SYNOPSIS

OF The Ph.D. Thesis entitled

Heterogeneous Traffic Flow Modeling for an Urban Corridor using Cellular Automata

Submitted in

Partial fulfilment of the degree of

DOCTOR OF PHILOSOPHY

of the

GUJARAT TECHNOLOGICAL UNIVERSITY

by

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January 2016
Mid blocks and intersections are a part of corridors, which connects one part of city to another. Urban corridors are formed by number of intersections and links, and the performance of any of these links or intersections determines the performance of nearby elements. A residual queue on one signal in the corridor can result in queues extending over the preceding intersections, thus bringing traffic to a standstill. This condition necessitates signal coordination and the effect of such a measure can be studied economically only by means of simulation. Cellular automata (CA) have been used by many researchers for homogeneous traffic flow modelling. Traffic flow model for an urban corridor comprises of mid-block section model and intersection model. The objective of the study is to get into the details of traffic movements as well as to study the feasibility of CA for corridor simulation.

In country like India, non-lane based traffic prevails; hence, designing control systems for such situations is a challenging task. Traffic simulation helps the analyst to model the behaviour of such complex systems. To represent multiple vehicle types, a multi cell representation was adopted. The position and speed of vehicles are assumed to be discrete in developed model. The speed of each vehicle changes in accordance with its interactions with other vehicles and is governed by some pre-assigned (stochastic) rules. The behaviour of traffic in the heterogeneous environment of an urban signalized intersection is complex, chaotic and difficult to model.

In present study, mid-block section heterogeneous traffic flow model (MBTFM) using CA is presented. While addressing heterogeneity, essentials features of the CA like uniform cell size, simple rules, and the computational efficiency achieved in homogeneous models are retained to a great extent by modifying cell size and developing certain rules which control vehicles as well as the road characteristics. The cell size is reduced to accommodate more ranges of speed, acceleration, size of vehicles and deceleration as well as to represent aggregate behaviour of vehicles. Further, to address the issue of non-lane based movement, lateral movement rules were proposed. New rules are developed to analyse the impact of speed breaking on traffic characteristics. Calibration and validation of the MBTFM model is carried out at macroscopic level using real-world data. The model is verified for the microscopic characteristics. The model performed reasonably well in predicting the speed at bump and overall delay. The results show that developed model can be used as an effective tool for heterogeneous traffic flow modelling.

Present study also aims to develop Intersection traffic flow model (ITFM) integrating the concepts of cellular automata to imitate the flow of heterogeneous traffic through a signalized intersection. To represent variety in vehicle types, a multi cell representation is adopted. To
signify the issue of non lane-based movement, modified lateral movement rules are proposed. Traffic flow behaviour at intersection is captured in developed model by introducing novel rules for amber; green and red. Turning movement rules according to prevailing conditions in India are proposed. Calibration and validation of ITFM model in terms of delay and saturation flow is carried out. Simulation result shows that the model perform reasonably well in predicting the delays as well as saturation flow and found to be satisfactorily replicating the field conditions.

The later research focused on interrupted traffic conditions like slow-to-start rule (Benjamin et al. 1996), signal-controlled stream (Spyropoulou 2007), signalized intersections (Nagatani and Seno 1994; Freund and Poschel 1995; Simon and Nagel 1998; Fouladvand et al. 2004), and networks (Yang et al. 2004). An important contribution among these is the online simulation model (OLSIM) developed by Pottmeier et al. (2005). However, most of these studies are focused on single-cell representation of vehicles (cars), which does not hold in heterogeneous traffic. Esser and Schreckenberg (1997) introduced the concept of edges and crossings to represent intersections. This concept serves well in homogeneous, lane-based traffic, but the edges are not easily distinguishable in heterogeneous, non-lane-based traffic. Also, the intersections modelled in these studies ignored the amber intervals, which are crucial in the case of signalized intersections. Chowdhury et al. (1997) had developed a stochastic two-lane flow model in CA with two kinds of vehicles, classified by dynamics as fast and slow ones. A few studies have been reported on multi-cell representation in cellular automata for addressing different vehicle types and lateral movements (Gundaliya et al. 2005, 2008; Lan and Chang 2005). However these studies are focused on free-flow situations at mid-blocks. (Padmakumar Radhakrishnan et al. 2013) developed computationally efficient traffic flow simulation model integrating the concepts of cellular automata and driver-vehicle-objects, thus making a behavioral model of traffic. This model was then used to predict saturation flows at signalized intersections. The model performed reasonably well in predicting the delays, but the saturation flow values showed up to 30% variability. The aforementioned review shows that most of the previous studies have not fully been successful in replicating realistic behaviour of traffic at signalized intersections with non-lane-based heterogeneous traffic conditions. Many of them use car following concepts, which are more applicable in uninterrupted traffic conditions. In interrupted conditions like signals, steady-state car following is not achieved in non-lane-based heterogeneous traffic.
CA-ITFM Model

A cellular automata based intersection traffic flow (CA-ITFM) model is proposed here. The proposed model is a multi-cell, grid-based stochastic CA model, and the methodology adopted for modelling is discussed in Figure 1. The following sections discuss the features of the methodology and the modelling concepts used in the study.

![Flowchart of CA-ITFM Model]

**Figure 1 Methodology of CA-ITFM Model**
**Road Representation**

Road space is divided into imaginary cells of equal, both longitudinally and transversely (Figure 2). There is no lane based traffic in the model; hence, only the road width is necessary, which is divided into cells based on an assumed cell size. In this model, size of the cell is carefully decided in such a way that it represents the actual size of vehicles and the total width of the road as close as possible (Gundaliya et al. 2005). The physical representation of the vehicle should be kept slightly more than the actual size of vehicle to provide some clearance. A size of 0.9 m is used in this study. The cells can be either empty or occupied by a vehicle. No or more cells are occupied by the vehicle. The occupancy of a cell at any time step is denoted by the identification number of the vehicle.

**Vehicle Representation**

After deciding vehicle size, the vehicles are physically represented in the grid as per their arrival. The parallel updation is considered for updating the vehicle in each time step, i.e. all vehicle speeds are updated simultaneously in single time step. In case where vehicles have the same row number, the left most vehicle is updated first and then the next one will be taken into consideration. All the vehicles are updated for their speeds as per the rules given for the updation. All vehicles move according to the front gap available and the speed of the vehicle at every time step. Moreover, the lane discipline is not followed and the vehicle also moves in either of the sides of the front vehicle as per the front gap available at sides. When the vehicle moves on the road, driver has to take two decisions- what would be the rate of change of the speed? And what would be the direction of movement (lateral movement) in the next time step? The decision on these two aspects, once taken should be carried on till the next decision point of that vehicle is reached. Location of the vehicle on the road stretch is considered with respect to x and y coordinates of the left most front corner of vehicle. Considering road stretch having width X and length Y and cells starting from the left most corner increases in X direction and Y direction (Figure 2). Five different vehicle types are simulated: two-wheeler (2w), three-wheeler or auto rickshaw (3w), car, light commercial vehicle (LCV) and heavy commercial vehicle (HCV).

![Figure 2: Physical representation of vehicles on 3.6 m wide road](image-url)
Vehicle Generation and Entry
In real observation it is found that many vehicles are moving simultaneously and in that condition real headway is almost zero. Therefore in present simulation model vehicles are generated as per the observation met during survey and vehicles are generated as per Monte Carlo simulation. Vehicles are placed as per cumulative headway distribution observed. Number of vehicles generated in each time step may be zero, one or more as per the real scenario observation. The vehicles are generated one after the other as per the headway-distribution. The headways of vehicles are generated and vehicle types are assigned by generating random numbers. If sufficient gap is not available, vehicles are kept in the queue. i.e. vehicle enters into the system as soon as first cell is found empty. The number of vehicles in queue at each time-step indicates the queue at entry point. It is assumed that the vehicles will directly enter the system with generated speeds (normally distributed) for the present study. The lateral placement of the vehicle is generated randomly. A vehicle can take lateral position along the width of the road as per the observation. This is because, as already discussed, there are no lanes in the simulations done in this study. Whenever vehicle is generated, it is assigned a free speed. It is assumed that all vehicles enter the simulation road stretch at normally distributed speeds; and during the simulation process, the vehicles will not exceed their assigned free speeds.

Lateral movements are incorporated in the model by specific rules. The traffic is non-lane based, and vehicles can occupy any lateral position on the road. However, it does incorporate overtaking operations. The vehicles are assigned a turning movement option at the time of entry, which they make use of during lateral movements and at the stop line. The gaps available in the system at every time step are informed to the vehicle. For this purpose, scanning is done on all sides of the vehicle, and the minimum gap available is informed. The vehicle moves forward according to the gaps and corresponding CA rules.

Signal
The signal is designed to show three indications: red, green and amber. A timer controls the signal indications, and the beginning of each interval (simulation clock time) is recorded. The signal is an object, having specific attributes like cycle time and location (i.e., cell identification). The cell at which the signal is located is considered the stop line. Based on the turning movement, each vehicle is assigned a signal head, and the vehicle behaves according to the status of the signal head.
Specific new rules are formulated in this study for the movement during three signal statuses: red, green, and amber intervals. Turning movement rules are also formulated. These rules are discussed in the following subsections. For a given intersection, a fixed time signal plan is repeated throughout the simulation time interval. The duration of the cycle is the time required to complete one sequence of signals. Let \( t_c, t_g, t_a, t_r \) are cycle time, green time, amber time and red time respectively. \( t_c = t_g + t_a + t_r \). Simulation time \( t = t_0, t_1, ..., t_n \) where \( t_0 \) is \( 0^{th} \) time step and \( t_n \) is \( n^{th} \) time step. Green time is assumed to be start from first time step, hence, \( t_g \to t_g, t_g + t_{c1}, ..., t_g + t_{cn} \). Amber time \( t_a \to (t_c - t_g - t_r) + t_{c1}, ..., (t_c - t_g - t_r) + t_{cn} \). Red time \( t_r \to (t_c - t_g - t_a) + t_{c1}, ..., (t_c - t_g - t_a) + t_{cn} \).

**Acceleration rule:** This rule follows the basic NaSch rule. But instead of accelerating by a fixed one cell per time step, here the vehicle accelerates according to the acceleration rate specific to the vehicle type. At each time step \( t \to t + \Delta t \), where \( \Delta t \) is selected as 1 s. The rule is as follows: if \( V_n^k < V_{max}^k \) then \( V_n^k = \min (V_n^k + a_n^k \Delta t, V_{max}^k) \) the speed of \( n^{th} \) vehicle is increased by \( a_n^k \), but remains unaltered if \( V_n^k + a_n^k \Delta t \geq V_{max}^k \). Here \( a_n^k \) is acceleration rate of \( n^{th} \) vehicle of type \( k \) in number of cells.

**Rules for movement during red:**

As shown in the Figure 3 let \( D_s \) represent the fixed position of the signal head. As per IRC 93 1985 signal ahead sign should be erected in advance to warn the approaching traffic. Minimum visibility distance up to the signal stop line for average approach speed of 50 to 55 kmph is 70 to 80 m. As per IRC SP 41 1994 the distance from signal stop line to signal ahead sign is 75-100m for major road and 30-50m for minor road for an urban four armed signalised intersection. Considering these IRC guide lines all the cells within the distance of 75 m from the signal head is said to be in speed reduction zone. Any time vehicle enters the speed reduction zone i.e. cells \( D_s-75 \) through \( D_s \), the vehicle decelerate so as to get the vehicle speed below \( V_{min}^k \) or Equal to zero. During red two situations exist; namely no front vehicle (Case - I) and vehicle at front (Case - II) to the current vehicle. Let \( X_n^k \) is the distance between \( n^{th} \) vehicle of \( k \) type and signal stop line. During the red, the rule checks there is any vehicle between the current vehicle and the signal head. If there is no other vehicle in front (Case-I), it adjusts its speed according to the distance to the signal head \( D_s \) and the deceleration \( d_n^k \) of the \( n^{th} \) vehicle of type \( k \) as per the following rule [Eq. (1 & 2)]. If there is a
vehicle in between current vehicle and signal head (Case-II), it adjusts its speed, as per Eq. (3 to 7).

\[ \text{Figure 3: Movement during red signal} \]

**CASE – I (No front vehicle)**

Vehicle is in motion and driver see the red light turns on and if there is no vehicle in front between current vehicle and signal stop line.

\[ \text{If } X^n_k / \Delta t \leq V^n_k \text{ and } D_S - 1 < X^n_k < D_S - 75 \]

then

\[ V^n_k \rightarrow (X^n_k / \Delta t - d^n_k \Delta t) \]

else

\[ V^n_k \rightarrow \max (V^n_k - d^n_k \Delta t, X^n_k / \Delta t) \]

\[ \text{.................. (1)} \]

\[ \text{.................. (2)} \]

**CASE – II (Vehicle in front)**

Vehicle is in motion and driver see the red light turns on and if there is vehicle in front between current vehicle and signal stop line.

\[ \text{if } \text{Gap}^f_n < V^n_k \]

Then,

\[ \text{if } \text{GapR}^f_n > \text{Gap}^f_n \text{ or } \text{GapL}^f_n > \text{Gap}^f_n \]

then

\[ \Delta Y^n_k = m^n_c \pm \text{ldist} \]

\[ V^n_k = V^n_k + a^n_k \Delta t \]

else

\[ \Delta Y^n_k = 0 \]

\[ V^n_k = \text{Gap}^f_n / \Delta t \]

\[ \text{.................. (3)} \]

\[ \text{.................. (4)} \]

\[ \text{.................. (5)} \]

\[ \text{.................. (6)} \]

else

\[ V^n_k = V^n_k + a^n_k \Delta t \]

\[ \text{.................. (7)} \]

Where
\[ \Delta Y_n^k = \text{Increment in } y \text{ direction} \]
\[ \text{l}d\text{ist} = \text{ lateral distance} \]
\[ d_n^k = \text{Deceleration of } n^{th} \text{ vehicle of type } k \text{ in cell per time step} \]
\[ X_n^k = \text{Distance between current vehicle and signal head.} \]
\[ Gap_n^f = \text{minimum front gap for } n^{th} \text{ vehicle at time } t. \]
\[ m_c^k = \text{Width of current vehicle of } k \text{ type} \]
\[ m_f^k = \text{Width of front vehicle of } k \text{ type} \]
\[ D_S = \text{Signal stop line} \]

**Rule for movement during Green:**

During green time, two situations may occur. Green time is on and vehicle may in motion (Situation A) or Vehicle is at stopping condition (Situation B) and Green time turns on. For above said both the situations novel rules were developed.

**SITUATION A : (Vehicle in motion)**

**CASE – I (No front vehicle)**

When green time is on and most of the saturated flow has passed through signal stop line and still green is on and there is no front vehicle between stop line and current vehicle.

If \( V_n^k < V_{\max}^k \), then the velocity of the \( n^{th} \) vehicle is increased by \( a_n^k \) but it remains unaltered if \( V_n^k = V_{\max}^k \) i.e.

\[ V_n^k \to \min ( V_n^k + a_n^k \Delta t, V_{\max}^k ) \] ........................ (8)

**CASE – II (Vehicle in front)**

If \( Gap_n^f / \Delta t \leq V_n^k \), which means if the vehicle continues moving, it will pass the front vehicle at the next time step. Hence it will check for right or left gap available and accordingly accelerate to move forward. Else, its velocity will be reduced as follows:

if \( Gap_n^f < V_n^k \)
then
if \( GapR_n^f > Gap_n^f \text{ or } GapL_n^f > Gap_n^f \)
then
\[ \Delta Y_n^k = m_c^k \pm \text{l}d\text{ist} \]
\[ V_n^k = V_n^k + a_n^k \Delta t \] ........................ (9)
else
\[ \Delta Y_n^k = 0 \] ........................ (11)
\[ V_n^k = Gap_n^f / \Delta t \] ........................ (12)
else
\[ V_n^k = V_n^k + a_n^k \Delta t \] ........................ (13)
SITUATION B : (Vehicle at rest)
CASE – I (No front vehicle)
if \( V_n^k = 0 \) (Vehicle at rest) and green time turns on and if there is no vehicle in between stop line and current vehicle, the velocity of the vehicle is increased as ;

\[
V_n^k \rightarrow \min ( V_n^k + a_n^k \Delta t, V_{max}^k ) \\
\text{.................. (14)}
\]

CASE – II (Vehicle in front)
if \( V_n = 0 \) (Vehicle at rest) and green time turns on and if there is vehicle in between stop line and current vehicle, the velocity of the vehicle is increased as ;

\[
V_n^k \rightarrow \min ( V_n^k + a_n^k \Delta t, \frac{Gap_f}{\Delta t} ) \\
\text{.................. (15)}
\]

Rule for movement during amber:
let Ds represent the fixed position of the signal head (Figure 3). All the cells within the distance of 75 m (IRC SP 41 1994, IRC 93 1985) from the signal head is said to be in dilemma zone. Any time vehicle enters into this zone i.e. cells Ds - 75 through Ds, the vehicle decelerate so as to get the vehicle speed below \( V_{min}^k \) or Equal to zero to stop at signal head or accelerate upto \( V_{max}^k \) to clear intersection. The traffic movements at amber are governed by the driver’s decision, which in turn is influenced by the position of the vehicle and its speed and amber timing (AT) when the signal turn on in this transition phase. The driver is said to be in a dilemma zone if caught in a position too close to the signal when the signal turns amber. The behaviour in this situation is modelled by the proposed amber rule, which computes the distance \( (X_n^k + d) \) with respect to the amber timing and current speed of the vehicle and then determines if the driver wants to stop or move forward and attempt to clear the intersection. If there is no other vehicle in front, it adjusts its speed according to the distance to the signal stop line and the acceleration \( a_n^k \) or deceleration \( d_n^k \) of the vehicle type k as per the following rule [Eq. (16) and Eq. (17)]. If there is a vehicle in between, it adjusts its speed, as in Eq. (18) and Eq.(19). The rules are formulated as;

CASE – I (No front vehicle)
There is no vehicle in front between current vehicle and signal stop line.

\[
t = t_a
\]

For \( 0 \leq t \leq t_a \)

if \( X_n^k + d \leq V_n^k t_a \) then

\[
V_n^k = V_n^k
\]

else \( V_n^k \rightarrow \min (V_n^k - d_n^k \Delta t, X_n^k) \) , \[16\] \[17\]

\[
t = t - 1, t_a = t
\]

Next t

Else
Where,  \( t_a = \) Amber time

**CASE – II (Vehicle in front)**

There is vehicle in front between current vehicle and signal stop line.

If \( V_n^k \geq Gap_n^f / \Delta t \)
then
\[
V_n^k = Gap_n^f / \Delta t
\] ........................ (18)

else
\[
V_n^k \rightarrow V_n^k + a_n^k \Delta t
\] ........................ (19)

**Rule for Right turn :**

![Figure 4: Right turning movement](image)

At each time step \( t \rightarrow t + \Delta t \) where \( \Delta t \) is selected as 1 second, the arrangement of each vehicle is updated in parallel according to the following rules.

if
1. \( V_n^k \rightarrow V_n^k + a_n^k \)
2. \( Gap_p^f \geq \frac{d}{2} + m_c^k \)
3. \( Gap_n^f \geq n_c^k \)
4. \( \frac{d}{2} < a_n^k < d \)
then

\[
RT(A) = A + M_{RT}
\] ........................ (20)

Where,

\( A = \) initial position matrix at signal head for \( i \)th vehicle

\( M_{RT} = \) Transformation matrix for right turn movement

\( RT(A) = \) position of \( n \)th vehicle after right turn

\[
A = \begin{bmatrix}
(x, y) & (x + m, y) \\
(x, y - n) & (x + m, y - n) \\
(x + m, y + m) & (x + m + n, y + m)
\end{bmatrix}
\]

\[
M_{RT} = \begin{bmatrix}
(m, m) & (n, m) \\
(m, n) & (n, n)
\end{bmatrix}
\]

\[
RT(A) = \begin{bmatrix}
(x + m, y) & (x + m + n, y)
\end{bmatrix}
\]

Here
\( m^k \) = width of current vehicle of type \( k \)
\( l^k \) = length of current vehicle of type \( k \)

\( Gap^f_p \) = Front gap of vehicle at present place in number of cells
\( GapR^f_n \) = Front gap of vehicle at right in number of cells

**Rule for left turn:**

if

1. \( V^k_n \rightarrow V^k_n + a^k_n \)
2. \( Gap^f_n \geq n^k_c \)

then

\[ LT(A) = A + M_{LT} \] ........................ (21)

Where,

\( A \) = initial position matrix at signal head for \( i \)th vehicle

\( M_{RT} \) = Transformation matrix for left turn movement

\( LT(A) \) = position of \( i \)th vehicle after left turn

\[
A = \begin{pmatrix}
(x, y) & (x + m, y) \\
(x, y - n) & (x + m, y - n)
\end{pmatrix}
\]

\[
M_{LT} = \begin{pmatrix}
(-n, m) & (-m, m) \\
(-n, n) & (-m, n)
\end{pmatrix}
\]

\[
LT(A) = \begin{pmatrix}
(x - n, y + m) & (x, y + m) \\
(x - n, y) & (x, y)
\end{pmatrix}
\]

here \( Gap^f_n \) = Front gap of vehicle at left in number of cells

**Randomization rule:**

Randomization rule is incorporated to capture realistic behaviour of traffic stream or driver behaviour. Randomization step leads to an additional deceleration equal to \( a^k_n \) (acceleration of type \( k \) \( n \)th vehicle) with probability \( p \) and is due to several behaviours of human drivers:

The first one is an overreaction at braking and keeping a too large distance to the car in front.
Secondly, when distance to the front vehicle increases, one might have a delay in the acceleration process. The randomization is the basis for the formation of jams, because otherwise every car would drive with the ideal velocity, the maximum possible velocity
without crashing into the car ahead. The modified randomization rule is presented in following Eq.

if $V_{n}^{k} > 0$ then $V_{n}^{k} = V_{n}^{k} - a_{n}^{k}\Delta t$ the speed of $n^{th}$ vehicle is decreased randomly by $a_{n}^{k}$, but remains unaltered if $V_{n}^{k} = 0$. Here $a_{k}$ is acceleration in cells per time step of vehicle type $k$ in number of cells.

**Lateral movement criteria**

Lane-changing criteria is proposed based on two-lane model developed by Nagel et al. (1998). This rule is modified for heterogeneous traffic by specifying probability of lateral movement and considering the maximum speed for each vehicle type. The lateral movement rule for a vehicle consists of the fulfilment of the following five criteria:

1. $\frac{gap_{c}^{f}}{\Delta t} - 1 < V_{max}^{lc}$
2. $\frac{gap_{t}^{f}}{\Delta t} - 1 > V_{max}^{k}$
3. $X_{n}^{t} = 0$ (empty)
4. $\frac{gap_{t}^{b}}{\Delta t} - 1 > V_{max}^{lt}$
5. $p_{l} \geq rand()$

where, $gap_{c}^{f}$ is the front gap in the current lane, $gap_{t}^{f}$ front gap in the target lane, $gap_{t}^{b}$ is the back gap in the target lane, $V_{max}^{lc}$ is the maximum speed allowed on the current lane, $V_{max}^{lt}$ is the maximum speed allowed in target lane, $x_{n}^{t}$ indicate whether target space is empty or not, rand() is a function which generates a random number between 0 and 1, and $p_{l}$ is the lateral movement probability.

Criteria 1 ensures that when the front gap available in the current lane is less than the gap required to maintain the desired speed, then the lateral movement could take place. Criteria 2 ensure that the vehicle has sufficient front gap in the target lane to move with desired speed. Criteria 1 and 2 are known as the trigger criteria or incentive criteria which imply that a vehicle move with desired speed. The criteria 3 looks if target space is empty or not. Criteria 4 ensure that the speed of the following vehicle in the target lane is not affected. Criteria 3 and 4 are known as the safety criteria, which ensure that lateral movement is safe by avoiding collision with the following vehicle in the target lane. The criteria 5 take care of the randomness in the behaviour of drivers in lateral movement by introducing a lateral movement probability ($p_{l}$). If all the above criteria are satisfied for a vehicle then that vehicle is eligible for lateral movement.
In Figure 5 lateral movement rule is illustrated for 3.6 m wide road. Here, two wheeler (2W) is considered for lateral movement. The left most corner coordinates are (2,8). It is assumed that two wheeler has speed as $V_n^k = 3$ cells per time step at the instant. The front gap of the two wheeler is $gap_f^p = 2$ cells and is less than its maximum speed ($V_{max}^k = 4$). Hence, the first trigger criterion gets satisfied. The front gap in the neighbour cells at right side is $gap_R^f = 5$ considering front two wheeler (3,3). Similarly front gap at left side is $gap_L^f = 2$ considering front vehicle HCV (0,0) $gap_L^f < V_n^k$ is not satisfied. Hence vehicle cannot have lateral movement on the left side. But $gap_R^f > V_n^k$ is satisfied i.e., second trigger criterion is satisfied and hence, lateral movement on right side is possible. Looking to safety criteria maximum allowable speed is on link with $V_{max}^k = 4$ and back gap in left and right side are $gap_L^b, gap_R^b = 5$. Hence, these criteria are satisfied. Moreover, the adjacent cell is also empty to occupy place on right side. Now, if $p_1$ is satisfied, the vehicle will move to the right side. For each, such instant the grid is updated and the vehicle occupies its new position laterally. Figure 5 shows the details of the front gap and back gap in the neighbouring place of two wheeler (2,8). In this model, vehicles will move in the lateral direction by one cell and hence, the lateral movement may not be possible in single time step, but it is possible after one or more time steps depending on the vehicle type. Hence, lateral movement in this model is more realistic than the same in CA model. In CA model, lateral movement occurs in single time step (one second) whereas in actual it is observed that it takes three to four seconds. This completes the lateral movement process for all vehicles for the current time step. The procedure will be continued until the end of the given simulation time. After the simulation, the model gives individual vehicle trajectory, average travel time of each type of vehicle, classified volume count, and number of lateral movement.
Vehicle updation rule:
Application of the acceleration and randomization rules will result in a new speed. The vehicles move forward according to the new speed. By using this speed and the position in the current time-step, the position at the next time-step is updated. Vehicle updation rule for through, right turn and left turn traffic is as follows;

**Through traffic:**
The vehicle forward movement update rule is presented in Eq. (22)

\[ X_n^k \rightarrow X_n^k + V_n^k \Delta t. \] .......................... (22)

At the same time, the vehicles move laterally, in accordance with the lateral movement rule discussed in the previous section. The vehicle lateral movement update rule is presented in Eq. (23).

\[ Y_n^k \rightarrow Y_n^k \pm \Delta Y_n^k. \] .......................... (23)

where
\[ X_n^k \] and \[ Y_n^k \] = x- and y-coordinates of n\textsuperscript{th} vehicle of type k and \[ \Delta Y_n^k \] is increment or decrement in y direction, if the movement is toward the right or the left respectively.
\[ \Delta Y_n^k = \text{lateral distance. (Increment/decrement in y direction)} \]

**Right Turning traffic:**
After taking a right turn the vehicle forward movement update rule is presented in Eq. (24)

\[ Y_n^k \rightarrow Y_n^k + V_n^k \Delta t. \] .......................... (24)

At the same time, the vehicles move laterally, in accordance with the lateral movement rule discussed in the previous section. The vehicle lateral movement update rule is presented in Eq. (25).

\[ X_n^k \rightarrow X_n^k \pm \Delta X_n^k. \] .......................... (25)

\[ X_n^k \] and \[ Y_n^k \] = x- and y-coordinates of n\textsuperscript{th} vehicle of type k and \[ \Delta X_n^k \] is increment or decrement if the movement is toward the left or right respectively.
\[ \Delta X_n^k = \text{lateral distance. (Increment/decrement in x direction)} \]

**Left Turning traffic:**
After taking a left turn the vehicle forward movement update rule is presented in Eq. (26)

\[ Y_n^k \rightarrow Y_n^k - V_n^k \Delta t. \] .......................... (26)

At the same time, the vehicles move laterally, in accordance with the lateral movement rule discussed in the previous section. The vehicle lateral movement update rule is presented in Eq. (27).

\[ X_n^k \rightarrow X_n^k \pm \Delta X_n^k. \] .......................... (27)
and \( y_n \) = x- and y-coordinates of \( n^{th} \) vehicle of type \( k \) and \( \Delta X_n^k \) is increment or decrement if the movement is toward the right or left respectively.

\( \Delta X_n^k \) = lateral distance. (Increment/decrement in x direction)

**Implementation and Testing**

The model was developed in C#. The required inputs such as vehicular data (types, dimensions, speed, acceleration, and deceleration), traffic data (inflow and composition), signal data (location, heads, and timing), and evaluation data (length of approach, width, cell size, and period of evaluation) were provided from a database. Vehicles were generated as objects with specific attributes. The road was modelled as an individual approach, and each approach was divided into an array of cells. Vehicles were placed randomly along the cross section at the entrance to the section. Time-space diagrams were prepared for varying scenarios and analyzed to check the simulation logic. Delay, space-mean speed, and saturation flow data were extracted, in addition to the vehicle data for each time step.

**Model calibration:**

The developed model is first calibrated for noise parameters like noise probability, and probabilities for lateral movement using travel time data collecting from the field. The noise value is calibrated by exhaustive search method such that the travel time of the vehicles closely matches with the travel time observed. The noise value is found to be 0.45 for the present case study. The lateral movement probability is assumed to be 1.0.

**Model validation:**

The model was validated using delay and saturation flow measured from the field. Digital video camera was used to collect data on the field during peak hours (9.30 a.m. to 11.30 a.m.) at Girish cross road, Ahmedabad city. All signals are pre-timed signals. The video camera was focused covering the one leg of the intersection. Care was taken to cover full queue formed on the study approach. The recording was done for about 90 minutes to 120 minutes for each approach during peak hours. Simultaneously data on signal timing i.e. cycle length, number of phases, phase length was collected manually using stopwatch. The recorded video was replayed to extract the desired information using program developed in C by monitoring keystrokes.

Average stopped delay was measured from the video data during red, when the vehicles were stopped completely or at the verge of stopping. The vehicle-in-queue count method recommended by Highway Capacity Manual (HCM) [Transportation Research Board (TRB) 2000] was used in this study. A vehicles stopping multiple times was counted only once as a
stopping vehicle as per HCM 2000 delay measurement guideline. Speeds were measured from the video, and acceleration and deceleration values were computed. These speeds, acceleration and deceleration values, inflow rates, and traffic compositions were input to the simulation model.

Observation point was selected by playing video cassette. The observation point is normally signal stop line. Start of the green was noted down from video camera timer. Conventional stop watch was used to measure time in seconds. Stop watch is set to zero, by pausing the cassette at the moment signal turn to green. Now cassette is played until the last vehicle from the queue crossed the observation point. Saturation period was noted down from the VCP timer. The period of saturation flow begins when the green has been displayed for 3 seconds (Following ROAD NOTE 34 it was measured). Saturation flow ends when the rear axle of the last vehicle from a queue crosses the stop line. Initial 3 seconds from the start of green are left to take into account start up loss time. It is not possible to count all types of vehicle count at a time for all movements. Therefore, cassette was replayed number of times and every time vehicle count of one or two types was done. The above procedure was repeated for each cycle of saturation period.

Validation was attempted for individual intersection approaches. The results of calibration were used for validation with data from all the approaches. Delay in s/vehicles and absolute error in validation are presented in Table 1. The results indicate that the model represents non lane-based, heterogeneous traffic at signalized intersection approaches reasonably well. The validation results are also acceptable and confirms with similar studies. For example Padmakumar et.al(2013) has reported an error in delay of the order of 3.51 to 8.83 seconds.

### Table 1 Results of model validation (Delay)

<table>
<thead>
<tr>
<th>Approach</th>
<th>Field delay (S/Vehicle)</th>
<th>Simulated delay (S/Vehicle)</th>
<th>Absolute error (S/Vehicle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>62.96</td>
<td>60.55</td>
<td>2.41</td>
</tr>
<tr>
<td>B</td>
<td>93.88</td>
<td>98.50</td>
<td>4.62</td>
</tr>
<tr>
<td>C</td>
<td>34.80</td>
<td>32.70</td>
<td>2.10</td>
</tr>
<tr>
<td>D</td>
<td>37.04</td>
<td>40.17</td>
<td>3.13</td>
</tr>
</tbody>
</table>

The saturation flow during green was also compared with the corresponding field values The comparison between simulated and observed saturation flows is presented in Table 2. The model is thus able to simulate saturation flow conditions. Simulation result shows that the model performs reasonably well in predicting the saturation flow and found to be satisfactorily replicating the field conditions. The validation results are also acceptable and
confirms with similar studies. For example Padmakumar et.al(2013) has reported an error in saturation flow value up to 30%.

### Table 2 Results of model validation (Saturation flow)

<table>
<thead>
<tr>
<th>Approach</th>
<th>Field saturation flow rate (Vehicle/h)</th>
<th>Simulated saturation flow rate (Vehicle/h)</th>
<th>Absolute % error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3857</td>
<td>4371</td>
<td>11.76</td>
</tr>
<tr>
<td>B</td>
<td>5400</td>
<td>4860</td>
<td>11.11</td>
</tr>
<tr>
<td>C</td>
<td>4436</td>
<td>4800</td>
<td>7.59</td>
</tr>
<tr>
<td>D</td>
<td>4000</td>
<td>4800</td>
<td>16.66</td>
</tr>
</tbody>
</table>

**Model Application :**

After calibration and validation, the model was used to analyze two important aspects of heterogeneous traffic: the effect of lateral movements and the impact of composition of traffic. For this purpose, various signalized intersections from across the city of Ahmedabad were studied.

**Conclusion**

A CA based intersection traffic flow model framework was proposed, combining the modelling and computational simplicity of CA. Two key issues of heterogeneous traffic, namely, multiple vehicle types and non lane-based movement, were addressed using multi cell representation of road space occupied by the vehicles and by introducing rules for lateral movement. In addition, novel rules were formulated for vehicular movements during red, green, and amber. Rules for turning movement were also formulated. Also, the lateral movement rule are further modified to incorporate a wider range of options like returning to the previous lateral position after overtaking, cancelling of overtaking in risky situation.

Calibration and validation were done by comparing the delays and saturation flow obtained from signalized intersections carrying highly heterogeneous traffic with the simulated data obtained from the model. The result shows that the model performs reasonably well in predicting the delay (variability up to 4.62 seconds) and saturation flow (absolute error up to 16.66 %) and found to be satisfactorily replicating the field conditions.

**References**


