Feasibility and Accuracy Study of Cell Transmission Model for Real Time Traffic Prediction in Signalized Urban Networks

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Abstract: Traffic prediction is one of the most critical components in intelligent traffic light control systems to project future vehicle evolution in order to make optimal decisions for all competing demand on road in real-time. In this paper, we study the use of cell transmission for traffic prediction in signalized urban network. Existing cell transmission models treat the traffic flow on a link as a single commodity until the flow reaches the diverge point or turn bay. Turning ratio is applied at the diverge point to compute the flow going to individual movement. Lane blockage and spill-back usually happens due to insufficient green time or imperfect road structure such as short turn bay length. In addition, road incidents can cause lane blockage and spill-back anywhere on the road. Most likely the effect of lane blockage and spill-back will not have equal influence on every movement. Thus the turning ratio becomes no longer applicable and will result in vehicles intended to go to one movement being discharged as another movement. To address this, we extend cell transmission model to keep track of vehicle route intent in every cell and to perform vehicle progression at the movement level. To evaluate the feasibility and accuracy of cell transmission model for use in real-time, this study has developed a complete modeling framework comprising connected vehicle traffic simulation platform, real-time traffic tracking and prediction platforms and has conducted extensive simulation experiments with a segment of Corporation Road and Boon Lay Way in Jurong West, Singapore.

1 Introduction

Traffic tracking and prediction has been one of the fundamental components required for intelligent traffic light control and route guidance applications. Traffic tracking is real-time live capturing of the traffic snapshots on the road while traffic prediction is projecting future traffic distribution over the finite time horizon given the current traffic state and future traffic light control setting. Traffic prediction has to not only respond in real-time but also consider complex road geometry and capture traffic progression on the road as simple and accurate as possible to derive the control objective function parameters without failing to account effect due to road incidents and weather conditions.

Traffic prediction result is used by the traffic light control optimizer to find the optimal traffic signal phase sequences. Depending on the type of traffic control applications such as local-level, area-level and network-level, performance requirement of traffic prediction such as accuracy and response time can be varied. Local-level concerns with one intersection and a shorter time horizon, area-level concerns with a cluster of intersections usually needed to have coordinated control over a slightly longer horizon and network-level concerns with multiple clusters of intersections required by perimeter traffic control. This paper studies area-level traffic prediction in signalized urban networks.

Many traffic prediction models for area-level have been proposed in the literature. Cell transmission model [1][2], Platoon Dispersion Model [3], Store and Forward Model [4], Vertical Cell Model [6], BLX and S Models [7] have been proposed and applied in many area-level traffic control applications. In this paper, we study the feasibility and accuracy of cell transmission model for real time traffic prediction in signalized urban networks. We choose to study CTM for the following reasons. It has the flexibility to consider various factors of road geometry such as lane split, bus lane, and road merge and diverge. It is simple to derive control objective function parameters such as number of stops and delay. It has the ability to emulate traffic incidents based on the location of cell. It is applicable for both local-level control and area-level coordination control purposes.

The cell transmission model (CTM) [1][2] is proposed by Carlos F. Daganzo to predict traffic evolution over time and space with the ability to capture building, propagation and dissipation of queues. It has been used in many traffic control approaches [8][13][17][18]. Extensions of the CTM [9][10][12][16][17] have been discussed in the literature. In this paper, we consider various extensions made in the literature and improve the CTM further with new feature additions. We develop a complete modeling framework which comprises building real road network environment, connected vehicle traffic simulation platform, real-time traffic tracking platform, and real-time traffic prediction platform. The performance in terms of feasibility and accuracy is studied under extensive simulation experiments.

The rest of the paper is organized as follows. We first review different types of traffic prediction models and extensions of CTM in Section 2. We then discuss existing cell transmission model formulations in Section 3. A modified cell transmission with new feature additions are presented in Section 4. In Section 5, we present various platforms in modeling framework for network traffic tracking and prediction. In Section 6, we present the experimental studies and results. We conclude with some closing remarks and future works in Section 7.

2 Related Work

We first review area-level traffic prediction models used for modeling traffic progression in network of intersections. Basically, a prediction model first identifies the current state of vehicle snapshots and then progress them into the future based on the travel time, turning ratios, traffic plan of intersections, and road traffic conditions.

Platoon dispersion model (PDM) [3] has been used in control approaches [22][23] to predict future traffic distributions. As traffic signal divides traffic flows into a series of platoons, PDM identifies traffic platoons based on upstream discharge flow rate, propagates the identified platoons to the downstream intersection based on the travel time on the link and the platoon dispersion factor of the link...
and outputs the arrival flow profile at the stop-line of the downstream intersection. It is shown to be suitable for long links and uncongested traffic. Cell transmission model (CTM) \cite{1} \cite{2} represents traffic flow by number of vehicles in short road segments called cells. Minimum cell length is equivalent to free-flow distance per second. Vehicle progression between adjacent cells is dependent on cell density through the use of network fundamental diagram. CTM is first used in dynamic network traffic control \cite{8} for signalized urban intersections. It validated that delay estimation of CTM matches reasonably well with the actual field measurements under a variety of traffic conditions. Store and forward \cite{4} model represents traffic flow by number of vehicles within the link based on the link input flow and link output flow in a cycle-by-cycle manner. Model time step being equal to the cycle length, it is not able to model short-term queue oscillations due to red-green switching within a cycle. Vertical cell model (VCM) \cite{6}, similar to CTM, subdivides the link into multiple transit cells and one queue cell. In contrast to CTM, link receiving constraint is based on occupancy of all cells of the link and vehicles progress through transit cells without constraints. Approximate prediction in response to a signal network (APRES-NET) \cite{20} is used in real-time hierarchical traffic management system called RHODES \cite{21}. APRES-NET identifies traffic platoons using detectors and propagates them to the downstream detectors. By using future signal plan, turning ratio, average waiting time in queue, travel time and delay time, it predicts area-wide traffic distribution for a given time horizon. Performance comparison between CTM and PDM has been conducted in \cite{5} and between CTM and VCM in \cite{6}.

Extensions of CTM have also been proposed in the literature. We discuss the most related extensions of CTM here. Discussion on other extensions of CTM can be found in \cite{9}. The link-node cell transmission model (LN-CTM) is proposed in \cite{10} \cite{11} to model traffic progression in signalized intersections. It allows non-uniform cell length where a cell can be larger than free flow distance per time step. It considers general network topology with multiple entering and leaving links. In LN-CTM, a link between two intersections is divided into two parts where the upstream part is shared by all movement and diverge into individual link (right, through, left) in the downstream part. Diverge point is the approximate location where traffic flow splits into different movement lane. To capture lane blockage and spillback effect caused by a particular movement at the queue area, a new type of cell representation is introduced in \cite{12}. The diverging location where traffic flow splits into different movement lane is presented with a diverging cell, which is further divided into sub-cells where the total number of sub-cells is equivalent to one sub-cell for each explicit movement plus one additional sub-cell for shared movement. A modified CTM with realistic queue discharge features at signalized intersections is proposed in \cite{15} \cite{16}. When the traffic light turns green, traditional CTM discharges queue at the saturation flow rate, over-estimating the intersection capacity. It states that although introducing start-up lost time to account for capacity loss due to start-up acceleration of vehicles, the cumulative flow may not be accurate and discharge headways do not match the observed pattern. In the modified model, a new demand or sending function is added in the fundamental diagram to account for realistic discharge flow rate and headway profile when queue discharges. Urban cell transmission model (UCTM) for prediction of traffic delay to be used by local-level traffic control optimizer is proposed in \cite{17}. In UCTM, source model that generate platoons of vehicles is used to inject edge link input flow. The link is divided into cells with variable cell length with larger cell length before the bay area and shorter cell length for the bay area. As the prediction is used for fast switching of traffic light in the near future in 5 to 10 seconds, shorter cell length is used for bay area to have accurate predictions. The area where traffic splits into different movement lane is represented by parallel cells where a cell corresponds to one movement. Regardless of the cell length, the model time step for state update is set as one second. It uses modified fundamental diagram in \cite{15} for every cell state update. To account for lane blockage and spillback effect caused by a particular movement at the bay area, a parameter to represent how strongly the diverging streams influence each other is defined and used to compute the receiving flow for each movement cell.

### 3 Cell Transmission Model

To predict the evolution of multi-commodity traffic flows over complex networks over a finite time horizon, Daganzo proposed cell transmission model which uses simple macroscopic state formulation to keep track of traffic state over time. A traffic on a link between two intersections is modeled by a set of cells and their interconnections. A cell length $L$ has to be $\geq v_f \Delta t$ where $v_f$ is the free flow speed and $\Delta t$ is the time step interval. Vehicle progression between adjacent cells is dependent on cell density through the use of network fundamental diagram. At each time step $t$, each cell $i$ computes vehicle state $n_i$ based on the receiving flow $y_{in}$ (from previous cell) and sending flow $y_{out}$ (to next cell) as in (1).

$$n_{i+1} = n_i + y_{in} - y_{out}$$  \hfill (1)

The flow from a cell $i$ to cell $i+1$ is computed based on the flow-density relationship in (2) which is also illustrated in the fundamental diagram Fig. 1.

$$y_i^t = \min \{n_i^t, Q_i^t, \delta [N_{i+1} - n_{i+1}^t] \}$$  \hfill (2)

The flow-density relationship can also be written as in (3).

$$y_i^t = \min \{v_f K_i, Q_i^t, w[K_{i+1}^t - K_i^t] \}$$  \hfill (3)

Where $Q_i$ is the saturation flow rate, $K_i$ is the critical density, $K_i^t$ is the jam density, $N_i$ is the maximum cell capacity or number of vehicles that a cell can hold, which is computed as $L_i K_i$ and $w$ is the shockwave speed.

If we define sending and receiving function of a cell as $S_i^t = \min \{n_i^t, Q_i^t \}$ and $R_i^t = \min \{Q_i^t, \delta [N_i^t - n_i^t] \}$, the flow progression in (2) can be written as:

$$y_i^t = \min \{S_i^t, R_i^t + 1 \}$$  \hfill (4)

The flow equation (4) states that flow from cell $i$ to cell $i+1$ should be the maximum that can be sent by cell $i$ unless prevented to do so by cell $i+1$. When $S_i^t > R_i^t + 1$, which is usually the case when vehicle approaches queue or the bottleneck, shockwave speed $w$ has to be considered and it is usually several times slower than the free flow speed $v_f$. Therefore, the condition $\delta = 1$ if $n_i^t \leq Q_i$ and $\delta = w/v_f$ otherwise is added to allow shockwave speed in the flow progression and to eliminate spreading it further to upstream cells.

The first cell (most upstream cell) of the link takes in the flow from the last cell (most downstream cell) of the input links. The traditional CTM assumes that at signalized intersections, there is no conflict for input flow from different input links as they will be given different priorities by the traffic light signal phase sequence to enter the downstream link.

Traffic diverges to different output links at the last cell (most downstream cell). When the light is red, $Q_i^t = 0$. When the traffic light fundamental diagram is green, traditional CTM discharges queue at the saturation flow rate $Q_i^t$, over-estimating the intersection capacity. In the modified CTM \cite{15}, a new constraint is added in the sending function (5) when $n_i^t > Q_i$ to have realistic queue discharge rate and headway profiles. The new fundamental diagram is shown in Fig. 2.
\[ S'_i = \min \{ n'_i, Q'_i, Q_j + \delta_d [N_i - n'_i] \} \]

The new constraint in (5) is \( Q_j + \delta_d [N_i - n'_i] \) where \( Q_j \) is the jam demand flow rate, \( \delta_d = w_d/v_f \) and \( w_d \) is the slope of the demand curve as illustrated in the sending function of new fundamental diagram.

4 A Modified Cell Transmission Model

In this section, we present new modifications added into the existing cell transmission model. Traffic prediction has to not only respond in real-time but also consider complex road geometry and capture traffic progression on the road as simple and accurate as possible without failing to account effect due to road incidents and weather conditions. Lane-blockage and spill-back is one of the critical factors with high impact on traffic flow progression. Lane blockage and spill-back usually happens due to insufficient green time or imperfect road structure such as short turn bay length. In addition, road incidents can cause lane blockage and spill-back anywhere on the road.

Both works in [12] and [17] address the lane blockage and spill-back effect caused by a particular movement at the turn bay area. In [12], a diverging cell with sub-cells is introduced where the total number of sub-cells is equivalent to one sub-cell for each explicit movement plus one additional sub-cell for shared movement to represent the area where traffic splits into different movement lane. The input flow for each movement is computed based on the turning ratio of total input flow to the diverging cell. In [17], a diverging cell with sub-cells where one sub-cell corresponds to one explicit movement without having a shared sub-cell is used. Similarly, the input flow for each movement is computed based on the turning ratio of total input flow to the diverging cell. The actual input flow to each movement cell is weighted averaged over the two cases where one for no blockage at all (optimistic case) and another for maximum blockage causing total input flow to be slowed down at the same rate (pessimistic case).

In both cases, the receiving flow from the upstream cell is taken as a whole lot and turning ratio is applied to get the input flow for each movement. In addition, the lane blockage and spill-back can happen anywhere on the road. Most likely the effect of lane blockage and spill-back will not have equal influence on every movement. Thus the turning ratio becomes no longer applicable and will result in vehicles intended to go to one movement being discharged as another movement. To address this, we extend cell transmission model to keep track of vehicle route intent in every cell and to perform vehicle progression at the movement level.

We consider three turning directions: right (R), through (T), left (L) in the paper. U-turn is not considered and can be added without any change in the model. For cell with all directions, the state update in (1) can be written as:

\[ n_i^{t+1} = n_i^t + y_{in}^t - y_{out}^t \]
\[ n_i^t = n_i(R) + n_i(T) + n_i(L) \]
\[ y_{in}^t = y_{in}(R) + y_{in}(T) + y_{in}(L) \]
\[ y_{out}^t = y_{out}(R) + y_{out}(T) + y_{out}(L) \]

The flow from a cell \( i \) to cell \( i + 1 \) is computed as \( y_i^t = \min \{ S'_i, R_i^t+1 \} \). For each movement \( y_i(R), y_i(T), \) and \( y_i(L) \), drawing lot is carried out on the entire vehicle population \( n_i(R) + n_i(T) + n_i(L) \) such that \( y_i(R) + y_i(T) + y_i(L) = y_i^t \).

To capture the vehicle moving into correct movement lane at the traffic split location (right split and/or left split whichever is earlier), cell is divided into sub-cells with each sub-cell corresponds to either explicit or shared movement. We consider five different types of sub-cells: right (R), through (T), left (L), right-through (RT), through+left (TL) based on the actual lane movement coding on the road. Each sub-cell has its own holding capacity and saturation flow rate. Any cell or sub-cell with shared movement R+T+L or R+T or R L keeps track of vehicle state for each route intent R, T, and L. The cell representation of a link is shown in Fig. 3.

4.1 Merge cell

Merge cell which is the first cell or the most upstream cell of the link takes in the vehicles released from the last cell of the input links. Although it can be assumed that there is no conflict between vehicles from different input links due to different priority given by signal phase sequence, a conflict can still arise when an input link evacuates vehicles through filter lane without any signal light. To address this, we use yellow-box concept with finite capacity. If vehicle input exceeds the available space, it will be placed into the yellow-box. The input flow \( y_{in}^t \) from the upstream links is divided into \( y_{in}(R), y_{in}(T), \) and \( y_{in}(L) \) based on the turning ratio of link such that \( y_{in}(R) + y_{in}(T) + y_{in}(L) = y_{in}^t \). The new state of the cell is computed as follows:

\[ n_i^{t+1} = n_i^t + y_{in}^t - y_{out}^t \]
\[ n_i^t = n_i(R) + n_i(T) + n_i(L) \]
\[ y_{in}^t = y_{in}(R) + y_{in}(T) + y_{in}(L) \]
\[ y_{out}^t = y_{out}(R) + y_{out}(T) + y_{out}(L) \]

4.2 Normal cell

A normal cell is a cell within the main cell section. The total output flow from a normal cell to next normal cell is computed as \( y_i^t = \)
min\{S^t_i, R^t_{i+1}\} based on the entire vehicle population of the cell \(n^t_i\). The output flow for each movement is obtained by drawing of lots such that \(y^t_i(R) + y^t_i(T) + y^t_i(L) = y^t_i\). The new state of the cell is then computed as in (7).

There can also be a side road merge or diverge with this cell. In side road merge case, we assume that priority is given to the main flow, and in diverge case, we assume that the side road has sufficient capacity to accommodate the flow diverging from the main road.

### 4.3 Sub-cell

A sub-cell is a cell within the sub-cell section. It also has cell capacity \(N_t\) and saturation flow rate \(Q_t\). A sub-cell ID can be one of the five types: right (R), through (T), left (L), right-through (RT), through-left (TL). A sub-cell with shared type RT or TL keeps track of the vehicle state of each type, \(n^t_i(R), n^t_i(T), n^t_i(L)\) and \(y^t_i(R), y^t_i(T), y^t_i(L)\) for RT sub-cell and \(n^t_i(T), y^t_i(T), y^t_i(L)\) for TL sub-cell.

#### 4.3.1 Normal cell to sub-cells: The vehicle progression from a normal cell to a cell i + 1 with sub-cells is shown in Fig. 4. Each vehicle state \(n^t_i(R), n^t_i(T), n^t_i(L)\) tries to progress to sub-cell for explicit movement as follows.

\[
\begin{align*}
S^t_i(M) &= \min\{n^t_i(M), Q_j(M) + \delta_d[N_i - n^t_i(M)]\} \\
R^t_i + 1(M) &= \min\{Q_i + 1(M), \delta[N_i + 1(M) - n_i + 1(M)]\} \\
M &= R, T, L
\end{align*}
\]

The remaining vehicles \(n^t_i(R'), n^t_i(T'), n^t_i(L')\) are then discharged to sub-cell with shared movement. As \(n_i^t(T')\) can be discharged to both RT and TL sub-cells, it will first try to progress to TL sub-cell and the remaining \(n_i^t(T')\) to RT sub-cell by considering the traffic rule of vehicle keeping left. The \(y_i^{t(TL)}\) and \(y_i^{t(RT)}\) are obtained by sending function as in (9) while the receiving function is the same as in (8) where \(M = TL, RT\):

\[
\begin{align*}
S^t_i(TL) &= \min\{n^t_i(T'), n^t_i(L'), Q_j(TL) + \delta_d[N_i(TL) - (n^t_i(T') + n^t_i(L'))]\} \\
S^t_i(RT) &= \min\{n^t_i(R'), n^t_i(T'), Q_j(RT) + \delta_d[N_i(RT) - (n^t_i(R') + n^t_i(T'))]\}
\end{align*}
\]

The actual flow \(y^t_i(T')\) and \(y^t_i(L')\) is computed by drawing of lots on vehicle population \(n_i^t(T')\) such that \(y^t_i(T') + y^t_i(L') = y^t_i(TL)\). The total flow from cell i to cell i + 1 becomes

\[
y_i = y^t_i(R) + y^t_i(R') + y^t_i(T) + y^t_i(T') + y^t_i(L) + y^t_i(L')
\]

### 4.3.2 Sub-cells to sub-cells: Fig. 5 shows vehicle progression from sub-cells to next sub-cells. Sub-cells with explicit movement R, T, or L type are progressed to next sub-cell with the same movement type. For sub-cell with shared movement type TL and RT, indicated by * and ** in Fig. 5, it will first try to progress over to explicit movement sub-cell if there is any space available and the remaining vehicle will be progressed over to next shared movement sub-cell.

#### 4.4 Diverge cell

Diverge cell is the last cell with sub-cells where vehicle leaves and joins the downstream link. For some links, the left-turn vehicle can be discharged through filter lane while some links use traffic light to control the left-turn vehicle discharge. A conflict may happen between vehicles discharged through filter lane and vehicles from another input link. To resolve this, a yellow-box concept with finite capacity is used.

Each sub-cell discharges corresponding movement vehicles when the traffic light state for that movement is green. Sub-cell with explicit movement discharge first followed by the shared movement sub-cell. The discharge process can be written as

\[
\begin{align*}
y^t_i(M) &= \min\{S^t_i(M), R^t_{i+1}\} \\
S^t_i(M) &= \min\{n^t_i(M), Q_j(M) + \delta_d[N_i - n^t_i(M)]\} \\
R^t_{i+1} &= \min\{Q_i + 1(M), \delta[N_i + 1(M) - n_i + 1(M)]\}
\end{align*}
\]

where \(Q_j(M)\) is zero when traffic light is red or saturation flow rate when the light turns green. \(n_i^t\) is the number of vehicles occupying the yellow box. Therefore, the diverge flow \(y^t_i(M) = 0\) when \(Q^t_i(M) = 0\) or when \(n_i^t \geq \delta[N_i + 1 - n_i + 1]\) i.e., until all vehicles in the yellow-box have been cleared.

### 5 Modeling Network Traffic Tracking and Prediction

In this section, we present framework developed for modeling network traffic tracking and prediction. The entire framework is written in C++. The illustration of the framework comprising various platforms is shown in Fig. 6. Connected vehicle emulator, road-side unit, traffic tracking platform, and traffic prediction platforms are running in parallel independently. The simulation experiments are conducted with a segment of Corporation Road and Boon Lay Way in Jurong West, Singapore, shown in Fig. 7.
5.1 Connected Vehicle Traffic Simulation Platform

CTM performance is usually studied at the flow level in existing works as the availability and the accuracy of data is limited and usually obtained through static cameras or scanners. With the advancement of dedicated short range communication (DSRC) technologies, in the near future, vehicles will be equipped with on-board radio and the position of the vehicles can be known in real-time. With these rich vehicle location data, the detail ground truth snapshot of traffic distributions on the road network can be obtained. The traffic predictor can then use the vehicle snapshots as a starting point and progress the vehicles over the road network in a given time horizon. The prediction accuracy or error can be obtained by comparing predicted cell state against ground truth cell state.

We use VISSIM simulator [24] to emulate connected vehicles sending DSRC message every second. The message contains the location (x,y, lane number) and speed of the vehicle on the link. The road-side unit accumulates the messages received and periodically sends an update to the vehicle tracking platform. A database is maintained in the vehicle tracking platform to keep record of cell-based vehicle snapshot for each link. Periodically, the platform processes the new messages and generates the snapshots. Based on the location of the vehicle on the link, the corresponding cell state of the link is updated. The link configurations of the study network shown in Fig. 7 is given in Table 1.

5.2 Building baseline network

Before tracking and prediction is started, a baseline network which represents the exact road geometry is built. We divide the road/link into equal length cells with \( L = \frac{v}{f} \Delta t \). Based on the right/left split distance (whichever is earlier) to the stop-line and the lane movement coding at the stop-line, the sub-cell section is formed. In the study, we also consider side roads on links 433601, 434201, and 433703 where traffic from the main road diverge to the side road.

<table>
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<th>Link</th>
<th>Junction</th>
<th>Approach</th>
<th>Length(m)</th>
<th>Right split distance(m)</th>
<th>Left split distance(m)</th>
<th>No. of lane main section</th>
<th>No. of lane sub section</th>
<th>Movement coding</th>
<th>Turning ratio R,T,L</th>
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The jam density is the number of queued vehicles per unit queue length. The saturation headway and initial discharge headway values are obtained as follows. At the start of the green time, the queued vehicles discharged with headway values decreases from initial discharge headway to saturation headway value, which has been studied in [14][15]. For each vehicle $i$, the headway value $h_i$ is computed as $t_i - t_{i-1}$ where $t_i$ is the time taken for a vehicle $i$ to pass the stop-line and $t_{i-1}$ is the time taken for the vehicle in front. The first vehicle headway value is the initial discharge headway and the last is the saturation headway. The result is obtained by averaging over different lanes of the link and 8 different cycles of traffic light, which is shown in Fig. 8.

With headway values $h_d$ and $h_s$, the saturation flow rate $Q$ is computed as $1/h_s$, jam demand $Q_j$ as $1/h_d$, and critical density $K_c$ as $Q/v_j$. The shock-wave speed $w$ can be computed as $w = Q/(K_c - K_e)$ and slope of demand curve $w_d = (Q - Q_j)/(K_c - K_j)$. The default parameters used in modeling are 18 meter per second for free-flow speed, 0.5 vehicle per second for saturation flow rate, and 0.125 vehicle per meter for jam density.

### 5.4 Vehicle input estimation

For merge cell (the most upstream cell) discussed in Section 4.1, it takes in the vehicles released from the last cell of the input links and divides the total input into right state, through state and left state based on the link turning ratio given in Table 1. We use a simple random sampling to discretize the input into different movement states. We study this accuracy by injecting vehicle input from one hour ground truth input flow and applying the sampling model to generate vehicle turning count at each time step. The model turning ratio at the end of the simulation is then compared against the ground truth turning ratio to get error. The mean error shown in Fig. 9 is obtained by averaging over 100 simulation runs. It can be observed that the maximum error between model turning ratio and ground truth turning ratio is at most 0.01 for each movement on all links in the study network. For edge link, exact vehicle input as in the ground truth is used to inject vehicle. Modeling edge link input flow by generating vehicle platoon based on the upstream phase sequence plan is the future work.

#### 6 Performance Study

The performance of cell transmission model is studied under heavy traffic condition and insufficient service rate or green time. The major input flows come from source links at junctions 4403 and 4335 where the flow is in range between 0.26 vehicles per second and 0.42 vehicles per second. The source links at other junctions have lower input flow which is around 0.1 vehicles per second. We focus on the performance of southbound traffic flow from junctions 4403 and 4335 to 4337 where traffic flows from higher capacity links (more lanes) to lower capacity links (fewer lanes). The service rate or green time over cycle length $g/C$ for each movement of the link is shown in Fig. 10. Fixed time signal plan is used and cycle length is set as 140 seconds. It can be observed that the right turn traffic has only 10% of the total service rate and through flow has about 33%. Most of the links in the network have filter lane for left turn traffic, and thus having permanent green. This will likely result in conflict with other traffic flows when joining downstream link in CTM model.

To study the accuracy, the CTM prediction is called at 140 second and run for progression over 900 second horizon. At 140 second, every link in the network sets each cell state by reading traffic distribution or snapshots from vehicle tracking platform. The flow progression from cell to cell is then performed at every step with one second step size. The accuracy of progression is then studied by comparing against ground truth data at every step.
We particularly look into right and through movements which have limited service rate. We first study link 433501 which has vehicle input of 0.42 vehicles per second. Explicit right turn and left turn starts at 127 m and 92 m from the stop-line. At the right split point, a cell with two sub-cells: one for right (R) and another for through and left (TL) movement is formed. At the left split point, a cell with three sub-cells: R sub-cell, T sub-cell and L sub-cell is formed. In total, there are 7 cells with sub-cells within the sub-cell section on link 433501. The predicted and ground truth number of vehicles within sub-cell section is shown in Fig. 11 and error per cell distribution is given in Fig. 12. We observe that most of the queue build up and queue discharge are predicted quite close to the ground truth. The average error per cell over 900 second horizon is about 0.5 vehicles.

The link 433701 performance which is the most downstream link in southbound traffic flow is given in Fig. 14. Its error per cell distribution is given in Fig. 15. The right turn bay length of this link is about 50 m from the stop-line. Due to heavy through movement demand which is about 73%, we observe lane blockage and spill-back caused by through flow. The spill-back propagated to main-cell section where entire cell (two lanes) is taken up by through flow. It is observed that the spill-back reaches about 7 cells from the stop-line at around 400 second and 700 second as shown in Fig. 13. Due to short right turn bay length, this spill-back results in blockage to right turn flow. Given this condition, it is observed that CTM closely predicts vehicle progression with around 0.9 average error per cell over the 900 second horizon.

In the following discussion, we present the cases where prediction can be off from ground truth. As shown in Fig. 16, severe lane blockage and spill-back happens on link 440301 starting from 700 second. On this link, sub-cell section starts at 5 cells from the stop-line where the most upstream cell in this section has two sub-cells: one for explicit right movement with one lane capacity and another
for through and left shared movements with three lanes capacity. In the main cell section, each cell has three lane capacity and all movements share the capacity equally. We found that this assumption of capacity being shared equally among movements in the model causes large error. This link has vehicle input flow at rate 0.28 vehicles per second, where 27% of the vehicles are turning right. However, the service rate for these right turn vehicles is only 10% of the cycle, resulting in more and more right turn vehicles in the queue as time progresses. In ground-truth main cell section, we observe that right turn vehicles tend to queue on two inner most lanes when the right turn bay is full. This behavior results in having one-lane free for through and left movements. However, in CTM, the entire cell in main cell section is taken up by right-turn vehicles causing complete blockage to the through and left movements. This results in large error around 740 second onward as shown in Fig. 17.

We then study link 440302 where CTM is shown to exactly predict queue build up and discharge pattern as in the ground truth however having a large difference in number of vehicles report as shown in Fig. 18. On this link, sub-cell section starts at 5 cells from the stop-line where the most upstream cell in this section has three sub-cells: one for explicit right movement with one lane capacity, second for right and through (RT) shared movements with one lane capacity and third for through and left shared movements with two lanes capacity. This link has vehicle input flow at the rate of 0.26 vehicles per second where 27% of the vehicles are turning right. The service rate for these right turn vehicles is also 10% of the cycle. In the model, right turn vehicles progress to explicit right turn sub-cell whenever there is a space available and only moving into RT sub-cell otherwise. However, in ground truth, both R sub-cell and RT sub-cell are used almost equally by the right-turn vehicles resulting in being able to discharge all right-turn vehicles within very short green time. As the model makes right turn vehicles take explicit right lane first, we observe permanent queue along R sub-cells, resulting in large difference in number of vehicles report.

We then look at the overall progression pattern for all links in the network. In this study, the CTM prediction is called at 600 second. The vehicle progression snapshot in ground truth and in CTM for the entire network at time 689 second is shown in Fig. 19. It is observed that CTM closely predicts the traffic pattern for all junctions in the network. However, as discussed above, in ground truth, right turn vehicles tend to take inner most lanes while through vehicles take all lanes equally. The model currently does not capture this behavior resulting in some error when lane blockage and spill-back gets severe and reaches to the main-cell section. This behavior can be seen in the snapshot at time 724 second shown in Fig. 20 where the link 433601 discharges through vehicles in ground truth while they are being blocked due to right turn vehicles taking up all lanes in the model.

7 Conclusion

In this paper, a modified cell transmission model which keeps track of vehicle route intent in every cell and performs vehicle progression at the movement level is presented. A modeling framework comprising connected vehicle simulation platform, traffic tracking platform and traffic prediction platform is discussed. Extensive simulation experiments are conducted under real road geometry along a segment of Corporation Road and Boon Lay Way in Jurong West, Singapore. Prediction performance is studied under insufficient green time, imperfect bay length, and complex lane movement coding scenarios. The study shows that CTM with movement level progression closely predicts the traffic flow. We particularly look at effect of lane blockage and spill-back on different movements. We observe that different behavior of vehicle with different route intent taking up the lanes has to be considered to improve the performance further. This will be added in the future work. In addition, as traffic flow can be varied on different links and on different time of the day, auto-tuning of parameters will be considered in the future work to optimize the model parameters in order to have better accuracy.
Fig. 19: Vehicle progression in the network at time 689 second.

Fig. 20: Vehicle progression in the network at time 724 second.

8 References


