Simulation of Arterial Traffic Using Cell Transmission Model

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Abstract

Cell transmission model (CTM) is one of the widely used macroscopic traffic models. There was a lot of research to show this model could provide reliable simulation of freeway traffic, and it has many applications in traffic management design. But there was insufficient proof to demonstrate this model can accurately simulate urban traffic. This paper illustrates the use of cell transmission model on a segment of signalized arterial. The data source is the NGSIM data collected on Lankershim Blvd. The simulation result agrees with the measurement.

INTRODUCTION

Traffic simulation tools are useful in traffic management and operation planning. It helps to test and evaluate the traffic control strategy or road design before adopting it. It can save time or money by fast evaluation of the influence of the control or design. It shortens the process of testing the control or design on a road, and reduces the possible harmful effect on traffic. To get a valid evaluation of the control or design through simulation, we need a solid traffic simulation model, which can accurately simulate the traffic characteristics and re-create the traffic condition.

A macroscopic traffic model considers traffic in the level of density and flow. Traffic is treated as streams. In the contrast, a microscopic model considers traffic in the level of individual vehicles, and it models the dynamics of every single vehicle. Compared with microscopic models, macroscopic models have the advantage that it usually has fewer parameters to calibrate. Also, to calibrate or validate a macroscopic model, it only requires traffic data like flow, density or occupancy. This type of data can be collected easily by loop detectors. On the other hand, calibrating a microscopic model requires trajectories of individual vehicles, which has to be obtained through camera or GPS. Thus, macroscopic models have a larger source of available data and it is easier to access. Further, macroscopic models can be computed faster and take less computer resource.

Cell Transmission Model(1,2) is one of the macroscopic traffic models that are widely used. It originated from LWR(3,4) model and can reproduce traffic shocks. It has very few parameters to calibrate. It's efficient in computation. Some research on simulation and calibration of cell transmission model demonstrated that CTM was able to offer reliable simulation of freeway traffic. In the early effect, Lin et al.(5) validated the cell transmission model on a signal freeway link without on-ramp and off-ramp, using data from I-680 in California. Later Munoz et al.(6) calibrated the CTM with traffic data on a segment of I-210 in California, which contained on-ramps and off-ramps. In his calibration procedure, the free-flow speed, shockwave speed and jam density were selected by least-square fitting, and bottleneck capacity was estimated from downstream measured flow and on-ramp flow. Simulation showed that CTM could match the collected measured travel time. Muralidharan et al.(7) further extended the application of cell transmission model. In his paper, freeway flow and density data was used to calibrate the fundamental diagram and an adaptive iterative learning procedure was adopted to impute the missing ramp flow. The result showed that the simulation can re-create the traffic condition very well. The error in terms of density, speed, travel distance and travel time was attractively small.

Because of simplicity and reliability of cell transmission model, it was selected in a wide range of control strategy design. Ziliaskopoulos(8) and Golani et al.(9) applied it in traffic assignment. Waller et al.(10) used it in network design. Among the applications in urban street signal design, we can find Almasri(11), Lo(12), Ukkusuri(13), TRANSYT(14) and many other examples. Almasri et al. modeled the traffic flow on urban street with cell transmission model and developed an online offset optimization method. This optimization tried to minimize the delay using a Genetic Algorithm. Similarly, Lo et al. used cell transmission model to formulate the traffic dynamic and optimized signal timing by a mixed integer program. The optimization also took delay as the objective function. The optimization problem is a mixed integer program. Ukkusuri et al. proposed a robust signal timing optimization accounting for the uncertainty. The formulation of the optimization problem employed an embedded cell transmission model for the traffic dynamics. TRANSYT, a software developed by TRL, offered cell transmission model and platoon dispersion model in its traffic simulation and signal timing optimization.

However, compared with the work of calibrating and validating cell transmission model using freeway data, there was insufficient result on testing it using urban traffic data, even though we could see many control proposals on urban street based on this model. This paper tries to address the question that whether cell transmission model could accurately simulate urban traffic. The traffic data we used for the test and analysis is the NGSIM data collected in Lankershim Boulevard. This paper is organized into five sections. Section I is the introduction section. Section II describes the data set we used and some observation from the data. Section III explains the simulation model, which includes the network representation, the selection of the fundamental diagram, the demand, split ratio, initial density, and signal timing. Section IV discusses the simulation result. Finally, section V is the conclusion.

DATA DESCRIPTION

Data Set

The data set used in this simulation is the Lankershim dataset presented by Next Generation Simulation (NGSIM) project(15) from Federal Highway Administration (FHWA). The data was collected on a segment of Lankershim Boulevard in Los Angeles, California, between 8:28am and 9:00am on June 16, 2005. Fig. 1 shows a map of the studied road segment. This segment of arterial is about 1600 feet. It has 3 to 4 lanes in both directions. There are 4 signalized intersections and they are labeled from south to north in an ascent order in Fig. 1. There are left-turn bays at these intersections on the road. This road, from south to north, intersects with one off-ramp from US-101, Universal Holywood Dr, and James Stewart Ave/Valleyheart Dr. Speed limit on this segment is 35 mph. The 4 signalized intersections are under actuated control. There are 2 drive-ways to parking lot in this segment.

The whole package of this data set has many data files. It contains the vehicle trajectory data, raw/processed video data, ortho photographs, CAD drawings, signal timing, detector data, GIS files, and data analysis. We only use vehicle trajectory data and signal timing for the input of the simulation.

The vehicle trajectory data was collected by taking video from 5 cameras. Vehicles were detected and tracked from video images, and then vehicle trajectories were obtained through processing this tracking information. The data was divided into two pieces, 8:28-8:45am and 8:45-9:00am. The resolution is 0.1 second. There are about 1.6 million data points in two files, and each data point is a state of a vehicle. The information in a data point includes vehicle identification, time, local/global x & y position, vehicle length & width, speed, acceleration, origin & destination, the lane/intersection/section/direction the vehicle was driving on, preceding & following vehicle, etc. We extract demand and split ratio for simulation from this data.

In the signal timing files, it has signal timing sheets and real-time split monitor reports. In the signal timing sheet, we could get the information of phase, duration of yellow and red time, and cycle length. In the real-time monitor report, we could get the information of green length for each phase in each cycle, and the start and end time of each cycle.

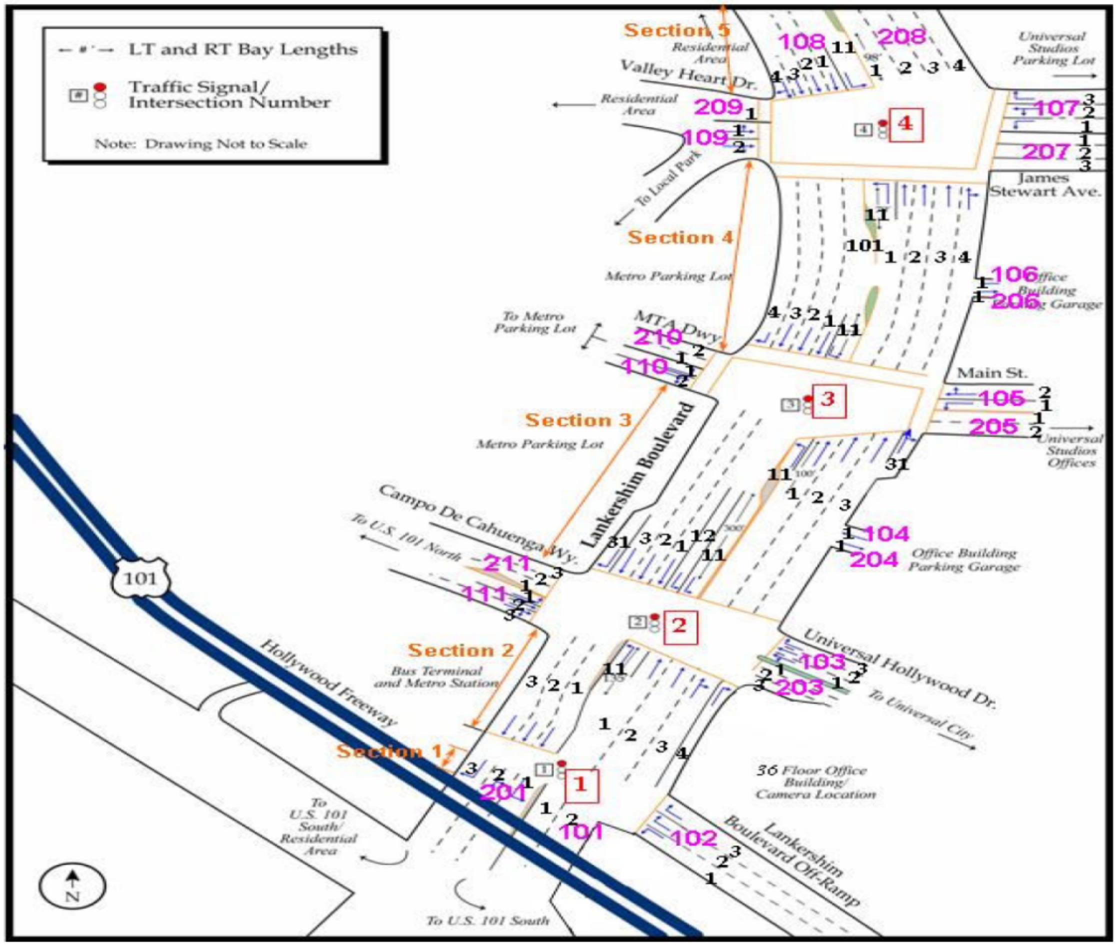

FIGURE 1 The map of the study road.

Demand Distribution

In Fig. 1, number 101 to 111 denote the 11 origins, and number 201 to 211, except for 202, are the 10 destinations. Table 1 shows the amounts of tracked vehicles for each origin-destination pair during the 32-min video. The largest flow was on the southbound from origin 108 to destination 201, which was the flow traveling along the road on southbound. The second largest flow was from origin 102 to destination 208, traveling on the northbound. This was the flow turning into Lankershim Blvd from the off-ramp of US-101. The third largest flow was from origins 108 to destination 203. This was the flow traveling on Lankershim Blvd and then turning to Universal Studio. It should also be noticed that the flow from origin 101 was also significant. This distribution of demand means that a large portion of the vehicles went straightly at the intersections, and there was a large left-turn flow at intersection #2.

Among the 2439 vehicles tracked, 2367 of them were automobiles. They accounted for 97.05% of the total vehicles. These automobiles had an average vehicle length of 15.14 feet. 68 of the vehicles were buses and trucks, with an average vehicle length of 32.71 feet. Buses and trucks are about 2.79% of all the vehicles. There were 4 motorcycles, only took 0.16% in all the tracked vehicles.

TABLE 1 The Demand Distribution

	destination											
origin		201	203	204	205	206	207	208	209	210	211	total
	101	0	106	9	11	4	11	149	3	7	22	322
	102	33	71	12	14	3	40	340	2	1	4	520
	103	20	0	2	0	0	1	70	0	1	28	122
	104	0	3	0	1	0	1	1	0	1	2	9
	105	7	6	1	0	1	0	13	0	0	2	30
	106	1	1	0	0	0	0	4	1	0	1	8
	107	2	8	2	0	0	0	10	1	0	1	24
	108	712	319	30	26	5	45	2	8	29	52	1228
	109	8	3	0	0	0	0	9	0	0	5	25
	110	2	2	0	0	0	0	6	0	0	0	10
	111	7	57	7	11	0	16	43	0	0	0	141
	total	792	576	63	63	13	114	647	15	39	117	2439

Traffic at Each Intersection

We analyze the traffic condition at each intersection from both video and trajectory data. The following paragraphs are some observations that we need to notice in our simulation.

At intersection #1, there was a signalized intersection close to this intersection in the south. Vehicles on the southbound were slowed down by the downstream queue sometimes. The downstream queue seldom spilled over. If it did, it resolved very quickly. On the northbound, a large portion of the vehicles from the off-ramp turned right during the red period. So the downstream segment was usually full. Queue spillover was observed from about 8:49am to 9:00am.

At intersection #2, there was a large left-turn flow on southbound. Left-turns on both directions on the arterial were protected. There was no queue spillover from downstream observed. But a bus stop near 8:43am on the northbound rightmost lane caused a small and temporary queue. There were occasional queue spillovers on the turn bays on the southbound. In the left-turn bay, the queue was long and the bay was fully occupied sometimes. But this queue spillover didn't affect the through vehicles much. The right-turn bay was short at this intersection. There were times that the right-turn vehicles failed to move into the bay due to the blockage caused by the queued through vehicles. Similarly to intersection #1, a significant amount of right-turn vehicles at this intersection were observed to turn at the red time. It should be noticed that there were a lot of pedestrians at this intersection, so the turning vehicles were delayed when it was green.

At intersection #3, the turning traffic was from/to a parking lot. This flow was low, so most of the vehicles went through, and the green time on Lankershim Blvd was very long. There was no downstream queue spillover observed at this intersection. Left-turn vehicles on Lankershim Blvd usually went during the permissive time. The left-turn bays had no spillover. Again, a lot of the right-turn vehicles from the parking lot were seen to turn during the red time after a stop.

At intersection #4, there was very little traffic from the cross-street. But the green time for the cross-street was still activated almost every cycle due to the pedestrian or vehicle call. There was no queue spillover from downstream or on the left-turn bay. Even one of the left-turn on Lankershim Blvd has protected green time, it was often not activated and vehicles usually came and left on permissive time.

The discrepancy of the video clock and signal clock needs to be mentioned here. When we tried to compare the information provided in the signal report and video, we found that the clock in signal report did not match the one in video. If we set the clock in video/trajectory data as a reference, we found that the clock at intersection #1 was about 3 seconds behind, and 28 second ahead for intersection #2, 17 second ahead for intersection #3, and 30 second ahead for intersection #4.

SIMULATION MODEL

Link-node representation of the network

The following denotations are used in this paper.

i, j: the index of a link.
v: free-flow speed of a link.
Q: capacity of a link.
ρ: density of a link;
ρ_{Jam}: the jam density.
w: shockwave speed.
f: flow; $f_{i,j}$ is the flow from link i to link j.
S: the demand function of a link.
R: the supply function of a link.
β: split ratio; $\beta_{i,j}$ is the split ratio from link i to link j.
p: priority factor.

The model we use in simulation is the cell transmission model. In this model, a network is represented as a directed graph with links and nodes. A link denotes a segment of road, and a node denotes a junction. For an ordinary node that connected with one input link and one output link, as in Fig 2(a), the flow is updated as (1)~(3). Equation (1) represents the demand from upstream link. Equation (2) represents the supply of downstream link. The flow from upstream to downstream cannot exceed upstream demand or downstream supply.

$$S_i = \min\{v\rho_i, Q_i\} \tag{1}$$
$$R_j = \min\{Q_j, w(\rho_j - \rho_{Jam})\} \tag{2}$$
$$f_{i,j} = \min\{S_i, R_j\} \tag{3}$$

When the node is a diverging node, as in Fig. 2(b), first-in-first-out is considered and the model updates according to (4) and (5). Here f is the total flow from upstream.

$$f = \min_j\{S_i, R_j/\beta_{i,j}\} \tag{4}$$
$$f_{i,j} = \beta_{i,j} f \tag{5}$$

When the node is a merging node, as in Fig. 2(c), the model updates as (6) and (7). Here, f is the total flow into downstream link. The priority factor p_i is chosen to be proportional to the demand of its link S_i, and the sum of p_i's is one.

$$f = \min\{\sum_i S_i, R_j\} \tag{6}$$

$$f_{i,j} = p_i f \tag{7}$$

A node that represents a signalized intersection usually has multiple input links and multiple output links. In this case, a split ratio matrix is needed to specify the turning percentage from one input link to one output link. Then a node is updated in similar rules as equation (4)~(7) show.

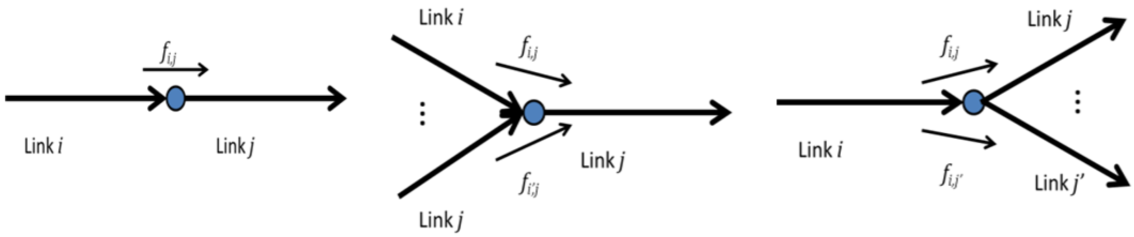

FIGURE 2 Different link-node connections. (a) ordinary; (b) diverge; (c) merge.

In the simulated network, a one-way section of road is represented by three links as Fig. 3. Link #1 denotes the segment from upstream intersection to the location where a left-turn bay starts. Then it splits into three links, #2 to #4, and each of them is for one allowable movement. These three links end at the downstream intersection, and they are controlled by the signal. When it is green for one movement, the associated link has the capacity as saturation flow; when it is red, the capacity is set to zero. One link may be subdivided into several cells. In this case, the update rule is the same as the ordinary node. The minimum length of a cell is no less than the product of simulation step and free-flow speed. At each origin, a source link is used to represent it. Demand information needs to be specified for every source link. A source link would also keep a queue if the generated demand fails to move to a downstream link. Similarly, at each destination, there is a sink link. This link is always empty to accept any flow into it.

Because there are two drive-ways in the studied network, two nodes are added to represent the connection of drive-ways to the road. These nodes and their links are modeled in the same way as a signalized intersection and its links, except that there is no signal to change the capacity of the links.

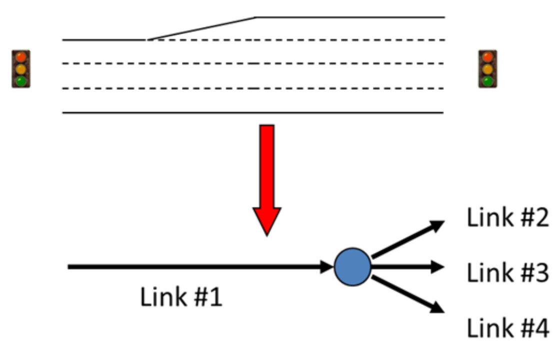

FIGURE 3 The representation of road segment.

Fundamental Diagram

We use a fundamental diagram of triangle shape in our simulation. The speed limit of this road is 35mph, so we can assume this is the free-flow speed. This assumption is valid. Fig. 4 shows the speed histograms on both northbound and southbound. The histograms take all the data points with speed no less than 30mph. The data points are highly concentrated at 35mph. Jam Density is assumed to be 200vpm, which means about 26.4 feet per vehicle when vehicles stop in queue.

The saturation flows at each intersection are estimated from headways. We assume that the headways were less than 3 seconds when vehicles were discharged from a queue. So we aggregate all the headways within 3 seconds for each direction at each intersection on this road, and then the saturation flow is 3600 divided by the mean headway. The saturation flows we get are about 1800~2000vph for the through movement on Lankershim Blvd, and about 1400~1600vph for the right-turn movement. For all left-turns and some right-turns, we fail to get enough samples of headways. So the saturation flows for those movements are assumed to be 1800vph. The sample size for flows from cross street were not large enough for saturation flow estimation, we also assume that they are 1800vph.

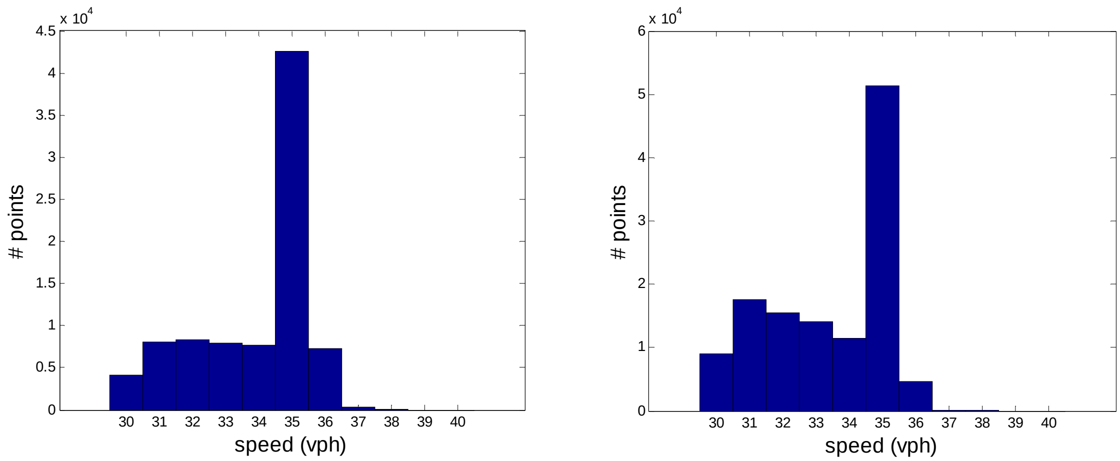

FIGURE 4 Speed histogram. (a) northbound; (b) southbound.

Demand, Split Ratio and Initial Density

For each source link, we need to provide the information of demand. From vehicle trajectory data, we can obtain the time when a vehicle appeared at its origin. So we counted the number of vehicles appeared during a period as the demand. The intersections on this road were under actuated control, which means the length of green time was time-varying. The green length for cross street could be 5~10 seconds in some cycles. To capture an accurate profile of vehicle arrival, the demand is updated every 10 seconds in our simulation.

At the nodes where traffic flow was split into through, left-turn and right-turn, split ratios are needed to define the flow split. To obtain this information, we put some virtual detectors at those locations. We know the vehicle trajectories and its destination from the data file, so we could tell whether a vehicle was going to go through, turn left or turn right when it passed a virtual detector. This enables us to get an accurate vehicle count for each movement. Same as what we do for the demand input, the split ratios in our simulation are updated every 10 seconds.

Since the network was not empty at the initial time of the study period, we need to specify the initial density of each link. This was done by measuring the number of vehicle in the link at the initial time. Then the density is the vehicle count divided by the link length.

Signal Control

The four intersections are under actuated control. When a vehicle passed a detector, it extended the green time if the length of green time did not reach its maximum limit. Cell Transmission Model is a macroscopic model, which considers the average flow and density over a period. It does not have discrete events like the arrival of a vehicle. Thus we cannot manipulate the signal as in reality. However, we get the exact information of green lengths in each cycle from the data files, so we can treat the signal control as pre-time control, keeping the green lengths changing every cycle. In this way, each movement would get exactly the same green time in the simulation as in the data. We also know the lengths of yellow time from the signal timing sheets. We saw some vehicles passed the intersection during yellow time. To simplify the simulation, yellow time is treated as red time, which means no flow would discharge during this period.

In Section II, we mentioned that a large percent of right-turn vehicles went during the red time period, especially at the intersection #1. Because our model doesn't have the function to model the right-turns in red time, and we don't want to over-restrict the right-turn flow, so all the right-turn links that are immediately linked to a signalized are not affected by the signal. This means it can discharge flow during red time same as during green time, as long as there is space to accept the flow in its downstream link. We understand that the discharge flow during red time is usually less than that in green time, because drivers need to make a complete stop and look for a safe gap before they turn. But it's hard to estimate the reduction in discharge flow during the red time from the data. So we keep it unchanged. This brings in some discrepancy, but it is in an acceptable range. We need to notice that, even though the right-turn links are not controlled by the signal, there can still be a right-turn queue, if the downstream link doesn't have enough space to accommodate the vehicles desired to get in, or if the queue of through movement is too long and block vehicles from entering the right-turn link.

In intersection #2, there were a lot of pedestrians, and they can affect the turning vehicles. In out simulation, we don't consider this influence and assume the turning flow is only affected by its demand and the space downstream.

SIMULATION RESULT AND ANALYSIS

We simulate traffic from 8:30am-9:00am. Each simulation step is one second. We choose flow and travel time for comparison. Fig. 5 shows the simulated flow and measured flow on northbound, while Fig. 6 is for southbound. Fig. 7 compares the travel time from simulation and measurement on both directions. Because the cycle length for signal control was 100 seconds, we choose it to be the time interval in our comparison. Thus, each point in Fig. 5 and Fig. 6 represents the aggregated flow passing the intersection over 100 seconds. Each point in Fig 7 is the sum of time for all vehicles travelled in the corresponding direction during 100 seconds. We use formula (8) to compute the percent of error.

$$\text{Error }\% = \frac{\sum |simulated\ value - measured\ value|}{\sum measured\ value} \times 100\% \tag{8}$$

From Fig. 5, we could see the simulated flow matches the measured flow. The errors from intersection #1 to #4 are 8.08%, 6.23%, 12.37%, 10.61%. And the average error for the northbound flow is 9.41%. We need to remember the right-turn flow from off-ramp is not controlled by the signal at intersection #1 in our simulation, and this flow is very large. So the downstream link is easily filled up and thus flow from Lankershim Blvd upstream is blocked.

This is why the error at intersection #1 seems to be large even though it is the most upstream. If we improve the way to model the right-turn flow during red time, this error can be reduced.

Fig. 6 shows the flow on southbound from upstream to downstream. The simulated flow again follows measured flow. The errors from intersection #4 to #1 are 2.96%, 9.31%, 8.77%, 15.50%. The overall error on southbound is 8.44%.

Fig. 7 plots the travel time on northbound and southbound. The simulated travel time on northbound is less than the measured one, with an error of 19.83%. The simulated travel time on southbound is higher than the measured one, with an error of 30.16%. Even though the value of error seems to be a little large, we could see that the lines of the lines of simulated travel time have a similar shape of those of the measured.

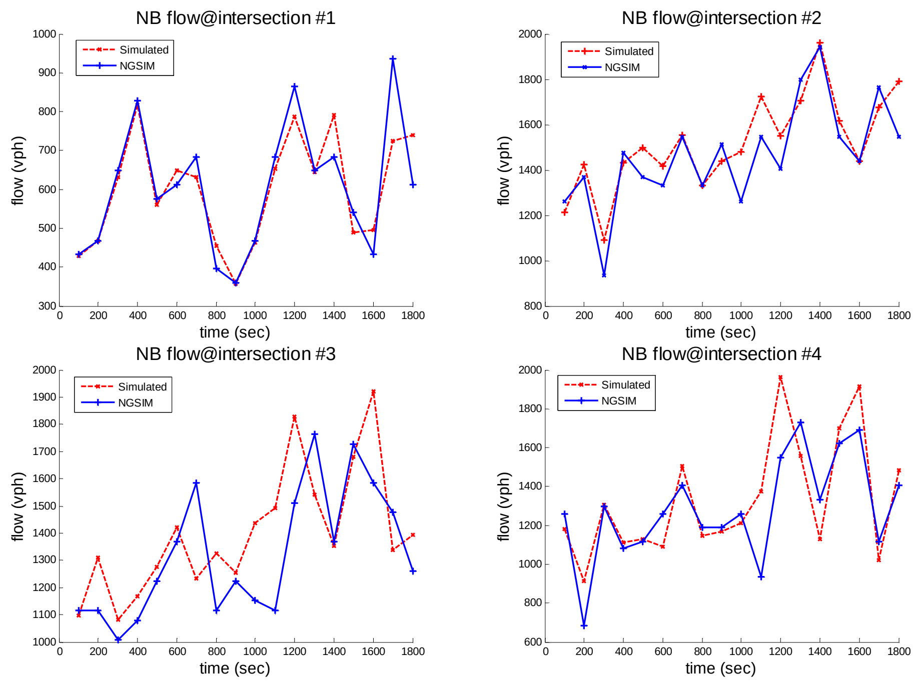

FIGURE 5 Flow on northbound. (a) intersection #1; (b) intersection #2; (c) intersection #3; (d) intersection #4.

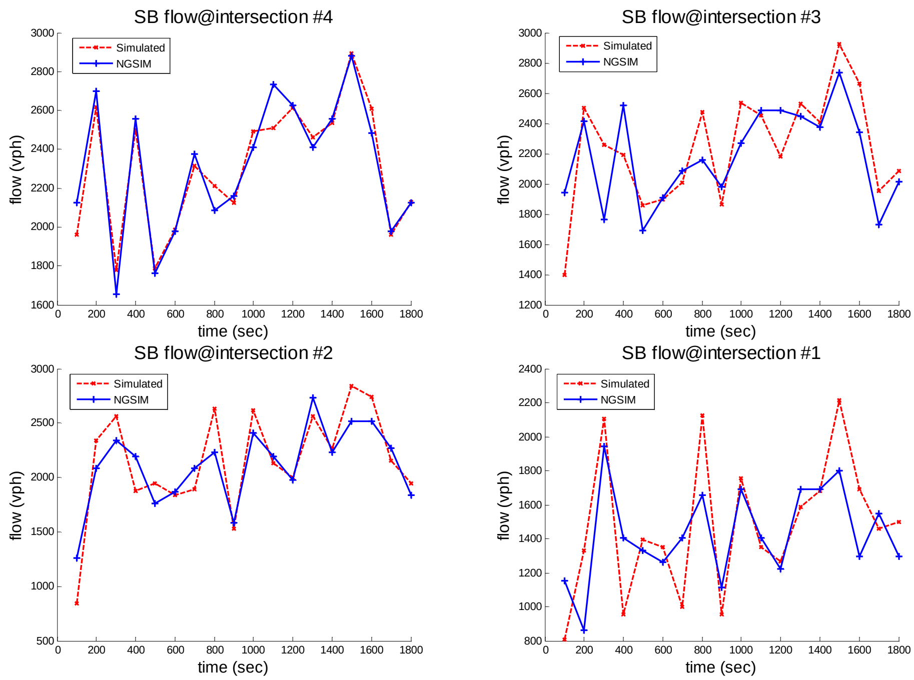

FIGURE 6 Flow on southbound. (a) intersection #4; (b) intersection #3; (c) intersection #2; (d) intersection #1.

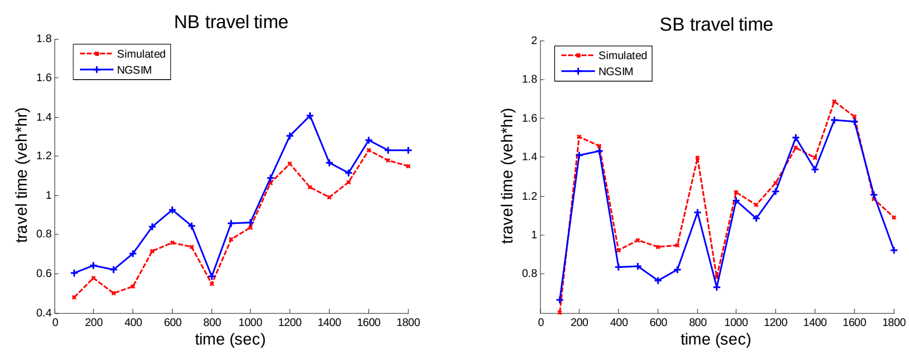

FIGURE 7 Travel time. (a) northbound; (b) southbound.

From the figures above, we see that the cell transmission is able to model the traffic on a signalized urban street. Given the fact that urban traffic is not as smooth as freeway traffic, and some conditions like the pedestrian crossing and right-turns during the red time are not considered in the model, the error is satisfactory even though it is slightly large. We notice that demand and split ratio are given in an interval of 10 seconds in our simulation, and we put some virtual detectors to obtain the accurate split ratio. This may not be achieved in some condition. We need to consider whether there are ways to lower the requirement of data. But this test still shows that using cell transmission model to simulate urban traffic is promising.

CONCLUSION

This paper discusses the modeling and simulating traffic on a segment of urban street. The model we use is the cell transmission model and the data for simulation is NGSIM data collected on Lankershim Blvd. We estimate the fundamental diagram in the model and process the data to obtain the demand and split ratio. The simulation result shows that the simulated traffic is close to the real traffic. Thus this proves that cell transmission can accurately simulate the traffic condition on urban street if the required data is available. In the future research, it is worth to consider: 1) whether there are ways to simulate urban traffic if we don't have high resolution of data or if some measurements are unavailable; 2) whether the model is robust under measurement noise.

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