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# Cellular Automata Model for Lane Changing Activity

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**Abstract**

In the present work, a microscopic traffic flow model using Cellular Automata is proposed. The model is intended to explain accurately the lane changing activity, which is treated as a continuous process rather than a discrete event as suggested by previous models. Various important properties of traffic flow could be explained by the proposed model and the simulated results are quite reasonable. The proposed model can give explanation to the microscopic properties, like, local stability, asymptotic stability, closing-in/shying-away and insensitivity of safe distance headway to perturbation pattern, initial distance headway and initial speed. Macroscopic properties like speed, flow and density were studied for a traffic stream under various conditions like varying road width. The results obtained from simulation of single lane and wide roads with lane discipline match closely to the values suggested by Highway Capacity Manual.

**Keywords** Microscopic traffic flow model · Microscopic properties · Macroscopic properties · Perception reaction time · Relative speed · Cellular automata

## 1 Introduction

Cellular automata has been extensively used for vehicular traffic simulation for its simplicity in application. Nagel and Schreckenberg (1992) [1] proposed the first probabilistic cellular automata. Subsequently many researchers have worked on the Nagel Schreckenberg model bringing about different results such as T2 model by Takayasu and Takayasu (1993) [2], BJH model by Benjamin et al. (1996) [3], VDR model by Barlovic et al. (1998) [4] and many more. The models considered the movement of vehicles only in one dimension i.e., the movement in longitudinal direction only. Such assumptions are valid when the road characteristics are same for long stretches, the vehicles follow proper lane discipline and lane-changing activities are rare occurrences. In real life traffic flow, such one-dimensional movements for long stretches occur very rarely. Hence, multilane cellular automata models replaced these one-dimensional cellular automata models.

A two-dimensional cellular automata model was introduced by Biham et al. (1992) [5]. Analysis of both the deterministic and non-deterministic variants of the proposed model showed similar behavior describing the model as a robust proposition, which can demonstrate traffic flow in two-dimensional lattice spaces. Vehicles either moved forward or change lanes in the model proposed by Nagatani (1993) [6]. Platoon of vehicles oscillating between lanes without forward movement showed an unrealistic movement of the traffic. Rickert et al. (1996) [7] proposed lane changing rules which showed demerits like ping-pong effect, tailgating dance and incorrect presentation of maximum flow regime. Benjaafar et al. (1997) [8] proposed a two lane traffic flow model under varying density conditions. However, the model provides satisfactory results for low density traffic only. Anticipation models with sequential update systems were introduced by Knospe et al. (1999) [9] where the vehicles move "side-wards" during the lane changing operation. The traffic flow model proposed Knospe et al. (2002) [10] shows property of lane inversion. Introducing asymmetry or priority of using right lane or restricting overtaking activity in the right lane fails to produce lane inversion. Simulation model for highway traffic with partial blocked lane was proposed by Zhu et al. (2009)

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[11]. The accident car creates a jam at the upstream as well as the adjacent lane. When the accident occurs in the right lane, the local jam disappears quickly using the asymmetric lane changing rule, whereas the local jam disperses quickly using symmetric lane changing behavior when accident occurs in the left lane. Cellular automata model for fast moving vehicles with symmetric lane changing rules was proposed by Li et al. (2006) [12]. Wagner et al. (1997) [13] used cellular automata for simulating multilane traffic. The results demonstrate the crowding of the passing lane with high flux than the one for slower cars. Nagel et al. (1998) [14] proposed cellular automata based microscopic model for multilane traffic which could produce phenomena like density inversion. The researchers conclude that the logical structure of lane changing rules is equally important as the microscopic details in producing the results. Chowdhury et al. (1997) [15] developed particle hopping models for two lane traffic with two different types of vehicles characterized by the different maximum allowable speed. Symmetric model seems to be simple, however, the drivers in asymmetric model could anticipate the probability of getting trapped behind slow moving vehicles. Fast moving vehicles adapt an aggressive lane changing behavior when preceded by slow moving vehicles. With the introduction of aggressive lane changing behavior, flow in the intermediate density region improves with disappearance of plug formed by slow vehicles. However, fast moving vehicles exhibit ping-pong lane changes when hindered by slow vehicles. Rawat et al. (2012) [16] used reduced cell size to study two lane traffic flows. With reduction in cell size small variations in traffic flow could be captured. Braking probability added with s-t-s probability increases the effectiveness of lane changing phenomenon. Lv et al. (2013) [17] treated the lane changing as a continuous process. Fictitious cars were introduced which occupy the position of the car in the present lane as well as the adjacent lane. The fictitious cars disappears as soon as the lane changing activity is complete and the final position is occupied by the original car. Zhu et al. (2015) [18] proposed lane changing model for two-lane traffic using cellular automata. The spatio-temporal profiles indicate that the vehicle can changes lane more realistically. As a result, the slow-moving vehicles which produce the plug can be avoided which increases the capacity.

The models discussed in the present section are computationally efficient and capable of simulating large traffic streams. Despite their efficiency, however, the above models had certain pitfalls. For instance, the movement characteristics demonstrated in many of the models were quite unrealistic which never happens in real world traffic scenario. Moreover, the models could not explain the microscopic properties (Chakraborty and Maurya, 2008 [19]). These pitfalls motivate the introduction of a newer version of cellular automata-based model which can explain lane-changing behavior well.

## 2 Proposed Model

a) Square shaped cells of 0.1 m are used as flow space in the simulation. Vehicles after travelling the flow space (i.e., from upstream end to downstream end) get repositioned at a space in the upstream end. If the upstream end is pre occupied with other vehicles, then the vehicle at the downstream end waits for its relocation giving rise to jam scenario. The simulation program proceeds with a time increment of 0.5 s.
b) Four-wheeler vehicles (4 W) of length 4.2 m and width 1.7 m (Arasan and Koshy [20]) were simulated in the present study. A maximum steering angle of 20$^{o}$ (Lv et al. [17]) is simulated for a safe and comfortable condition.
c) Desirable speed is the speed at which a driver drives the vehicle when not impeded by any obstruction. Depending on the desirable speeds, three types of drivers are simulated in the present study i.e., slow-moving drivers, aggressive drivers, and normal drivers. Aggressive drivers move at highest speed whereas the speed attained by slow moving drivers is the lowest. The maximum speed attained by each type of driver is calculated as per the maximum number of steps moved by the vehicle in each time-step i.e., aggressive drivers move 150 steps, normal drivers move 129 steps and slow drivers move 110 steps.
d) Apart from maintaining longitudinal distance, vehicles also maintain lateral distance from obstacles. Lateral clearance at zero speed is 0.3 m (Arasan and Koshy [20]) and maximum lateral clearance at different speeds varies as $0.011661v$, where $v$ is the speed of the vehicle in km/h.
e) Various inter-vehicular distances considered for simulation:

a. *Actual gap ($G_a$)*: The physical distance between the rear bumper of lead vehicle and front bumper of following vehicle is termed as actual gap.
b. *Buffer space (B)*: Every vehicle reserves certain space at the front from the lead vehicle in order to maintain a safe distance. This reserved space is called as buffer space. Mathematically,

$$B = C_1 + C_2 v \tag{1}$$

Where $C_1$ and $C_2$ are constants of calibration, $v$ is the speed of the vehicle.

iii. *Perceived gap ($G_p$)*: The space utilized by the vehicle for its safe movement is perceived gap. Mathematically,

$$G_p = G_a - B \tag{2}$$

Various longitudinal spaces considered for simulation are illustrated in Fig. 1.

f) Relative Speed: Relative speed is used by the following vehicle to change its path when obstructed by a lead vehicle which is moving slowly. It is calculated as the difference in speed value of the lead vehicle and the following vehicle. If relative speed becomes negative, the following vehicle checks other conditions to be suitable for changing trajectory.

## 3 Implementation of the Model

Square cells of 0.1 m are used to discretize the flow space both in lateral as well as longitudinal direction. Time step of 0.5 s is used for a total simulation time of 7200 s. Position of the vehicle and speed is updated (parallel updating scheme) after every time step (Fig. 2).

**Step 1:**

Road geometry and vehicles are generated in this step. Arbitrary speed is assigned to every vehicle which will be used for the first step of simulation only. Updated speeds are used for rest of the simulation. These arbitrary speeds are less than that of desirable speeds of the vehicles. A flowchart showing the computer implementation of the model is shown in Fig. 3.

**Step 2:**

Computation of Buffer space (B) (using eq. 1), actual gap ($G_a$) and perceived gap ($G_p$) (using eq. 2) takes place in this step. Speed values obtained in the previous time step are used in Eq. 1. A check is performed in every time-step to verify whether the value of actual gap is higher than buffer space or not, using the following equation.

If $B > G_a$

$$v = v.\left({G_a}/{B}\right)^n \tag{3}$$

Else

Calculate $G_p$ as per Eq. 2.

Where ($n \in Z, 1 \le n \le 100$).

There may be circumstances when value of Ga is large; $v$ is small as a result the buffer space computed (B) becomes small. Under such circumstances, value of Gp becomes large. Hence a vehicle may move from very low speed to very high speed in one time step (i.e. $\Delta = 0.5$ s) which is practically impossible. Hence, a limiting value of acceleration of 1.4 $m/s^2$ (AASHTO (2001), [21]) is adopted for the simulation. Acceleration is calculated using the formula

$$v^2 - u^2 = 2aS \tag{4}$$

Where, $v$ is the speed of the vehicle in the present time step, u is the speed of the vehicle in the previous time step, a is the acceleration and S is the distance covered.

It may be noted that Eq. 2 takes care about the acceleration as well as deceleration of vehicles. Sometimes it may happen that a vehicle undergoes sudden deceleration, which is beyond comfortable deceleration (3.4 $m/s^2$, AASHTO (2004), [22]). Such actions are to avoid collision with the

Fig. 1 Space consideration for simulation

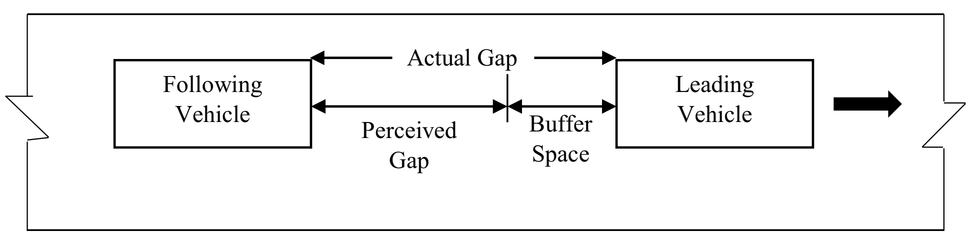
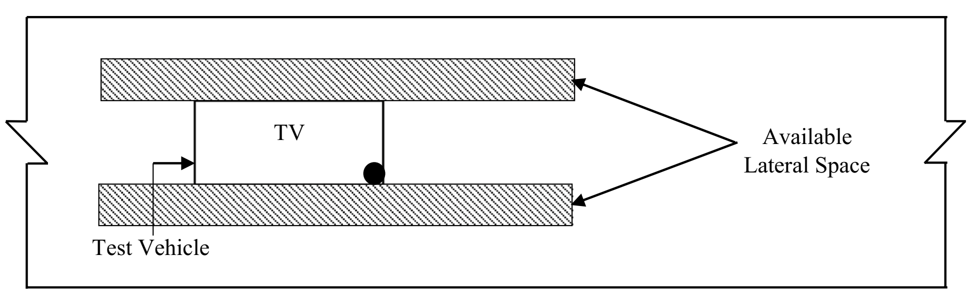



Fig. 2 Lateral vacancy check



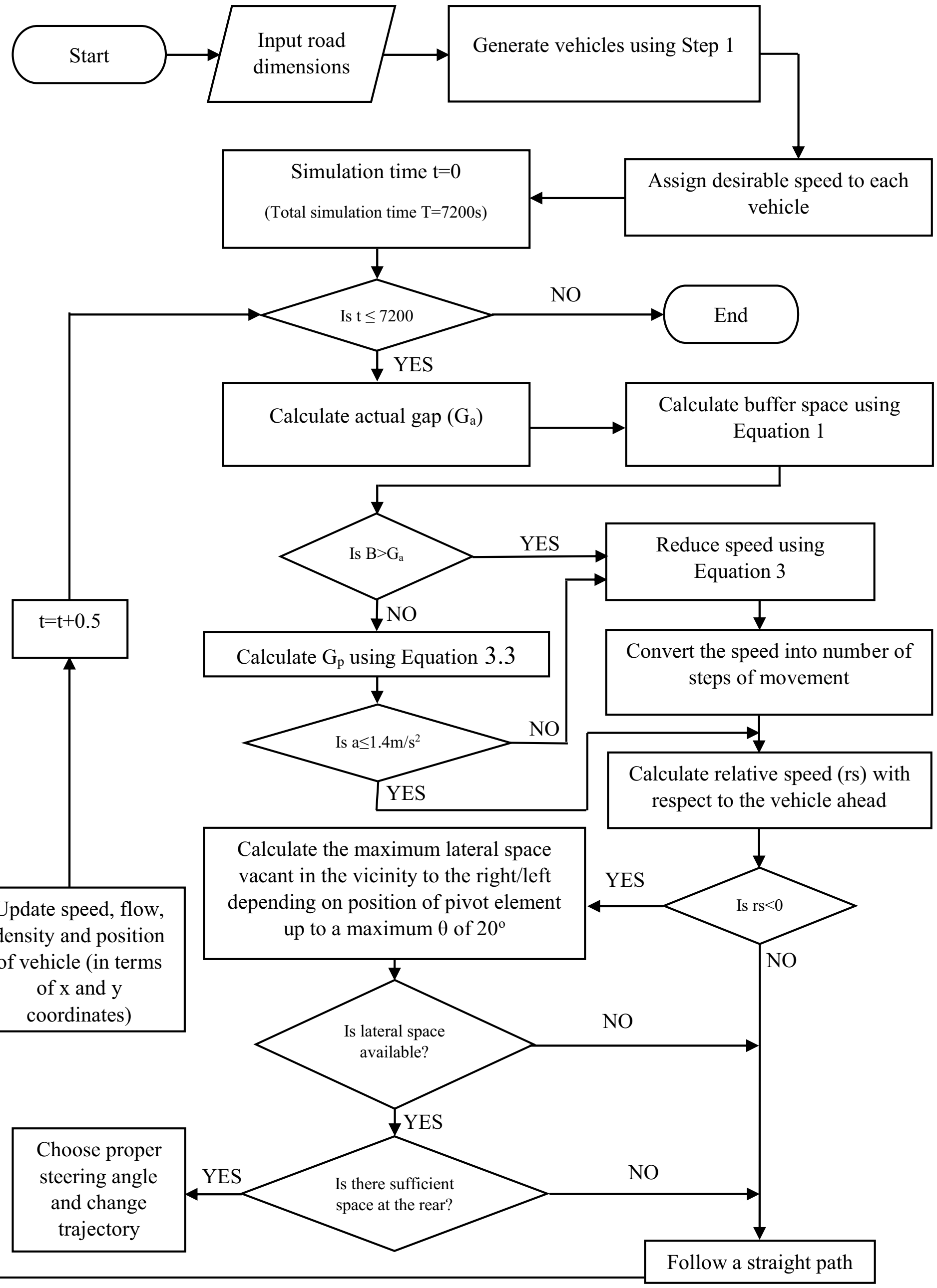



**Fig. 3** Flow-chart explaining the computer implementation of the proposed model

**Table 1** Decision making process for change in steering angle

| Position of the pivot point of the following vehicle with respect to line of symmetry (AA') of leading vehicle | Decision taken | Shown in Figure |
|---|---|---|
| Right | Right steering movement | 3a |
| Same alignment | Preference for right steering movement | 3b |
| Left | Left steering movement | 3c |

vehicle ahead. However, the occurrence of such situation is very rare as B is adjusted according to the value of Ga as per Eq. 3 at every instant of time.

**Step 3:**

The decision for lateral movement of the vehicle is taken in this step. Figure 2 presents the lateral space

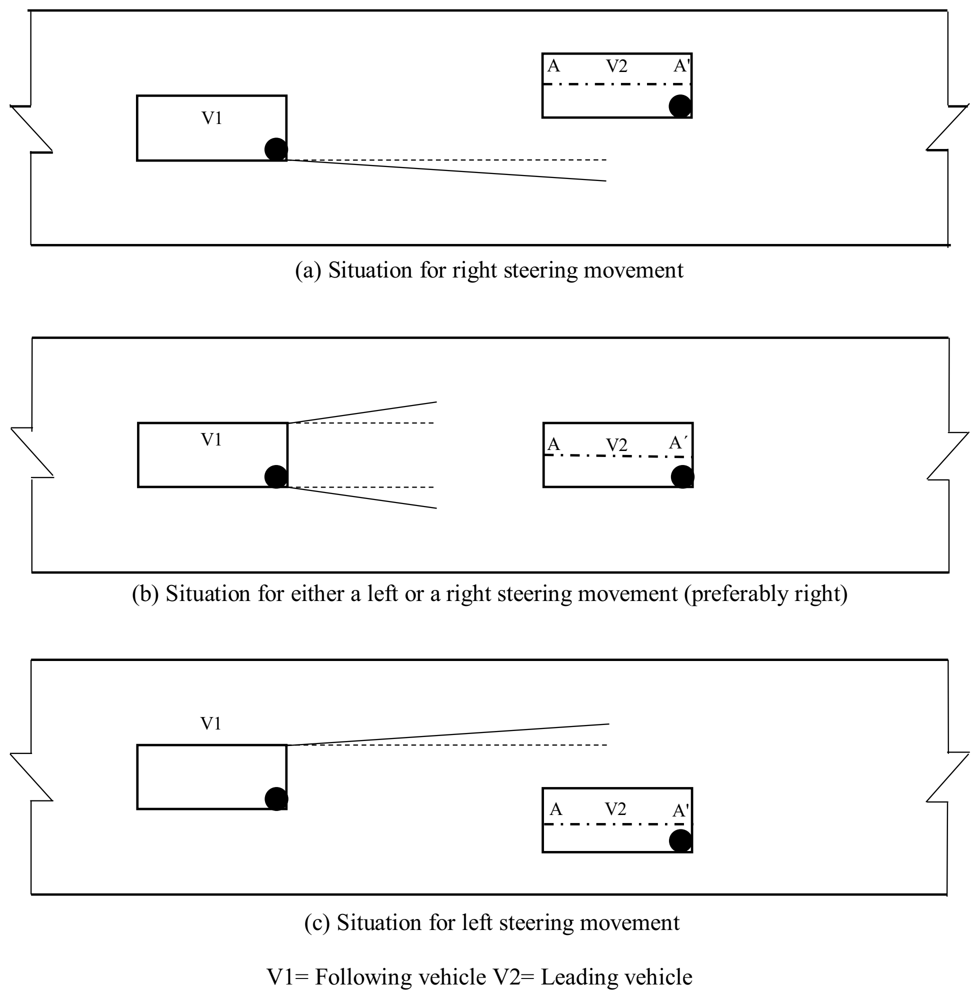



**Fig. 4** **a** Condition for turning right (**b**) Condition for either a turning right or a left (**c**) Condition for turning left

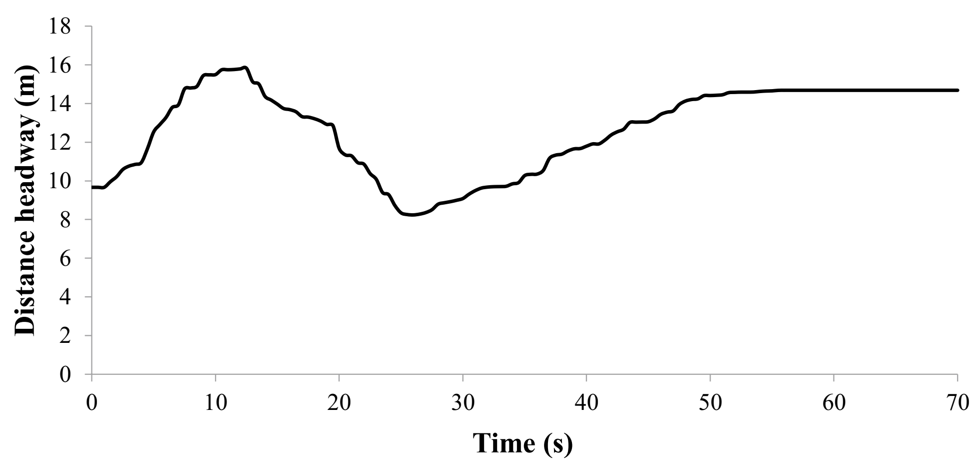



**Fig. 5** Local stability demonstrated by the proposed model

check criteria which has to be satisfied prior making decision of steering angle change. Depending on the respective position of the pivot point of the vehicle under consideration and the leading vehicle, the decision for right or left steering movement is taken as shown in Table 1. Figure 4 presents the situation under which the driver takes a decision for a right/left steering movement.

In addition to it, the rear vacancy rule should be satisfied. Every vehicle intending a change in trajectory with a change in steering angle should possess rear vacant space, which should be half the width and length of the vehicle. If either of the two rules are violated, the vehicle prefers a straight path.

**Step 4:**

The x and y coordinates (i.e., new spatial occupancy) of the vehicle is recorded.

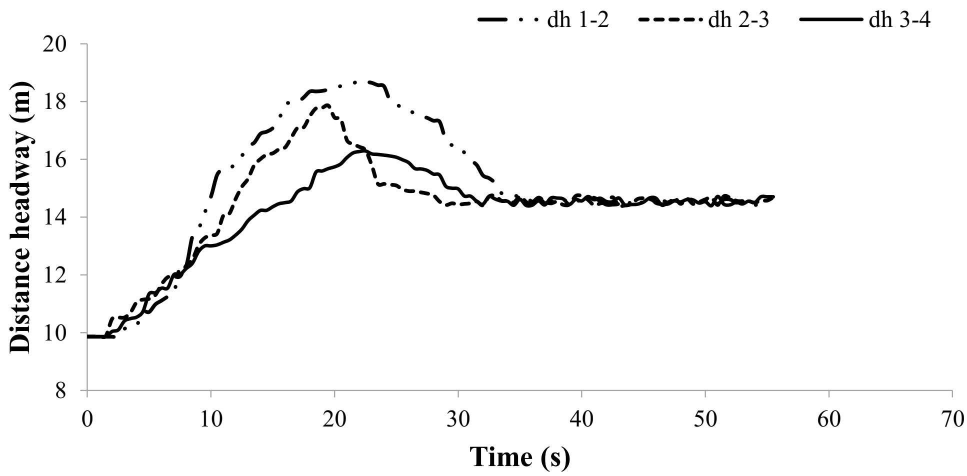



**Fig. 6** Asymptotic stability as demonstrated by the proposed model

**Table 2** Situations and decisions for closing-in and shying-away behavior

| Situation | Speeds of LV and FV | Distance between LV and FV | Decision taken |
|---|---|---|---|
| 1 (Dotted line) | ISLV = ISFV = 45.36 km/h | Higher than SDH | FV accelerates until SDH is achieved |
| 2 (Solid line) | ISLV = ISFV = 45.36 km/h | Smaller than SDH | FV reduces speed until SDH is achieved |

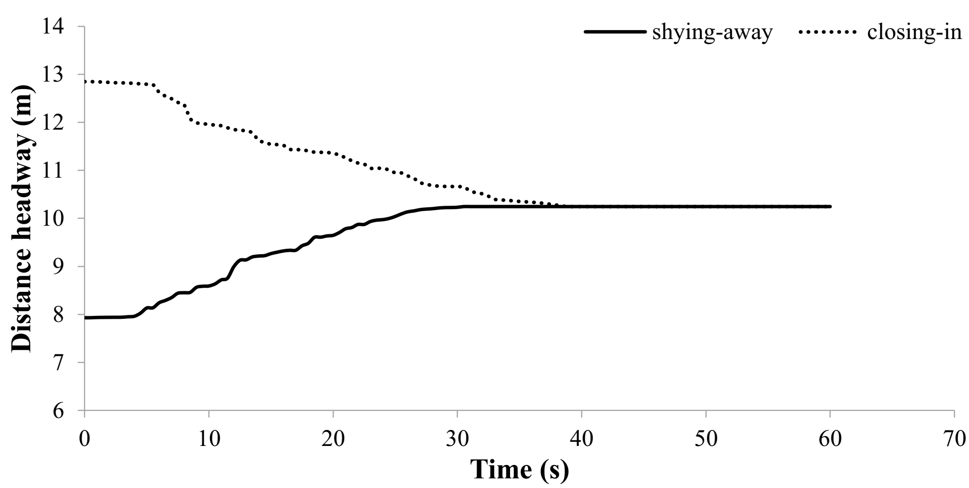
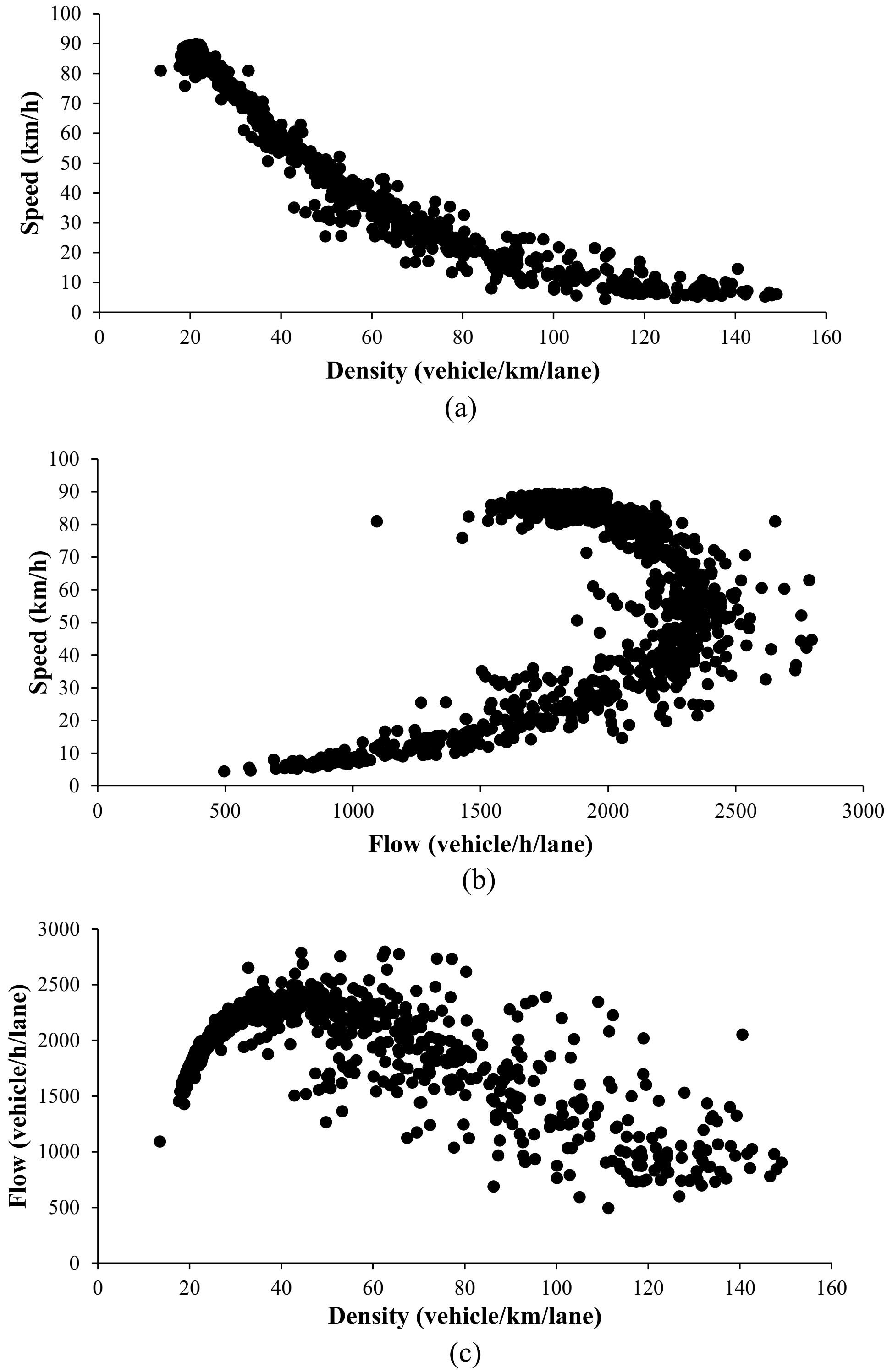



**Fig. 7** Closing-in and shying-away behavior as demonstrated by the proposed model

**Fig. 8** **a** Speed-density relationship (**b**) Speed-flow relationship (**c**) Flow-density relationship




## 4 Results and Analysis

Using the proposed model, microscopic as well as macroscopic properties were obtained as explained below.

**Table 3** Capacity values for various lane widths obtained by the simulation

| Number of lanes | Capacity values (vehicles/h/lane) |
|---|---|
| 2 | 2200–2400 |
| 3 | 3250–3400 |
| 4 | 4200–4400 |

### 4.1 Local Stability

Local stability speaks about localized behaviour which occurs between a pair of vehicles. The response of a following vehicle owing to the changes in the motion of vehicle directly at the front is described by local stability. Figure 5 demonstrates the distance headway versus time plot for local stability. A constant distance headway is attained (for a pair of LV-FV) after certain time depicting local stability.

### 4.2 Asymptotic Stability

The fluctuation to the motion of a vehicle at the front propagated to the platoon of vehicles at the upstream is asymptotic stability. Figure 6 depicts the distance headway versus time plot for a platoon of four vehicles. dh1–2 shows the distance headway for vehicle pair 1 and 2. The figure depicts that the perturbation gets damped while moving upstream confirming asymptotic stability.

### 4.3 Closing-in and Shying-Away Behavior

Every pair of vehicles maintain safe distance headway (SDH) during their movement. If the gap between the vehicle ahead and the following vehicle is much large, then the following vehicle would reduce the gap by accelerating, unless and until SDH is attained. This behaviour is called closing in behaviour. Similarly, if the gap between the pair of vehicles is small than the SDH, then the following vehicle would increase the gap by decelerating unless and until SDH is obtained. Such behavior is known as shying away behavior. Table 2 shows the situations and decisions for closing-in and shying-away behavior. Figure 7 demonstrates closing-in and shying-away behavior.

*ISLV* Initial speed of leading vehicle ISFV = Initial speed of following vehicle.

### 4.4 Explanation of Macroscopic Properties

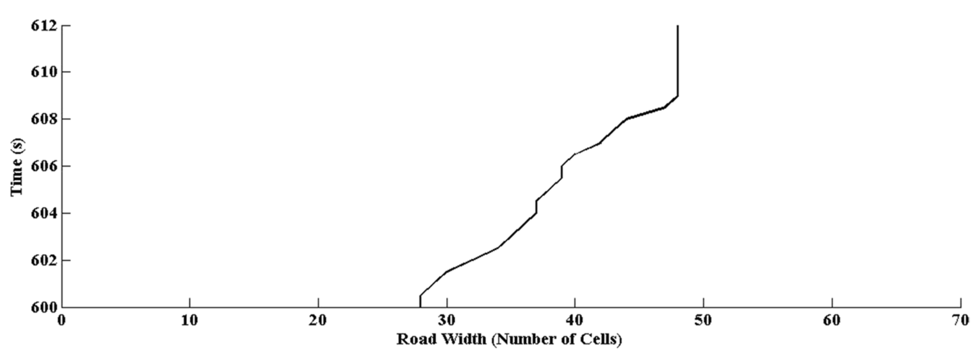
Fundamental properties like density, speed and flow were attained for a two lane (7 m) traffic stream (containing passenger cars only) and following lane discipline. The capacity values match closely with the values suggested by Highway Capacity Manual, 2010 i.e., 2250 vehicles/h/lane. Figure 8 shows the relation between various fundamental quantities.

Various capacity values obtained by the proposed model for different lane widths are presented in Table 3.

### 4.5 Lane Changing Activity

The proposed model considers the lane changing activity as a continuous process rather than an instantaneous activity. For this purpose, the flow space is divided into strips of width equivalent to nine cells i.e. (0.9 m). Dividing the flow space into nine cells width does not make it mandatory for the vehicle to jump nine cells laterally in a time step. Rather this arrangement is made to keep a restriction on the side-wise movement in a single time step and adhering to the maximum steering movement of a vehicle i.e., 20°. A vehicle which becomes dissatisfied in the present lane i.e., relative speed becomes negative, tries to move to the adjacent lane provided the vacancy criteria (step-3, Section 3) are satisfied. This action of lane changing by shifting to adjacent sub-lanes occurs until the vehicle does not shift to the adjacent lane completely. Once the vehicle crosses the lane demarcation to move to the desired lane, the lane changing activity continues until the process is complete. At this stage, vacant space is considered as the combination of frontal space, lateral space and rear space. Position change during lane changing process occurs with change in vehicle position both laterally and longitudinally. After changing lane, the test vehicle remains in the new lane as long as it does not become dissatisfied again. Figure 9 depicts the lane changing activity of a vehicle whose lateral movement can be seen with respect to time.

**Fig. 9** Lane changing activity of a vehicle



## 5 Conclusion

Lane changing characteristics for homogeneous traffic using cellular automata has been proposed. Concept of buffer space has been used, where different inter vehicular spaces are computed and adjusted in every time step. Sufficient care has been taken to avoid situations of acceleration and deceleration beyond permissible limits. The proposed model successfully demonstrates microscopic properties. Lane changing characteristics of vehicles has been shown as a continuous process rather than an instantaneous event. The flow space has been divided into strips which acts as a reference line for the vehicle to continue the lane changing process with a minimum change in steering angle. Relative speed and space criteria have to be checked for the lane changing process to continue. If any of the criteria does not satisfy, vehicles choose a straight path. With the combination of different rules, the lane changing process is completed. The predicted capacity values using the proposed model is found to be close to the values proposed by Highway Capacity Manual 2010.

**Author Contribution** Conception: AKD, UC. Analysis: AKD. Interpretation: AKD, UC. Writing: AKD, UC. All authors declare that they approve the manuscript as submitted.

## Declarations

**Competing Interests** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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