sustainable speed at that point (also see Item 7 in the “General framework” section). The parameter $d$ is a user-specified constant used to ensure that $\beta(t)$ does not become negative in practical situations.

The parameters $k_1$ and $k_2$ are constants which specify the relative effect of the two factors (of the term inside the brackets) on the actions of the TD. These are user-specified (calibration) constants.

From the above discussion on the SRM and ARM it becomes amply clear that one of the key aspects of the models is the potential on the road. As described earlier, the potential on the road is defined by the potentials emanated by the obstacles (or features) and the goals on the road. The potential emanated by an obstacle or a goal is described through the potential field function for that obstacle or goal. Different kinds of obstacles (like road edges versus moving vehicles) have different potential field functions. In the next section the potential field functions for some of the basic types of obstacles faced by drivers and the potential field function for goals are described.

### Potential Field Functions

In this section, the proposed potential field functions (PFFs) which describe the potentials emanated by the following kinds of commonly encountered obstacles are presented: (1) road edges; (2) lane markings; (3) static obstacles (like potholes, parked vehicles, etc.); (4) dynamic obstacles of Type I (these are vehicles which move in the same direction as that of the TV; such vehicles are denoted as same direction vehicles or SDV); and (5) dynamic obstacles of Type II (these are vehicles which move in the opposite direction to that of the TV; such vehicles are denoted as opposite direction vehicles or ODVs). In addition to the above types of obstacles the PFF for a goal is also presented here.

### Potential Field Functions for Road Edges

Every road has two edges, the left edge (LE) and the right edge (RE) which mark the physical boundaries of a road. These are, therefore, treated as obstacles by the drivers. It is logical to assume that as a driver goes closer to an edge the repulsive force (or positive potential) faced by the driver due to that road edge increases and vice versa. Further, the potential at a point due to a road edge should only depend on the lateral distance of the point from the road edge. Based on these, the following form for the PFF is proposed (although any other function which satisfies the above requirements can also be used):

$$U_{LE}(x,y) = a_1 e^{-b_1 x}$$

$$U_{RE}(x,y) = a_2 e^{-b_2 (w-x)}$$

Here, $x$ and $y$ have their usual meanings; $w=$ width of the road (this makes $w-x$ as the distance from the right edge); and $a_1$, $a_2$, $b_1$, and $b_2$ = positive constants which control the shape of the functions. Since all roads have necessarily two edges it is more convenient to look at a pair of road edges as a whole and express the PFF due to the pair of road edges, $U_E(x,y)$ as the sum of $U_{LE}(x,y)$ and $U_{RE}(x,y)$.

$$U_E(x,y) = a_1 e^{-b_1 x} + a_2 e^{-b_2 (w-x)}$$

### Potential Field Functions for Lane Markings

As lane markings act as boundaries for a vehicle’s travel path, the PFF for them must be similar to that of road edges. However, there are two distinctions, (1) the PFF for lane markings, $U_{LM}(x,y)$ has two parts, one extending to the left of the lane marking, $U_{LLM}(x,y)$, and the other to the right of the lane marking, $U_{RLM}(x,y)$, since a lane marking affects vehicles traveling on either side of it and (2) the magnitude of the PFF and the distance to which it extends should be much lesser than that of the PFF for road edges; this is so, because unlike the road edges lane markings are not physical boundaries of a road and violating them does not always pose a major safety hazard.

The proposed PFF for lane markings is as follows:

$$U_{LM}(x,y) = \begin{cases} 
U_{LLM}(x,y) = c_1 + c_2 e^{-b_3 (x-x_{LM})} & \text{if } x \leq x_{LM} \\
U_{RLM}(x,y) = c_2 + c_4 e^{-b_4 (x-x_{LM})} & \text{if } x > x_{LM} 
\end{cases}$$

where, $x_{LM}=$ distance of the lane marking from the left edge of the road and $x$ and $y$ have their usual meanings; the parameters $c_1$, $c_2$, $c_3$, $c_4$, $b_3$, and $b_4$ are user-specified (calibration) constants which control the shape of the PFF.

### Potential Field Functions for Static Obstacles

Unlike the lane markings and road edges which stretch over a long distance, static obstacles are defined over a small space. Consequently, the PFF emanated by them should look like a symmetric hill (with the obstacle in the middle) with higher potentials near the obstacle and lower potentials away from it. The shape and size of the PFF obviously depends on the size and nature of the static obstacle. The general form of the PFF for static obstacles, $U_{SO}(x,y)$ proposed here is as shown. It may be pointed out that the shape of the PFF given in Eq. (10) is like a flat-topped symmetric hill.

$$U_{SO}(x,y) = a_5 e^{-b_5 [(x-x_0/m_1)^2 + (y-y_0/m_2)^2]} \mu_1$$

where, $(x_0,y_0)$ = location of the static obstacles (SO), and $a_5$, $b_5$, $m_1$, and $m_2$ = user-specified (calibration) constants which control the shape of the PFF, these constants take different values for different types of static obstacles like potholes, parked vehicles of different sizes, etc. The constant $\mu_1$ is a binary constant indicating whether or not a point $(x,y)$ is very close to the obstacle, in such cases $\mu_1 = 0$, otherwise $\mu_1 = 1$. Mathematically,
Potential Field Functions for Dynamic Obstacles of Type I
A SDV is, as stated earlier, a dynamic obstacle which is moving in the same direction as that of the TV. The effect of such obstacles is more pronounced in the longitudinal direction than in the transverse direction. Further, the TV feels the effect (of the SDV) over a longer distance when it is behind the SDV than when it is in front of it. Based on these observations and the general driving experience the proposed form for the PFF for SDV, $U_{SDV}(x,y)$, is shown in Fig. 2. The figure shows a contour plot for $U_{SDV}(x,y)$ (the potential values for each contour line is written on the line) for a given set of parameter values for the function $U_{SDV}(x,y)$. The algebraic description of the function serves little in helping the reader to visualize the nature of the PFF, and hence, it is omitted here. The details of the function can be found in Agrawal (2000).

Potential Field Functions for Dynamic Obstacles of Type II
An ODV is, as stated earlier, a dynamic obstacle which is moving in the opposite direction to that of the TV. The effect of such obstacles is more pronounced in the longitudinal direction than in the transverse direction. Further, the TV feels the effect (of the ODV) over a longer distance when it is approaching the ODV than when it has crossed the ODV. Based on these observations and the general driving experience the proposed form for the PFF for ODV, $U_{ODV}(x,y)$, is shown in Fig. 3. The figure shows a contour plot for $U_{ODV}(x,y)$ for a given set of parameter values for the function $U_{ODV}(x,y)$. The algebraic description of the function serves little in helping the reader to visualize the nature of the PFF, and hence, it is omitted here. The details of the function can be found in Agrawal (2000).

Potential Field Functions for Goals
A goal is a point on the road (for example, the point may be “in front of the vehicle ahead”) which the driver, for some reason, prefers. That is, the goal may be thought of as a point which attracts the driver. Hence, it emanates an attractive force or a negative potential. Further, the strength of the pull should increase as the lateral distance from the goal increases, and at any given lateral distance the pull should decrease as the longitudinal distance from the goal increases. This is so, because when longitudinal distances are larger the TD realizes that the lateral deviation from the goal can be covered over a longer distance and therefore is affected to a lesser degree by the deviation from the goal. Based on this understanding of the desirable effect of a goal on the TD the proposed form for the PFF for goal, $U_{G}(x,y)$, is shown in Fig. 4. The figure shows a contour plot for $U_{G}(x,y)$ for a given set of parameter values for the function $U_{G}(x,y)$. The algebraic description of the function serves little in helping the reader to visualize the nature of the PFF, and hence, it is omitted here. The details of the function can be found in Agrawal (2000).

Results
In this section results from simulations of driver behavior (using the proposed model) in the following driving scenarios are presented:

1. Free flow conditions
   • Case I: Roads with different widths,
   • Case II: Roads with lane markings, and
   • Case III: Roads with static obstacles like parked vehicles or potholes.

2. Forced (constrained) flow conditions
   • Case IV: Car-Following situations,
   • Case V: Passing (overtaking) situations, and
   • Case VI: Bidirectional flow with the streams not strictly separated; for example, driver behavior in the presence of oncoming vehicle on narrow (or local) roads.

As stated earlier, in this paper it is assumed that the behavior of a driver (say, the TD) can be completely described by specifying the lateral positioning of the vehicle (the TV) over time.

\[
\mu_i = \begin{cases} 
1 & \text{if } \left(\frac{x-x_0}{m_i} \right)^2 + \left(\frac{y-y_0}{m_a} \right)^2 \geq 1 \\
0 & \text{otherwise} 
\end{cases}
\]
(henceforth referred to as position profile) and speed of the vehicle over time (henceforth referred to as speed profile). However, owing to space restrictions, results on both position profile and speed profile are presented only for the cases where it is essential to look at both. Otherwise, either position profile or speed profile results are presented.

Another point that may be noted here is that in the presentation of the results the constants of the PFF’s are chosen (see explanation under Case I discussions) such that the drivers prefer to be closer to the left edge of the road than the right edge. This choice is motivated by the fact that in India, like in the United Kingdom, drivers follow the “keep left” policy while driving.

The exact values of the parameters assumed for the purposes of obtaining the results are stated in each of the cases. The values are assumed based on the understanding of the driving process and preliminary observations on driving behavior under similar circumstances. The behavior of the TD can be changed by changing these constants. That is, the output from the model can be made to fit the observed behavior by calibrating the various constants of the model. Further, the relation \( f(\cdot) \) [see Eq. (5)] is assumed to be of the following form:

\[
V_s(x,y) = f(U(x,y)) = p_1 - p_2 U(x,y) \tag{11}
\]

where \( p_1 \) and \( p_2 \) = positive constants. The values of \( p_1 \) and \( p_2 \) used here are 172 and 18.7, respectively. These values are obtained using a real-world speed-density data set provided in Chakraborty (1993). The details of the procedure are given in Agrawal (2000).

### Case I: Empty Road with Varying Widths

In this section, results on driver behavior on roads with very little or no traffic are presented. Since, in this case, it is assumed that there are no lane markings, the only obstacles are the road edges. Hence, the only potential faced by a TD is that due to the road edges.

According to the SRM the position of the TV will be at a point which has the minimum potential among all accessible points. Now, since there are no other PFFs, the TD will maintain a position that gives the minimum of the function \( U_E(x,y) \) given in Eq. (8), subject to the constraint that the position is accessible.

Relaxing this constraint for the moment it can be shown that the minimum, for any \( y \), will occur at a point whose \( x \) value, denoted as \( x^* \), is given by

\[
x^* = \frac{b_2}{b_1 + b_2} w + \frac{\ln(a_1 b_1/a_2 b_2)}{b_1 + b_2} \tag{12}
\]

If a “keep left” policy is followed (i.e., \( b_1 > b_2 \) and \( a_2 > a_1 \)) then the above equation implies that the distance of \( x^* \) from the center line (which is at \( x = 0.5w \)) increases and \( x^* \) moves toward the left edge of the road as the width \( w \) increases. This is the expected behavior in this case; i.e., on a wider road the driver will be closer to the left side of the road whereas when the road width is less the driver will try to tend toward the center of the road. The above equation also implies the opposite behavior than the one mentioned here if the constants are chosen so as to suggest a “keep right” policy (i.e., \( b_1 < b_2 \) and \( a_2 < a_1 \)). Further, it may be mentioned that for standard road geometries, simple calculations on possible angles (with the vertical) formed by a line joining successive minima shows that in this case (i.e., only for conditions defining Case I) the maximum steering angle constraint is never violated and hence can be ignored.

What remains to be shown is that the speed of the TV is constant on a constant width section of a road and that the speed of the TV is lower on a road section which is narrower. In order to show these two aspects two things need to be proven: (1) the minimum potential is constant on a constant width road section and (2) the value of the minimum potential increases as the road width narrows. The latter implies that the speed maintained by the TV will be lower on a narrower road. This implication follows from the fact that in free flow situations (since \( \alpha \) of ARM is 0) a TV (in steady state) will maintain the sustainable speed which, the reader may recall, is inversely related to the potential at a point [see Eq. (11)]. Note that the same assertion holds for Cases II and III, also. In fact, in these cases, since \( \alpha = 0 \), the parameters of ARM, like \( k_1 \), \( k_2 \), etc., do not assume any significance. These parameters become significant for the cases under “forced flow conditions” where the general form of the ARM is relevant. Hence the values of the parameters of ARM are mentioned for the cases under “forced flow conditions.”

The minimum potential \( U^*(y) \) along any cross-section can be obtained by substituting \( x^* \) from Eq. (12) in the expression for \( U_E(x,y) \) given by Eq. (8).

\[
U^*(y) = a_1 e^{-b_1 y} e^{-b_1 w} + a_2 e^{-b_2 y} e^{-b_2 (1-y)w} \tag{13}
\]

where, \( \eta_1 = \ln(a_1 b_1/a_2 b_2)/(b_1 + b_2) \) and \( \eta_2 = b_2/(b_1 + b_2) \).

The above equation illustrates that \( U^*(y) \) is a constant with respect to \( y \) if the width of the road \( w \) is constant. Further, since \( b_1 > 0 \), \( b_2 > 0 \) and \( \eta_2 \) is always less than 1, the above equation implies that \( U^*(y) \) increases as \( w \) reduces.

The above discussion shows that the proposed model produces speed and position profiles of TVs which mirror expected driver behavior in the case studied here.

### Case II: Empty Road with Lane Markings

In this section, results are presented to show the effect of lane markings on driver behavior as predicted by the proposed model. Results on position profile are only presented as results on speed profile do not provide any additional information about the properties of the model and due to space restrictions.

The “obstacles” present in the driving scenarios studied here are the road edges and the lane markings. Thus, only two types of PFF are active, namely, \( U_E(x,y) \) and \( U_{LM}(x,y) \). That is, the potential at any point on the road, \( U(x,y) = U_E(x,y) + \sum_{i=1}^{n} U_{LM}(x,y) \), where \( i \) is an index denoting a particular lane marking and \( n \) is the total number of lane markings on the road.

In order to study the effect of lane markings, one driving scenario is studied. In this scenario, the road has a width of 12 m in the upstream section, a width of 4 m in the downstream section, and an intermediate section where the width varies from 12 to 4 m. In the 12 m section of the road three lane markings exist (i.e., \( n = 3 \)) at \( x = 3 \) m, \( x = 6 \) m, and \( x = 9 \) m. The 4 m section does not have any lane marking. The entire road section is assumed to be a two-way street operating under the “keep left” policy. The results are obtained for the following values of the parameters: parameters of \( U_E(x,y) \) are as stated earlier; \( a_5 = 0.8 \), \( a_4 = 0.2 \), \( b_3 = 4.0 \), \( b_4 = 2.0 \), \( c_1 = 0.4 \), and \( c_2 = 0.3 \); and parameters of SRM are as stated before.

The position profile results are shown in Fig. 5. The broken lines (except the dashed lines which represent the lane markings) show the possible position profiles of a TV. There are two position profiles as the TV can move in either of the two lanes ear-marked for the northbound vehicles. Interestingly, (1) these two position profiles merge into one in the 4 m section of the road as there are no lane markings in this section and (2) the merged
position profile is at the center of the 4 m section as is expected for a narrow two-way road.

**Case III: Roads with Static Obstacles**

In this section, the proposed model’s capability in predicting driver behavior in the presence of static obstacles on the road is studied. The obstacles present in this case are the road edges and the static obstacle; thus the PFFs which are active are $U_E(x,y)$ and $U_{SDV}(x,y)$. The parameter values of the PFFs and SRM used to obtain the results in this case are as follows: parameters of $U_E(x,y)$ are as stated earlier; $a_3=4.0$, $b_3=2.0$, $m_u=8.0$ m, and $m_1$ is the radius of the circle circumscribing the obstacle; the parameters of the SRM are as stated earlier.

Results on position and speed profiles of the TV are discussed (figures are not provided due to space restrictions) for four different scenarios, namely, Scenarios III(a), III(b), III(c) and III(d). In all the scenarios, the road width is 6 m, and the obstacle is circular with 1 m diameter; however, in III(a) the obstacle touches the left edge of the road, in III(b) the center of the obstacle is 2 m from the left edge, this distance increases to 2.75 m in III(c) and is 4 m in III(d).

In Scenarios III(a) and III(d), it is observed that the TD keeps traveling on its initial path and at its initial speed. It does not deviate due to the presence of the obstacle. This is, as expected, since in these two cases the obstacles are far from the initial travel path of the TD (which is parallel to the edges and 2.3 m from the left edge). In these cases, there is no change in the speed profile of TD. In Scenario III(b) the TD starts deviating to the right of its original travel path as it nears the obstacle and reaches a maximum deviation of 1.1 m when it is half-way across the obstacle. The TD attains its original path about 10 m after it crosses the obstacle. The speed of the TD drops as it deviates from the original path, but subsequently regains the speed once it is back on the original path. In Scenario III(c) the ND avoids the obstacle by going to the left of the obstacle; the reason for this anomalous behavior (because in “keep left” policy drivers are expected to avoid static or dynamic obstacles by going around it from the right) is that the obstacle is now very close to the center of the road and circumventing it from the right would mean moving quite close to the right edge and well into the road space for the opposing movement. The results from these scenarios match the general observations of driver behavior made in India.

**Case IV: Car-Following Situations**

In order to observe the capabilities of the model in describing driver behavior in constrained flow situations, first a study is conducted on the behavior of the TD in car-following scenarios. As is the general practice (for example, see Chakroborty and Kikuchi 1999 or May 1990), two basic properties of car-following behavior are studied, namely, local stability and asymptotic stability. In addition to these, other properties (as identified in Chakroborty and Kikuchi 1999) such as closing-in and shying-away are also studied.

In this case, there are two types of PFFs which are active, namely, the PFF for road edges $U_E(x,y)$ and the PFF for SDVs, $U_{SDV}(x,y)$. Note that in local stability analysis only a pair of vehicles is involved—the following vehicle FV being the TV and the leading vehicle LV being the SDV. In asymptotic stability studies there are more than one SDV since in a platoon of vehicles all the vehicles ahead of a given vehicle are obstacles (of the SDV type) for that vehicle. The results shown here are for the following values of the parameters of $U_E(x,y)$, $U_{SDV}(x,y)$, and ARM (note that the SRM is ignored here since the TVs are constrained to follow the leading vehicle): parameter values of

<table>
<thead>
<tr>
<th>Table 1. Description of Different Scenarios Studied under Local Stability Analysis and Closing-In and Shying-Away</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of a situation</td>
</tr>
<tr>
<td>Scenario</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>IV(a)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>IV(b)</td>
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<tr>
<td></td>
</tr>
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<td></td>
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<tr>
<td></td>
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<tr>
<td>IV(c)</td>
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<tr>
<td></td>
</tr>
<tr>
<td>IV(d)</td>
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<tr>
<td>IV(e)</td>
</tr>
</tbody>
</table>
$U_e(x,y)$ are as stated before; $U_{SDV}(x,y)$ is as shown in Fig. 2: $d = 10$, $k_1 = 0.015$, $k_2 = 4.0$, $\alpha = 0$ if distance headway between SDV and TV > 60 m, $\alpha = 1$ if distance headway between SDV and TV < 56 m, $\alpha$ varies from 0 to 1 as distance headway varies from 60 to 56 m.

**Local Stability Analysis**

The aim of this section is to show that the predictions of the proposed model (in terms of accelerations or decelerations of the TV) are such that local stability is achieved in car-following situations. That is, the actions of the FV should be such that the distance headway between the FV and LV eventually stabilizes to a “safe” (or stable) distance headway (SDH) once the initial speed variations of the LV die out (i.e., the LV starts moving at a constant speed). Note that a stable distance headway implies that the stable relative speed is zero. Further, this section aims to show that the SDH achieved under local stability is independent of the initial distance headway between the vehicles (IDH), the initial speed of the vehicles, and speed variations of the LV and dependent only on the final speed of the LV (these are the properties of local stability, see Chakroborty and Kikuchi 1999).

Results are obtained for various car-following scenarios and are presented through figures which plot the distance headway between the vehicles versus time. It may be noted that such a plot completely describes the behavior of any car-following model since speed versus time graphs can be derived from these plots. However, only for the first scenario studied here both the distance headway versus time and speed versus time are plotted in order to give the reader a feel for the behavior predicted by the proposed model.

In all, results from three different scenarios are presented here. These scenarios are described as Scenarios IV(a), IV(b), and IV(c) in Table 1. Each scenario consists of one or more car-following situations. Each situation is described in terms of the IDH between the LV and FV, initial speeds of LV and FV, and the user-specified speed profile of LV (or perturbation pattern). The perturbation pattern of LV (PPLV) is described using the following convention $v(t_1) - v(t_2) - v(t_3) - \ldots - v(t_n)$. This convention means that the speed of the LV is $v_1$ m/s at time $t_1$ s and it reaches $v_2$ m/s at time $t_2$ s through constant acceleration/deceleration and so on; beyond time $t_n$, the LV maintains a constant speed of $v_n$ m/s.

The distance headway versus time and the speed versus time plots for Scenario IV(a) are shown in Figs. 6(a and b), respectively. As can be seen from the figure, the actions (accelerations/decelerations) of FV as predicted by the proposed model leads to local stability.

Results from the three car-following situations described under Scenario IV(b) are presented in Fig. 7. The figure shows that irrespective of the different IDHs in the three situations, eventually the distance headway stabilizes to the same value. (Note that the final speed in each of the three situations is the same).

Results from the six car-following situations described under Scenario IV(c) are presented in Fig. 8. The figure shows that the SDH depends only on the final speed of the vehicles and is independent of the initial speed and perturbation pattern of the LV. Further, the results also show that the SDH is higher at a higher speed, which is an observed fact.

**Closing-in and Shying-away**

This section presents results to show that the proposed model can describe the behavior of closing-in and shying-away. In closing-in behavior the FV closes in on the LV if the FV finds the distance headway to be too large, irrespective of the actions of LV. In shying-away the FV shies away from the LV if the distance headway is too small, irrespective of the actions of LV. For a good discussion on this important aspect of car-following behavior and the philosophical ramifications of a model’s inability to describe this behavior see Chakroborty and Kikuchi (1999).

Results from two car-following scenarios, Scenarios IV(d) and IV(e) are presented in order to show that the proposed model can describe closing-in and shying-away. The scenarios are first de-

**Fig. 6.** (a) Distance headway versus time and (b) speed versus time plots for the car-following situation described in Scenario IV(a)

**Fig. 7.** Distance headway versus time plots for the car-following situations described in Scenario IV(b)
scribed in Table 1. Note that, in both scenarios the LV continues to move at its initial speed (the column PPLV therefore says no perturbation).

Figs. 9(a and b) show the distance headway versus time plot and the speed versus time plot, respectively, for Scenario IV(d). As can be seen from Fig. 9, the FV first increased its speed and then reduced it to the initial value in order to close in on the LV (and stabilize at a distance headway of about 24 m), despite the fact that the LV maintained a constant speed. In this scenario the FV accelerated/decelerated because the driver of the FV found that a distance headway of 50 m was “large” for a speed of 12 m/s. The converse behavior is seen for Scenario IV(e). In this scenario the FV perceives the distance headway of 20 m to be small for a speed of 18 m/s. Hence, FV increases the distance headway by first decelerating and then accelerating to its initial speed even though LV maintains a constant speed. The figure depicting the behavior in this scenario is not provided due to space restrictions.

Asymptotic Stability Analysis
Asymptotic stability analysis studies how the perturbation introduced by the LV propagates in a platoon of vehicles led by the LV. A platoon is said to be asymptotically stable if the perturbation introduced by the LV reduces as it is transmitted upstream from one vehicle to the next.

Car-following behavior of drivers is, in general, asymptotically stable (otherwise any small perturbation will magnify as it proceeds upstream and always cause an accident among the last few vehicles of a long platoon). Hence, the purpose of this section is to study whether the actions predicted by the proposed model produce a behavior which is asymptotically stable. In order to show that the proposed model does satisfy the property of asymptotic stability result from one scenario, Scenario IV(f) is presented. In this scenario there are five vehicles including the LV. The IDH between every pair of vehicles is 33 m. The initial speed of each of the vehicles is 17 m/s. The PPLV is 17(0)-17(5)-22(10)-12(20)-17(25).

Fig. 10 shows the result obtained for this scenario. As can be seen in the figure the peak in the distance headway variations reduce from the downstream vehicle pair to the upstream vehicle pair. That is, the peak in distance headway variations between the LV and the first FV is more than that between the first FV and the second FV, and so on. This indicates that the actions predicted by the proposed model produce a behavior which is asymptotically stable.

Case V: Passing (Overtaking) Situations
In continuation of the study of the capabilities of the model in describing driver behavior in constrained flow situations, this section concentrates on analyzing the behavior of the TD in passing (overtaking) scenarios. This situation differs from car-following in the sense that the driver of the following vehicle is no longer constrained to move behind the leading vehicle but can pass (overtake) it by changing ones lateral position and speed appropriately. Hence, in this case the predictions from both the SRM
**Table 2. Description of Scenarios Studied under Passing (Overtaking) Situations**

<table>
<thead>
<tr>
<th>Descriptor of the scenario</th>
<th>Scenarios</th>
<th>V(a)</th>
<th>V(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of slow moving vehicles</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Number of passing vehicles (test vehicle)</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Distance between last slow moving and first test vehicles (m)</td>
<td>75</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Distance headway between slow moving vehicles (m)</td>
<td>–</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Distance headway between test vehicles (m)</td>
<td>26</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>Speed of slow moving vehicle (m/s)</td>
<td>14</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Initial speed of the test vehicles (m/s)</td>
<td>14</td>
<td>27.75</td>
<td></td>
</tr>
</tbody>
</table>

and the ARM assume importance. Therefore, all results in this case show the position profile and the speed profile of the TV.

In any passing situation one or more slow moving vehicles (SMVs) may be passed (overtaken) by one or more faster upstream vehicles. It is assumed that each faster upstream vehicle, before commencing the passing maneuver, makes a decision as to whether or not to pass (overtake) all the slow moving vehicles ahead of it, if not, whether it is possible to pass some of them at a time. That is, each passing vehicle at the end of its decision making has a desire to reach a particular point on the road, this point may be downstream of the first (i.e., the farthest) of the SMVs or somewhere in between the platoon of SMVs. In this paper, such a point is referred to as an immediate goal or simply a goal and, as stated earlier, emanates an attractive potential indicating the TDs desire to reach that point. Further, all vehicles in front of a given vehicle at any given time act as SDVs for that vehicle. Hence, in passing situations, the following types of PFFs are active: $U_G(x,y)$, $U_{SDV}(x,y)$ (there may be more than one SDV), and $U_{<}(x,y)$. The results shown here are for the following values of the parameters of $U_G(x,y)$, $U_{SDV}(x,y)$, $U_{<}(x,y)$, SRM, and ARM: parameter values of $U_G(x,y)$ and $U_{SDV}(x,y)$ are as stated before; $U_{<}(x,y)$ is similar to the function shown in Fig. 4; parameters of SRM are as stated before; parameters of ARM are as stated before with the addition that in the case distance headway between an SDV and TV < 56 m, $\alpha$ varies from 1 to 0 (and remains zero) as the lateral distance between the SDV and the TV increases from zero to 1.5 m (this additional degree of freedom for $\alpha$ was not mentioned earlier; this information is redundant in the case of car-following as lateral deviations in a “no-passing” situation do not assume any reasonable value).

Two different scenarios are studied here, Scenarios V(a) and V(b). Scenario V(a) is a situation where vehicles were initially forced to move at a low speed due to an upstream speed limit restriction; as these vehicles enter the test section the speed limit restriction is removed. However, the leading vehicle continues to move at the original slow speed and is passed (overtaken) by the vehicles following it. Scenario V(b) is a more traditional passing scenario, in which a faster moving platoon passes a slower moving platoon. The detailed description of these scenarios are given in Table 2.

Fig. 11 presents the results obtained for Scenarios V(a). Part (a) in the figure shows the position profile of all the six TVs (passing vehicles) and part (b) shows the speed profile of all the six TVs.

Fig. 11 shows that initially all the vehicles including the passed (overtaken) vehicle (the SMV, which, as stated earlier, acts as an SDV) are moving at a distance of 2.5 m from the left edge. However, after about 1 s the first TV initiates the passing maneuver by steadily increasing its speed and initially deviating laterally to its right (recall that the drivers are following a “keep left” policy). As the TV passes the vehicle ahead the speed of the former falls marginally (possibly due to the fact that the TV is in a constrained situation being very close to the right edge and having a SDV to its left). The speed then picks up again as the vehicle is passed and the TV moves back to its preferred lateral position of 2.5 m from the left edge. The TV then continues at a speed of about 27.75 m/s which is the free speed for an 8 m wide.
road (as per the parameter values chosen for the results presented in this paper). Similar behavior is exhibited by the other five TVs (which pass the slower vehicle) also. Before leaving this discussion, it should be pointed out that the scale in the position profile diagram is a bit lopsided—a centimeter in the vertical axis represents about 5.15 m whereas a centimeter in the horizontal axis represents about 3.33 s (or a longitudinal distance of about 92 m), assuming a constant speed of 27.75 m/s. This large difference in the scales of the two axes gives rise to the illusion that TVs make almost right angle turns, especially, when coming back to their original path.

A similar figure for Scenario V(b) is not shown here due to space restrictions. However, in order to highlight the passing (overtaking) maneuver better, the position profiles of all the vehicles in both the scenarios are plotted in Fig. 12. In part (a) of this figure the frame of reference is moving with the SMV of Scenario V(a), and in part (b) of this figure the frame of reference is moving with the farthest SMV of Scenario V(b). The plotted position profiles now become relative to the position of the SMV (which becomes a stationary point) and clearly show how the TVs pass the slower vehicles. It should be noted that in both the figures only one line is visible since the paths followed by all the TVs in a given scenario are identical.

Case VI: Bidirectional Flow Situations

This section concentrates on analyzing the behavior of the TD in the presence of on-coming (or opposing) vehicles on two-way roads without a median barrier. As stated earlier, the on-coming vehicles, in the proposed framework, are dynamic obstacles of the type ODV. Thus in this case the following PFFs are active: $U_E(x,y)$ and $U_{ODV}(x,y)$. Further, it should be pointed out that, each vehicle acts as an ODV to its opposing vehicle.

Since, in this case, it is expected that the drivers will modify their lateral positions as well as their speed as the opposing vehicles approach each other, results on both the position profiles and speed profiles of the vehicles are presented here. The results, presented here, are obtained for the following values of the parameters of $U_E(x,y)$, $U_{ODV}(x,y)$, SRM, and ARM: parameters of $U_E(x,y)$ are as stated earlier; $U_{ODV}(x,y)$ is same as the function shown in Fig. 3; parameters of SRM and ARM are as stated earlier.

Three scenarios, namely, Scenarios VI(a), VI(b), and VI(c), are studied here. The scenarios differ from one another in that the widths of the road in Scenarios VI(a), VI(b), and VI(c) are 6, 7, and 8 m, respectively. In all the scenarios, there are two vehicles, one in each direction; initially the vehicles are 140 m apart and traveling at the free speed.

Fig. 13 presents discrete time snapshots (derived from the position profiles and speed profiles of the vehicles) of the road for Scenario VI(a) at times equal to 0.25, 0.75, 1.25, 1.75, 2.50, 3.25, 3.75, and 4.00 s from the start of the simulation. This figure shows how the two vehicles (operating under “keep left” policy) initially proceed on their preferred lateral position but deviate toward their respective left edges as they close in on one another and again later (after crossing each other) come back to their initially preferred lateral location. This behavior, obtained from the proposed model, is on expected lines and hence realistic.

Similar figures could be plotted for the other two scenarios, but are not provided here, due to space restrictions. However, a comparison of the maximum lateral deviation (MLD) and the maximum drop in speed (MDS) among the three scenarios are provided in Table 3. The purpose of this comparison is to see whether, as is expected, MLD and MDS reduce as the width of the road increases (since at higher widths one would feel less constrained by opposing vehicles). As can be seen from the table these quantities do reduce as the width of the road increases from 6 m [Scenario VI(a)] to 7 m [Scenario VI(b)] to 8 m [Scenario VI(c)].

**Conclusion**

In this paper, the possibility of developing a comprehensive microscopic model of driver behavior is explored. It is envisaged that such a model will be able to predict the actions of drivers at small intervals of time under all kinds of traffic and roadway conditions. Such comprehensive models are not available in the literature. In fact, even models of driver behavior in response to road geometry features are not available and engineers primarily rely on data on macroscopic flow conditions to understand the effects. This dearth of a comprehensive microscopic model, the nemesis of traffic science, forms the motivation for the present work.

Here, a framework which builds a comprehensive microscopic model based on two simple assumptions on driver behavior is presented. The model consists of two modules—one which predicts the lateral position of a driver (or alternatively a driver’s choice of steering angles) at small time intervals, and one which predicts the speed of a driver (or alternatively the acceleration/deceleration rates used by a driver) at small time intervals.

In order to analyze the efficacy of the proposed model, driver behavior (as predicted by the proposed model) in numerous driving scenarios are studied. These scenarios ranged from free flow...
conditions to two-way vehicular movements on undivided roads. Due to space restrictions, results from only 19 scenarios are presented. The results presented include two basic kinds of flow conditions—free flow conditions and forced flow conditions and various road geometry conditions—different and varying road widths, lane markings, etc.

The results show that the proposed model using a single framework predicts the behavior along expected lines (obtained from observations of driver behavior) in all the driving scenarios. One area which has not been studied here is driver behavior in near-capacity or stop-and-go conditions. This was not possible because the writers did not have substantial observations on

Table 3. Comparison of Maximum Lateral Deviation and Maximum Drop in Speed between Three Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Maximum lateral deviation (m)</th>
<th>Maximum drop in speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI(a) (width=6 m)</td>
<td>0.75</td>
<td>6.70</td>
</tr>
<tr>
<td>VI(b) (width=7 m)</td>
<td>0.575</td>
<td>5.40</td>
</tr>
<tr>
<td>VI(c) (width=8 m)</td>
<td>0.45</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Fig. 13. Discrete time snapshots of a road section under Scenario VI(a)
driver behavior in such conditions. Further, in the simulations, different types of drivers were not included. Yet, it is felt that the proposed framework holds ample promise as a structure on which a comprehensive and complete model of traffic flow can be developed. This, if achieved, will strengthen the area of traffic science and help traffic engineers and planners to develop better and more efficient traffic networks by substantially reducing the need for empirical analysis and ad hoc assumptions.

It may be further mentioned here that work on calibrating the parameters of the PFFs and the SRM and ARM are underway and initial results (see Mahajan 2000) show that the parameters can be successfully calibrated to mimic a given driver behavior in different driving scenarios. However, the procedure for parameter calibration being studied could not be discussed here due to space restrictions.

References


Kanpur, India.


