Freeway traffic flow simulation using the Link Node Cell transmission model

Ajith Muralidharan, Gunes Dervisoglu and Roberto Horowitz

***Abstract*— This paper illustrates the calibration and imputation procedure implemented to specify the inputs to the Link-Node Cell Transmission model used for simulating traffic flow in freeways. Traffic flow and occupancy data from loop detectors is used for calibrating these models and specifying the inputs to the simulation. In addition, flow data from ramps are often found to be missing or incorrect. A model based iterative learning technique is used to impute these ramp flows by minimizing the error between simulated and measured densities. The simulation results using the calibrated parameters and imputed flows indicate good conformation with loop detector measurements.**

I. INTRODUCTION

Traffic flow simulation tools are essential for re-creating flow and speed characteristics of freeways. Operations planning, which include ramp metering, demand and incident management and its benefit assessment depend on the tools which successfully simulate the traffic flows in agreement with empirical data. The Tools for Operations planning (TOPL) is a set of tools that simulate traffic flows and control strategies. This forms an integral component of the California Department of Transportation (Caltrans) "corridor management program" - which was introduced to reduce the congestion in 2025 by 40 percent [1].

Traffic flow simulations have been frequently based on microscopic models, which simulate individual driver behavior to observe freeway network characteristics. While this would be ideal, extensive data collection requirements and extravagant calibration efforts make these models less lucrative for quick results. In comparison, Cell Transmission Models (CTM) simulate macroscopic traffic behavior which are specified by volume (flow), density and speed [2]. Also, the data required for simulation is available for California Freeways via loop detector based vehicle detector stations (vds). PeMS [3] routinely archives the flow, occupancy and speed data from these vds. TOPL is based on a modified version of the CTM - the Link-Node Cell Transmission Model (LN-CTM), which simulates traffic flow in networks.

Simulation of traffic flow in freeways requires fundamental diagram parameters for road sections, as well as input volumes (flow) from the onramps/freeway entry. Calibration is the process of extracting the fundamental diagram parameters from the flow and density measurements. The onramp flows need to be specified as an input, while the offramp flows are needed to extract the mainline split ratios. It is frequently observed that ramp flow data is either missing or incorrect, which makes imputation of these flows essential to specify the model completely.

This paper illustrates the modeling and simulation of a freeway network. Section II reviews the Link-Node Cell Transmission model used for traffic flow simulations and states a simple four-state switching model approximation used for imputation. Section III illustrates the steps in calibrating freeway section fundamental diagrams. Section IV explains the imputation procedure used for determining ramp flows. Finally, section V illustrates an example where the calibration and imputation procedures are used to specify inputs for the simulation of a 23-mile long Interstate-210 West freeway in the Los Angeles area.

II. LINK NODE CELL TRANSMISSION MODEL

The Link-Node Cell transmission model (LN-CTM) is an extension of the CTM, which can be used to simulate traffic in any road network. Aurora, a simulation tool in TOPL, is based on this CTM implementation [4]. TOPL was initially based on the Asymmetric Cell Transmission Model (ACTM) [5], which is specifically used for freeway traffic simulation. In comparison, the LN-CTM has the capability to simulate traffic networks which include freeways and arterial networks.

The traffic network is represented as a directed graph of links in the LN-CTM. Links represent road segments and nodes are formed at the junctions of links. A time-varying split-ratio matrix is used to specify the portion of traffic moving from a particular input link to an output link. While a normal link connects two Nodes, a "source" link is used to introduce traffic whereas a "sink" is used to accept traffic moving out of the network. A source link implements a queue model. A fundamental diagram (which specifies the flow-speed-density characteristics) is specified for each link, while the source links are also specified with an input demand profile. Figure 1 shows the directed graph representation of a freeway. The nodes specify the location of a merge between ramps and the mainline (freeway road segment). Each node contains a maximum of one on- and one off-ramp. In California freeways, the onramps are preceded by the offramps, therefore the split ratio matrix is specified to block any flow from the onramp to the offramp. Freeflow is assumed to prevail in both boundaries of the freeway.

A. Muralidharan is with the Department of Mechanical Engineering, University of California, Berkeley, ajith@berkeley.edu

G. Dervisoglu is with the Department of Mechanical Engineering, University of California, Berkeley, gunesder@berkeley.edu

R. Horowitz is a Professor at the Department of Mechanical Engineering, University of California, Berkeley. horowitz@berkeley.edu

This work is supported by the California Department of Transportation through the California PATH Program. The contents of this paper reflect the views of the author and not necessarily the official views or policy of the California Department of Transportation.

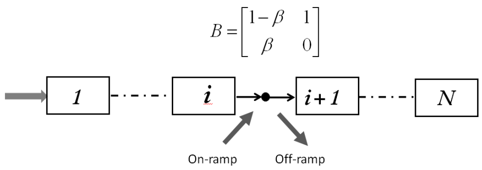

Fig. 1. Freeway with N links. Each Node contains a maximum of one on- and one off-ramp

A "source" node attached to the upstream cell is used to introduce traffic flow into the network. The onramps are also represented as source links, while the offramps are represented as sinks. It is also assumed that the off-ramps are in freeflow. Table I lists the model variables and parameters.

Symbol	Name	Unit
	section length	miles
	period	hours
F_i	capacity	veh/period
v_i	free flow speed	section/period
w_i	congestion wave speed	section/period
n_i^J	jam density	veh/section
β_i	split ratio	dimensionless
k	period number	dimensionless
$f_i^{in}(k)$	flow into section i period k	veh/period
$f_i^{out}(k)$	flow out of section i period k	veh/period
$s_i(k), r_i(k)$	off-ramp, on-ramp flow in node i in period k	veh/period
$d_i(k)$	on-ramp demand for Link $i+1$ in period k	veh/period
$c_i(k)$	Total demand for Link $i+1$ in period k	veh/period

TABLE I

MODEL VARIABLES AND PARAMETERS.

The LN-CTM is explained in [4]. The general algorithm implements density updates (Link Updates) and Flow updates (Node Updates) in separate steps. The conditional structure of the general equations are not easily amenable for ramp flow imputation. Specifically for traffic flow simulations, the general equations can be simplified to derive a four mode switching model for each link. This incorporates the flow updates directly into the density update equations.

For a section i (Figure 1), the density update equations belong to the following four modes - FF, CF, CC, and FC, where F denotes freeflow and C denotes congestion. These modes are decided based on the flow conditions existing at the input and output node of each link. The CF mode is said to be active in Link i , if the input flow into Link i is in congestion and the output flow from Link i (into Link $i+1$ and the offramp) is in freeflow. Other modes can be interpreted similarly. Here, the input into Link i is classified to be in congestion if the flow into it is determined (limited) by its available capacity rather than total input demand, i.e. $c_{i-1}(k) > \bar{w}_i(k)(n_i^J - n_i(k))$, where $c_{i-1}(k) = n_{i-1}(k)v_{i-1}(k)(1-\beta_{i-1}(k)) + d_{i-1}(k)$ is the input demand into Link i, which consists of flow from Link $i-1$ and the onramp. $\bar{w}_i(k)(n_i^J - n_i(k))$ represents the available output capacity. Thus, in freeflow, the flow into the link is not limited by the available space, thereby allowing for the freeway to cater to the actual demand. However, in the case of congestion, the flow is limited by the capacity in the destination link, and the flow from the onramp and the previous link is scaled accordingly to limit the flow to the capacity. The density update equations for the links of the freeway can be summarized as

(a) FF Mode

$$n_i(k+1) = n_i(k) + c_{i-1}(k) - n_i(k)\bar{v}_i(k) \tag{1}$$

(b) FC Mode

$$\begin{aligned} n_i(k+1) &= n_i(k) + c_{i-1}(k) \\ &\quad - \frac{\bar{w}_{i+1}(n_{i+1}^J - n_{i+1}(k))}{c_i(k)} n_i(k)\bar{v}_i(k) \end{aligned} \tag{2}$$

(c) CC Mode

$$\begin{aligned} n_i(k+1) &= n_i(k) + \bar{w}_i(n_i^J - n_i(k)) \\ &\quad - \frac{\bar{w}_{i+1}(n_{i+1}^J - n_{i+1}(k))}{c_i(k)} n_i(k)\bar{v}_i(k) \end{aligned} \tag{3}$$

(d) CF Mode

$$n_i(k+1) = n_i(k) + \bar{w}_i(n_i^J - n_i(k)) - n_i(k)\bar{v}_i(k) \tag{4}$$

where $\bar{w}_i(k) = min(w_i, \frac{F_i}{(n_i^J - n_i(k))})$ and $\bar{v}_i(k) = min(v_i, \frac{F_i}{n_i(k)})$. In addition, the mainline flows can be determined by

$$\begin{aligned} f_i^{out}(k) &= \frac{min(c_i(k), \bar{w}_{i+1}(k)(n_{i+1}^J - n_{i+1}(k)))}{c_i(k)} n_i(k)\bar{v}_i(k) \\ f_i^{in}(k) &= min(c_{i-1}(k), \bar{w}_i(k)(n_i^J - n_i(k))) \end{aligned} \tag{5}$$

while the ramp flows are determined by

$$\begin{aligned} s_i(k) &= \beta_i(k) f_i^{out}(k) \\ r_i(k) &= \frac{min(c_i(k), \bar{w}_{i+1}(k)(n_{i+1}^J - n_{i+1}(k)))}{c_i(k)} d_i(k) \\ d_i(k+1) &= d_i(k) + fl_i^{in}(k+1) - r_i(k) \end{aligned} \tag{6}$$

where fl_i^{in} is the input flow for the onramp i.

The above set of equations correctly represent the LN-CTM for freeways under a few assumptions. It is assumed that the offramp flows are not restricted by the flow capacity/congestion. Similarly onramps are also assumed to have no flow capacity restrictions. These assumptions are not restrictive for modeling purposes, since the offramps are usually specified to be in freeflow, while the capacity of the onramps will not affect the flow calculations if the capacity is defined to be the maximum flow observed in the ramps.

III. CALIBRATION

Like most macroscopic models of vehicular traffic flow, The LN-CTM makes use of the fundamental diagram, an empirical curve relating observed densities to observed flows at a particular point on the road. A calibrated fundamental diagram provides freeflow speed, congestion wave speed, critical density, jam density and capacity (Figure 2). The calibration procedure involves the following.

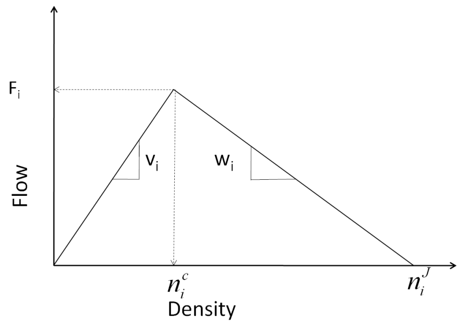

Fig. 2. Fundamental diagram for a freeway section.

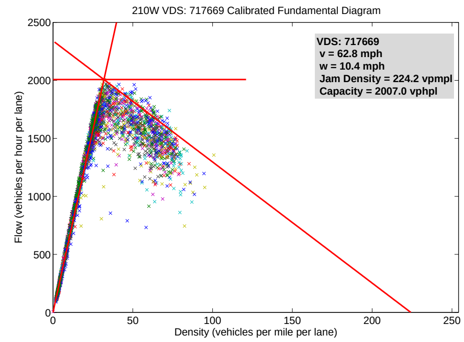

Fig. 3. Calibrated Flow vs. Density Scatter Plot of vds 717669 on I-210W over 15 days' data

A. Freeway Representation

The first step is to define the geometrical characteristics of the site- the locations of onramps and offramps, number of lanes, existence of HOV lanes etc. As the LN-CTM dictates, the freeway should be represented in the form of successive cells. Therefore, the freeway network is divided into cells each with at most one on- and/or off-ramp and one mainline vehicle detector station. The cells must be longer than the freeflow travel distance, i.e. $v_i \leq 1$; so that the algorithm converges. Each cell is assumed to be homogeneous in terms of number of lanes, grade and geometrical features so that each cell can be represented by a single fundamental diagram. The 23 mile stretch of I-210W (extending between the Fruit Street onramp and the Lake Avenue onramp) analyzed in this study consists of 33 such cells.

B. Data Acquisition and Selection

Vehicle detector stations(VDS) contain loop detectors that provide flow and occupancy data. PeMS [3] processes and archives these data in form of time series over different days of operation. PeMS also reports detector performance for each day of operation. The data for calibration were chosen from days for which PeMS reported over 80% functionality for all detectors. While PeMS imputes missing mainline data using data from adjacent detectors, an 80% detector health/functionality is preferred to ensure accuracy of data used. Further, for each detector station, only days on which that particular freeway section became congested (with speeds below 40mph) were chosen, in an effort to observe capacity and congested flow characteristics.

C. Calibration of the free-flow speed, v

The free-flow speed, v, is estimated by performing a least-squares fit on the flow vs. density data at the time instants where the speed was reported to be above 55 mph. The regression line for the free-flow speed can be seen in Figure 3.

D. Estimation of section capacity

In the fundamental diagram, the apex of the triangle corresponds to the section capacity and it is the highest observed flow. In fact, the definition and choice of capacity is a rather delicate point. The Highway Capacity Manual [6] defines capacity as the maximum amount of flow that can reasonably be expected to traverse the cross-section of a road segment. This deterministic notion of capacity has been challenged lately by stochastic approaches [7]. A study over the sections of the freeway yields that there is indeed a significant variation in observed maximum flows (Figure 4).

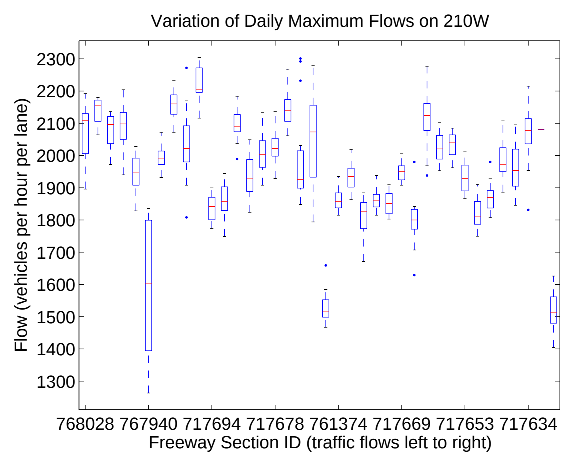

Fig. 4. Box plots showing the distribution of observed daily maximum flows for each section of I-210W.

In Figure 4, the horizontal axis is the detector IDs placed on the freeway in upstream to downstream (left to right) succession. The vertical axis reflects the normalized flow values across these sections of the freeway. The horizontal lines inside the boxes correspond to the median of the observed daily maximums among days. The lower and upper box boundaries represent 1st and 3rd quartiles, or 25th and 75th percentiles, respectively. The whiskers span from either end of the box to the smallest and largest data points that are non-outliers, i.e points within 1.5 interquartile range away from box boundaries. The figure reflects significant temporal and spatial variation of section capacities.

The stochastic approach to capacity is based on the notion of breakdown, which describes the operation of a freeway near a bottleneck at a time instance where there is a change from free-flow to congestion [8]. Numerous studies on the stochastic nature of capacity [7] suggest that the breakdown occurs randomly, affected by various external factors such as driver behavior, road and weather conditions, incidents, etc. and capacity can be defined as a random variable with a specific probability distribution depending on the probability of breakdown. This phenomenon was also investigated in this study. Figure 5 reflects the breakdown flows, capacity and observed daily maximum flow values for section 717644 on I-210W on Apr 3rd, 2008. In the figure, the speed plots for section 717644 and 717642, which is right downstream, are plotted to observe the breakdown phenomenon. The horizontal axis is the time of day and the vertical axis is the speed. The breakdown flows are recorded at instances when there is a switch in the flow regime in the upstream section (speeds less than 55mph imply dense flow and speeds below 40 mph imply congested flow) whereas the downstream section is in free flow (speeds above 55 mph); in other words, when the upstream section is operating at active bottleneck conditions. These instances are labeled with 1,2,3,... in the figure and the corresponding flow values before and after breakdown are listed to the left of the figure, among with the daily maximum flow and the capacity observed over the stretch of all investigated days.

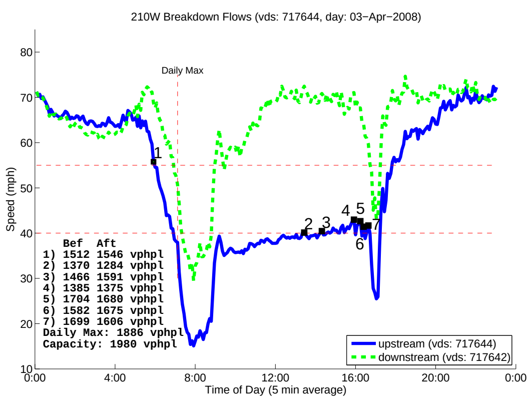

Fig. 5. Speed plots of sections 717644 and 717642 on Apr 3rd, 2008

Figure 5 (and many others pertaining to other sections of the freeway not included here) suggests that although related to the capacity of a section, the breakdown analysis is not suitable to the purposes of the capacity estimation in the fundamental diagram framework, since the breakdown flow values differ substantially from the observed maximum flows. A more detailed analysis on the variation of capacity and its comparison to breakdown can be found in [9]. The capacity estimate for model calibration is thus chosen deterministically to be the highest observed flow throughout all investigated days. The choice of this largest observed flow as the estimate of capacity is based on the assumption that external factors such as driver behavior, incidents, weather and road conditions always affect the capacity adversely and the actual capacities of freeway sections are rarely observed, if ever. This capacity estimate enables the model to replicate the ideal operating conditions of the freeway and is also essential to the testing of hypothetical control strategies, such as ramp metering. This maximum value of flow across the section is then projected horizontally to the free-flow line, to establish the tip of the triangular fundamental diagram (Figure 3). The intersection is defined as the critical density for the section, above which the flow is congested.

E. Calibration of the Congestion Speed Parameter, w

The last parameter to be calibrated is the congestion speed parameter, w, which also defines the jam density for the section. Similar to capacity, this parameter shows significant diversity. Therefore, an approximate quantile regression [10] was adopted to estimate this parameter at the higher end of its distribution.

After the critical density is determined, the flow-density points with density values higher than the critical density (the data points to the right of the tip) are partitioned along the horizontal axis (density axis) into non-overlapping bins of 10 data points each. Horizontally, each bin is summarized by ”BinDensity,” the mean of the 10 density values in the bin. Vertically, each bin is summarized by ”BinFlow,” the largest non-outlier flow values among the the 10 flow values in the bin. Formally, this largest non-outlier is determined as follows:

$$\begin{aligned} Bin &= \{f_1, f_2, ..., f_{10}\} \\ BinFlow &= \max_{f_i}(f_i | f_i \in Bin, f_i < Q_3 + 1.5IQR) \end{aligned} \quad (7)$$

where, f_1 through f_{10} are the flow values inside one such bin, Q_3 is the 75th percentile of the data points in the bin and IQR is defined as the difference between the 25th percentile and the 75th percentile of the data.

A constrained least-squares regression is performed on these BinDensity - BinFlow pairs to obtain the congested flow line and complete the fundamental diagram picture (Figure 3). It is required that the regression line passes through the tip of the fundamental diagram, so the regression is constrained accordingly. The point where the regression line crosses zero flow is chosen as the jam density of the section.

IV. IMPUTATION OF RAMP FLOWS

The LN-CTM model is utilized to impute the missing onramp input flows as well as the off-ramp split ratios for one day (24-hour) traffic flow simulation on a large freeway (eg. 40 miles) segment. The imputation procedure involves two stages. First, the total demands c_i are determined using an adaptive learning procedure that minimizes the error between the model calculated densities and the observed PeMS density profile. Then the demands and split-ratios are extracted from the total demand, using a linear program that minimizes the error between the model calculated flows and the observed flow profile [11].

The imputation procedure employs the adaptive iterative learning procedure described in [12]. The freeway traffic flow process is assumed to be 24-hour periodic, with respect to the flow and density profiles. This assumption is valid, since the freeway is always found to be in freeflow (with low densities, flows) at midnight. The LN-CTM algorithm is run multiple times, and at each run, the algorithm adapts the unknown demand estimates to minimize the error between the density generated by the model at each link and the data from the corresponding PeMS measurement. The procedure is repeated until the density error reduces to a sufficiently small value or stops decreasing.

As detailed in [12],because of the 24 hour periodicity, the demand vector can be represented as a convolution of a kernel on a constant influence vector, i.e $c_i(k) = K(k)^T C_i$ where $K(k)$ represents a 24 hour periodic time dependent kernel vector, and C_i is the influence vector. Some typical kernel functions ($K(k)$) include a unit-impulse or a Gaussian window centered at time k.

The imputation procedure assumes initial estimates for the influence vectors $\hat{C}_i$. Typical initial estimates incorporate zero onramp and offramp flows. These estimates are then dynamically adapted at each time step, so that the model calculated densities for the whole freeway match with the density profiles obtained from PeMS. At each time step, the mode for each cell is determined, and the corresponding learning update equations are used to adapt the influence vectors. In the following parameter update equations $\hat{n}^(k)$ represents density estimates, $\tilde{n}^(k) = n(k) - \hat{n}(k)$ represents the density error, and $\tilde{n}^o(k)$ represents the a-priori error estimate.

(a) FF Mode

$$\begin{aligned}
\tilde{n}_i^o(k+1) &= \hat{n}_i(k+1) - \\
&\quad (\hat{n}_i(k) + \hat{c}_{i-1}(k) - \hat{n}_i(k)\hat{v}_i(k) - a\tilde{n}_i(k)) \\
\tilde{n}_i(k+1) &= \frac{\tilde{n}_i^o(k+1)}{1 + GK^T(k)K(k)} \\
\hat{C}_{i-1}(k+1) &= \hat{C}_{i-1}(k) + GK(k)\tilde{n}_i(k+1) \\
\hat{n}_i(k+1) &= \hat{n}_i(k) + \hat{c}_{i-1}(k+1) - \hat{n}_i(k)\hat{v}_i(k) - a\tilde{n}_i(k)
\end{aligned} \tag{8}$$

(b) FC Mode

$$\begin{aligned}
\tilde{n}_i^o(k+1) &= \hat{n}_i(k+1) - \Bigg(\hat{n}_i(k) - a\tilde{n}_i(k) \\
&\quad + \hat{c}_{i-1}(k) - \frac{\hat{w}_{i+1}(n_{i+1}^J - \hat{n}_{i+1}(k))}{\hat{c}_i(k)}\hat{n}_i(k)\hat{v}_i(k)\Bigg) \\
\tilde{n}_i(k+1) &= \frac{\tilde{n}_i^o(k+1)}{(1 + G'K^T(k)K(k) + GK^T(k)K(k))} \\
\hat{C}_{i-1}(k+1) &= \hat{C}_{i-1}(k) + GK(k)\tilde{n}_i(k+1) \\
\hat{C}_i(k+1) &= \hat{C}_i(k) - \frac{K(k)}{G''} \times \\
&\quad \left(\hat{c}_i(k) - \frac{1}{1/\hat{c}_i(k) - G'K(k)\tilde{n}_i(k+1)}\right) \\
\hat{n}_i(k+1) &= \hat{n}_i(k) - a\tilde{n}_i(k) + \hat{c}_{i-1}(k+1) \\
&\quad - \frac{\hat{w}_{i+1}(n_{i+1}^J - \hat{n}_{i+1}(k))}{\hat{c}_i(k+1)}\hat{n}_i(k)\hat{v}_i(k)
\end{aligned} \tag{9}$$

(c) CF Mode

$$\hat{n}_i(k+1) = \hat{n}_i(k) + \bar{w}_i(n_i^J - \hat{n}_i(k)) - \hat{n}_i(k)\hat{v}_i(k) \tag{10}$$

(d) CC Mode

$$\begin{aligned}
\tilde{n}_i^o(k+1) &= \hat{n}_i(k+1) - \Bigg(\hat{n}_i(k) - a\tilde{n}_i(k) \\
&\quad + \hat{w}_i(n_i^J - \hat{n}_i(k)) - \frac{\hat{w}_{i+1}(n_{i+1}^J - \hat{n}_{i+1}(k))}{\hat{c}_i(k)}\hat{n}_i(k)\hat{v}_i(k)\Bigg) \\
\tilde{n}_i(k+1) &= \frac{\tilde{n}_i^o(k+1)}{(1 + G'K^T(k)K(k)} \\
\hat{C}_i(k+1) &= \hat{C}_i(k) - \frac{K(k)}{G''} \times \\
&\quad \left(\hat{c}_i(k) - \frac{1}{1/\hat{c}_i(k) - G'K(k)\tilde{n}_i(k+1)}\right) \\
\hat{n}_i(k+1) &= \hat{n}_i(k) - a\tilde{n}_i(k) + \hat{w}_i(n_i^J - \hat{n}_i(k)) \\
&\quad - \frac{\hat{w}_{i+1}(n_{i+1}^J - \hat{n}_{i+1}(k))}{\hat{c}_i(k+1)}\hat{n}_i(k)\hat{v}_i(k)
\end{aligned} \tag{11}$$

where $G'' = K^T(k)K(k)$, $\hat{c}_i(k) = K(k)^T\hat{C}_i(k)$ and G, G' are positive gains. The parameter a is chosen so that the error equation is asymptotically stable. As the adaptation procedure is carried out, the 'error' in the density profile, given by $\sum|n_i(k) - \hat{n}_i(k)|$ decreases. Since the CF mode does not involve adaptation equations, the error may converge to a non-zero value for when this mode is in effect, while other modes shows negligible error. This occurs due to incorrect mode identification at that time instant. In this case, the corresponding estimates are "triggered" automatically so that the correct modes are identified. After the trigger, the adaptation procedure is continued, till the error becomes negligible or stops decreasing.

The above procedure identifies the Total demand vector, from with the on-ramp demand and off-ramp split ratios are decoupled using a linear program. Figure 6 illustrates the position of the mainline detector, from which flow data is available. Depending on the existing flow conditions, the flows preceding the offramp and following the onramp can be described by the equations presented in Figure 6. A linear program that minimizes $|(f_{i+1}^{in}(k) - f_{i+1}^{meas}(k)) - r_{i+1}(k)| + |(f_i^{out}(k) - f_{i+1}^{meas}(k)) - s_{i+1}(k)|$ can be used to identify the onramp and offramp flows that best match the observed mainline flow. Once the onramp flows and demands are obtained, the onramp input flows can be back-calculated using the equations in II.

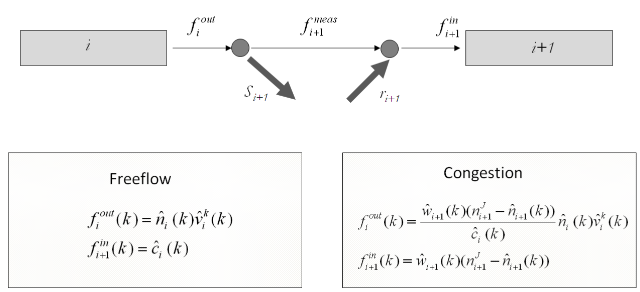

Fig. 6. Decouple on-ramp and off-ramp flows.

V. APPLICATION

The calibration and imputation procedure detailed in the previous sections were used to specify simulation parameters for a 23 mile section of I-210W freeway in Pasadena, California. After identifying days with good detector health, the data for these days were downloaded and processed to obtain the fundamental diagram parameters. The results have been indicated in Section III. The freeway section had a total of 32 onramps and 26 offramps of which a total of 8 onramps and 9 offramps were identified to have incorrect/missing data. The imputation procedure was carried out for these ramps. The final density error in the imputation was 4.92%. Figure 7 shows that the density estimates have converged to their true values without appreciable error.

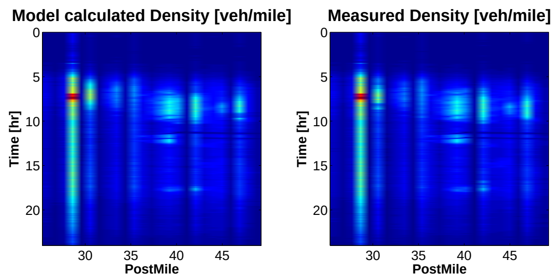

Fig. 7. Final density contours obtained after imputation.

The calibrated and imputed data are used to run the simulation. Figure 8 shows the simulated and the measured velocity contours, which indicate good conformation of the simulation with the actual PeMS detector data. The simulated contour plots not only reproduce the locations of the major bottlenecks, but also accurately capture the congestion present in the freeway network. The simulated and measured performance measures are compared in Figure 9, which also show good agreement. The simulated data had 4.95 % and 8.2 % density and flow errors (as compared to the PeMS measurements) respectively. This procedure was also implemented successfully for various freeways like I-880N/S and I-210E over different days of data. The results of the imputation algorithm and simulation for I-210E are given in [11].

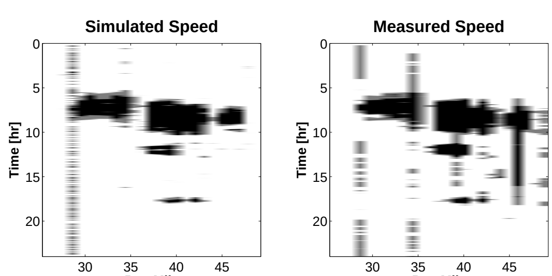

Fig. 8. Velocity Contours obtained from the I-210W simulation using calibrated parameters and the imputed ramp flows and split ratios.

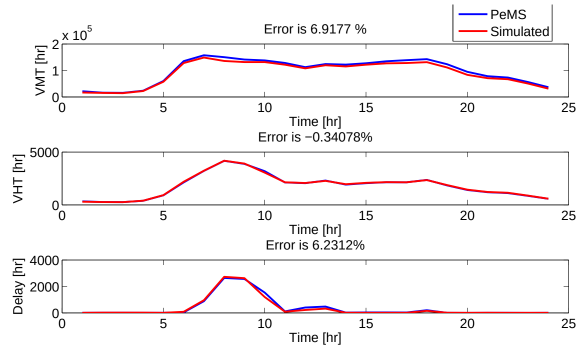

Fig. 9. Performance measures - Vehicle Hours Travelled (VHT), Vehicle Miles Travelled (VMT) and Delay.

VI. CONCLUSION

This paper specifies and elaborates the modeling procedure used for traffic flow simulation using the macroscopic Link-Node Cell Transmission Model. The calibration and imputation procedures are used for specifying the inputs to the LN-CTM. The calibration procedure implements linear least squares and approximate quantile regression methods on the available Flow vs. Density data to estimate the fundamental diagrams for each section of 23 mile long segment of I-210W freeway in California. The imputation procedure employs an adaptive identification technique and a linear program to determine the missing/incorrect onramp flows and offramp split ratios in this network. The simulations, using the calibrated fundamental diagram data as well as the imputed on-ramp flows and off-ramp split ratios, agree closely with the measurements, as shown by the speed contours and performance measures plots.

REFERENCES

[1] California Department of Transportation, "Strategic Growth Plan," 2006. www.dot.ca.gov/docs/strategicgrowth.pdf - 2006-10-10.

[2] C. Daganzo, "The cell transmission model: A dynamic representation of highway traffic consistent with the hydrodynamic theory," *Transportation Research, Part B*, vol. 28, no. 4, pp. 269–287, 1994.

[3] PeMS, "PeMS website," 2007. http://pems.eecs.berkeley.edu, accessed 8/28/2007.

[4] A. Kurzhanskiy, *Modeling and Software Tools for Freeway Operational Planning*. PhD thesis, University of California, Berkeley, 2007.

[5] A. C. et al., "Topl: Tools for operational planning of transportation networks." Submitted to DSCC 2008, 2008.

[6] T. R. Board, *Highway Capacity Manual 2000*, December 2000.

[7] W. Brilon, J. Geistefeldt, and M. Regler, "Reliability of freeway traffic flow: A stochastic concept of capacity," *Proceedings of the 16th Symposium on Transportation and Traffic Theory*, 2005.

[8] B. Persaud, S. Yagar, and R. Brownlee, "Exploration of the breakdown phenomenon in freeway traffic," *Transportation Research Record*, vol. 1634, pp. 64–69, 1998.

[9] G. Dervisoglu, G. Gomes, J. Kwon, R. Horowitz, and P. Varaiya, "Automatic calibration of the fundamental diagram and empirical observations on capacity." Submitted to TRB 88th Annual Meeting, 2009.

[10] R. W. Koenker, *Quantile Regression*. Cambridge U. Press, 2005.

[11] A. Muralidharan and R. Horowitz, "Imputation of ramp flow data for freeway traffic simulation." Submitted to TRB 88th Annual Meeting, 2009.

[12] W. Messner, R. Horowitz, W.-W. Kao, and M. Boals, "A new adaptive learning rule," *IEEE Transactions on Automatic Control*, vol. 36-2, pp. 188–197, 1991.