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Modelling Heterogeneous and Undisciplined Traffic Flow using Cell Transmission Model

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Abstract

This research calibrates Cell Transmission Model (CTM) for heterogeneous and non-lane disciplined traffic, as observed in Pakistan and some other developing countries by constructing a flow-density fundamental traffic flow diagram. Currently, most of the traffic simulation packages used for such heterogonous and non-lane-disciplined traffic are not calibrated for local traffic conditions and most of the traffic flow models are developed for comparatively less heterogeneous and lane-disciplined traffic. The flow-density fundamental traffic flow diagram is developed based on extensive field data collected from Karachi, Pakistan. The calibrated CTM model is validated by using actual data from another road and it was concluded that CTM is capable of modelling heterogeneous and non-lane disciplined traffic and performed very reasonably. The calibrated CTM will be a useful input for the application of traffic simulation and optimization packages such as TRANSYT, SIGMIX, DISCO, and CTMSIM.

Keywords: *Calibration, Cell Transmission Model, Macroscopic Traffic Flow Model, Heterogeneous Traffic, Flow-Density Relation.*

1. Introduction

Traffic congestion continues to remain a major problem in most cities around the world, resulting in enormous delays, increased fuel consumption and monetary losses. Traffic flow modelling is an important field in transportation engineering and traffic management. Numerous mathematical models have been developed for microscopic and macroscopic travel flow modelling to predict the behaviour of traffic in planning, design and operations of traffic networks. Cell Transmission Model (CTM) is one of the widely used macroscopic traffic flow models and now being used in various simulation and optimization packages.

When compared with modelling of other streams of flows such as fluid, heat or electricity, modelling traffic flow is more complicated as it involves human interaction. Each particle in the stream of traffic is controlled by a driver, which makes the process of traffic flow more dynamic and diverse. Numerous models have been proposed in the past few decades to model the process of traffic flow but still no single model claims to perfectly model this phenomenon. However, with the existing limitations of these models related to either the scale of traffic network or type of traffic system, these models are a valuable tool to evaluate the existing traffic condition, devise real-time traffic control strategies, forecast the impact of new infrastructure or traffic control, and to understand and simulate the process of traffic flow.

Traffic flow models can be classified into three main categories, which are microscopic, mesoscopic and macroscopic traffic flow models, based on the level of details modelled in a traffic flow model. There are various entities in a traffic system, such as road network, traffic controls, vehicles, drivers, environment, etc., and traffic flow models are classified based on the number of entities considered in a modelling framework. Traffic flow models with a higher level of details need more information and parameters to model a traffic system. On the other hand, traffic flow models with lesser entities to consider require comparatively fewer parameters and information about the traffic system. The level of details considered in a model is linked with the computing time and thus the scale of the network feasible for implementation of the model. Traffic flow models with a higher level of details are computationally more demanding and are feasible for modelling smaller network with higher accuracy, whereas the models with a lower level of details are computationally less expansive and suitable for modelling larger networks.

Macroscopic traffic flow models consider the flow of traffic on an aggregate level and define the relation between aggregated parameters of traffic flow. The aggregated parameters of traffic flow considered in modelling of traffic flow are traffic density, traffic flow rate, and mean speed. Based on the number of variables modelled using a macroscopic traffic flow model,

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these model are classified as first, second or higher-order traffic flow models. First-order traffic flow models treat traffic density or occupancy as an output variable. Second-order traffic flow models also consider the dynamics of average speed with traffic density, and the higher-order traffic flow models consider the variance of speed along with traffic density and mean speed when modelling dynamics of traffic flow.

CTM proposed by Daganzo [1, 2] is a discretized form of first-order traffic flow model, LWR, proposed by Lighthill and Whitham [3]and Richards [4]. CTM simulates traffic conditions by proposing a time-scan strategy where current conditions are updated with every tick of a clock in an imaginary division of road section called cells. Although CTM is simpler to implement on a network than other higher-order models, it fits well with the measurement data as discussed by Lin and Ahanotu [5] and Lin and Daganzo [6]. In comparison to other higher-order traffic flow models, CTM has fewer numbers of output variables and input parameters which qualifies CTM as a suitable model for real-time applications and modelling large traffic networks. CTM has been used for traffic state estimation [7-11] as well as for DTA applications of traffic network optimization[12-16].

CTM has been widely used to model traffic flow and various simulation and optimization packages have been developed which use CTM as a base model for traffic flow modelling and prediction. Existing traffic flow models and simulation packages are well suited to model homogeneous traffic systems with perfect lane discipline. However, as we observe in Pakistan and other places with similar traffic systems that traffic is highly heterogonous with motorbike as dominating mode of transport where vehicles try to percolate through the available gaps in the road section ahead of vehicles, thus causing serious lane discipline problem. The main objective of this paper is to calibrate and validate the cell transmission model for heterogeneous traffic of Karachi, which is the largest metropolis of Pakistan and among one of the most populated cities around the globe.

The CTM is calibrated and validated by developing a fundamental traffic flow-density diagram, based on traffic data extracted from recorded videos. Extensive traffic data for traffic density and the flow rate is extracted from recorded videos to develop fundamental traffic flow diagram, which is used as input for CTM. The calibrated CTM is tested for an independent urban arterial to validate the calibrated model.

2. Daganzo-Newell Fundamental Diagram

Daganzo [1] used a piecewise-linear relation of flow-density as shown in figure-1, in contrast to Greenshields et al. [17] who proposed a parabolic relation between these two variables. In free-flow condition, the relation between speed and density is considered as static [18]. The most commonly used form of a fundamental diagram is that of flow versus density [19].

A fundamental diagram relates the density ρ to the flow q. The capacity flow C is reached at the critical density (ρ c). The space-mean speed v at any point on the curve is defined as the slope of the line through that point and the origin. Taking the slope of the tangent to points on the curve gives the shock wave speed (w) [20].

The cell transmission model predicts and models the flow of traffic based on the fundamental traffic flow diagram. Therefore, a reasonable calibration of the diagram parameters is essential for a meaningful CTM output. The CTM transforms the differential equation from the LWR model into a simple difference equation to update traffic density for each future time-step and all the cells in a road network.

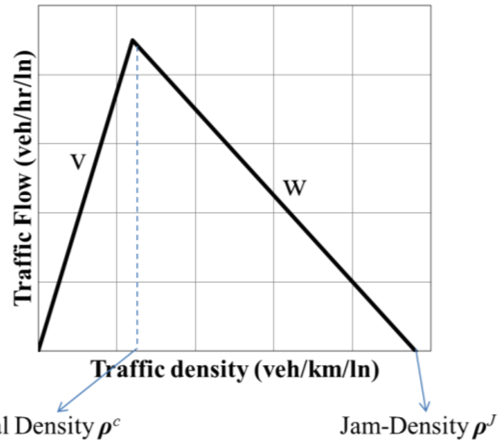

Fig. 1. Daganzo-Newell flow-density fundamental Diagram

The cells can be numbered consecutively from i=1:n. The cell length is homogenous and it is the distance travelled in free-flow traffic conditions by a vehicle in one simulation time-step. Under free-flow traffic condition, all the vehicles in a cell can be assumed to advance to the next with each clock tick. CTM predicts traffic density, $\rho_i(k+1)$, for all the cells in the network for future time-step k+1 based on the values of traffic density for traffic density at time-step k.

$$\rho_i(k+1) = \rho_i(k) + \frac{t}{l}\{q_i(k) - q_{i+1}(k)\} \qquad (1)$$

In equation (1), '*t*' is the duration of one time-step, '*L*' is the length of a cell of the road link, $q_i(k)$ is the inflow to cell i at time-step k, which is calculated using the following equation for each cell and each simulation time-step.

$$q_{(i,k)} = \min\{\rho_{(i-1,k)}v, C_i, w[\rho^j(k) - \rho_{(i,k)}]\} \qquad (2)$$

The fundamental diagram is developed to calibrate the parameters of CTM according to local traffic conditions, which include capacity flow rate $C_i(t)$, free-flow speeds v, shockwave speed w, critical density $\rho^c$and jam-density ρ^j.

3. Data Collection and Analysis

The fundamental traffic flow diagram is developed based on extensively collected traffic data for traffic density and flow rates. As there are no suitable traffic measuring devices to measure such heterogeneous and non-lane-disciplined traffic, the data for traffic flow rates and density is manually extracted from recorded traffic videos. The videos are recorded from various arterials roads having similar characteristics. Videos of traffic streams were recorded from the following roads on typical working days.

- University Road (NIPA)
- Khayaban-e-Seher
- Khayaban-e-Shamsheer
- Rashid Minhas Road
- Khayaban-e-Iqbal.

Traffic data for flow rates and traffic density was manually extracted using recorded videos. The heterogeneous traffic was divided into five different modes, as shown in table-1 and converted into equivalent flow rates in Passenger Car Units (PCU) using Passenger Car Equivalent (PCE) factors based on a study conducted by Adnan [21].

Table 1. Passenger Car Equivalent Factor

Type of Vehicle	Passenger Car Equivalent Factor
Bike	0.45
Rickshaw	0.90
Car	1
Bus	3.02
Truck	3.28

3.1. Development of Fundamental Diagram

Flow-density fundamental diagram is developed by plotting per minute flow rates against average per minute density observed during the same time interval. Per-minute flow and density are counted manually from the videos and converted into PCU using PCE factors. Approximately 4700 data points were collected to develop the fundamental traffic flow diagram. Each data point represents traffic flow in a one-minute time interval and average traffic density during that minute. The average traffic density for a given minute is determined by taking the average of density counted from 10 screenshots for that minute. Some of the outlier points were removed with speed higher than 100 km/hr, as some of the vehicles travelling at extremely higher speeds will affect the developed model. It is important to note here that there is no speed limit enforcement in Karachi and most of the roads exist without speed limit posts. Figure-2 shows the developed fundamental traffic flow diagram based on collected data.

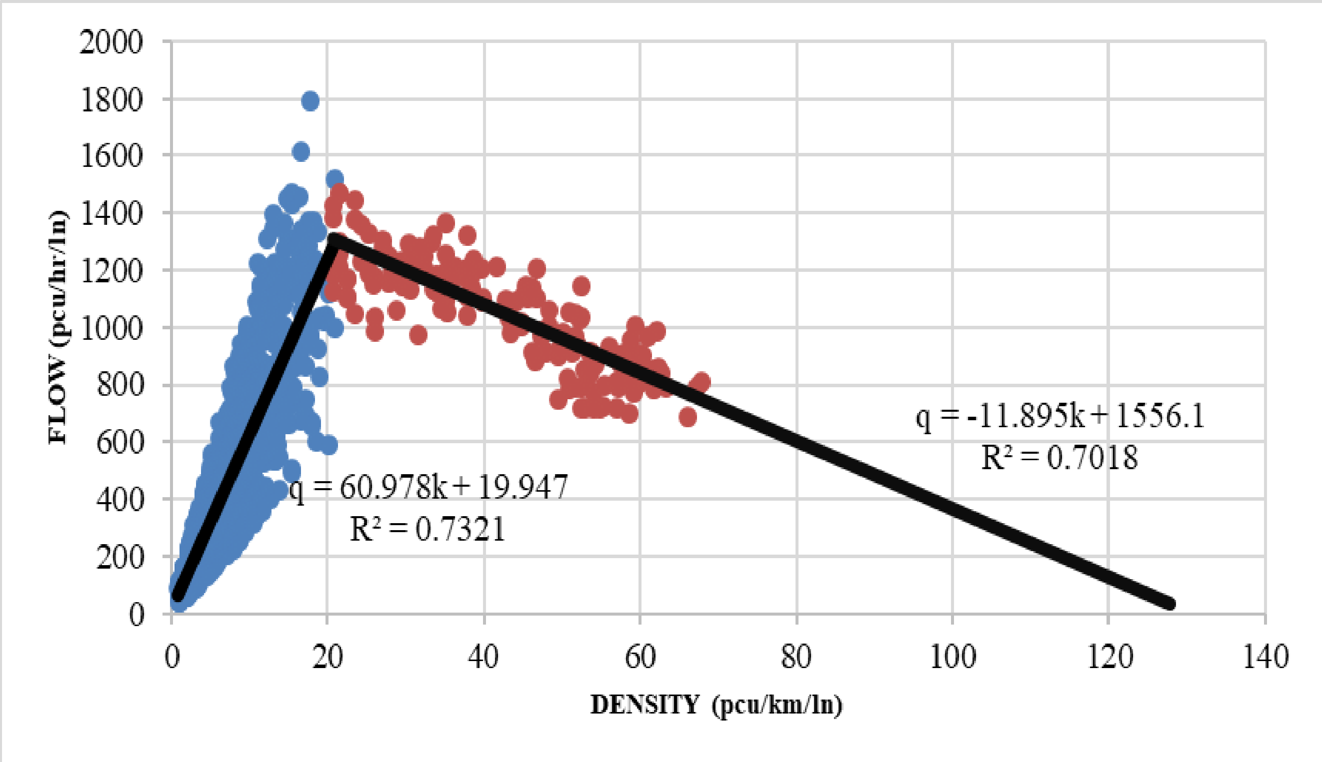

Fig. 2. Piecewise linear regression to develop the flow-density fundamental diagram

The regression equation is developed using piecewise linear relation, as the CTM is based on a piecewise linear flow-density diagram. The regression equation for the linear relation under free-flow condition is given as follows:

$$q = 60.978\rho + 19.947 \tag{3}$$

The slope of the regression line shows the free flow speed as 60.978 km/hr, which is a reasonable value for the free-flow speed of an urban arterial. The flow density equation for the congested regime is given in equation (4).

$$q = -11.895\rho + 1556.1 \tag{4}$$

The slope of the regression line shows that the shockwave speed is 11.895 km/hr, which is also a reasonable value. The calibrated values of input parameters extracted from figure 2 are given in table 2.

Table 2. Input Parameters for CTM based on Fundamental traffic flow diagram

Traffic flow parameters	Values
Capacity Flow	1306 PCU/hr/lane
Free Flow Speed (v)	61 km/hr
Shockwave Speed (w)	12 km/hr
Jam Density (ρ^j)	131 PCU/km/ln
Critical Density (ρ^c)	21 PCU/km/ln

3.2. Calibration and Validation of CTM

The input parameters for CTM are extracted from fundamental traffic flow diagram as shown in table-2. Equation (2) is used to determine inflow rates based on calibrated parameters for all the cell and simulation time-steps. The calibrated CTM is validated using data from another road to evaluate the performance of calibrated CTM and to examine the accuracy of the developed fundamental diagram.

To validate the calibrated CTM, a 300m long segment of Khayaban-e-Iqbal was selected to implement the calibrated CTM. The segment of road is shown on Google Maps in Fig. 3.

Fig. 3. Road Segment of Khayaban-e-Iqbal for validation of CTM

The inflow and outflow from the selected sections are measured using traffic data collected from two cameras placed at inlet and outlet of the section. The inflow profile is provided as input to the CTM and measured outflow profiles are compared with the modelled traffic flow.

The Cell Transmission Model requires the inflow, capacity flow, number of lanes, free-flow speed, and shockwave speed, which are based on values from table-2. The simulation time-step was fixed as 5 seconds which corresponds to a cell length of 84 m, by taking the free-flow speed of 61 km/hr based on fundamental traffic flow diagram shown in figure-2.

The comparison of measured and simulated outflows for the selected section is shown in figure-4. It is evident from the figure that calibrated CTM is performing very well to model the heterogeneous and non-lane-disciplined traffic.

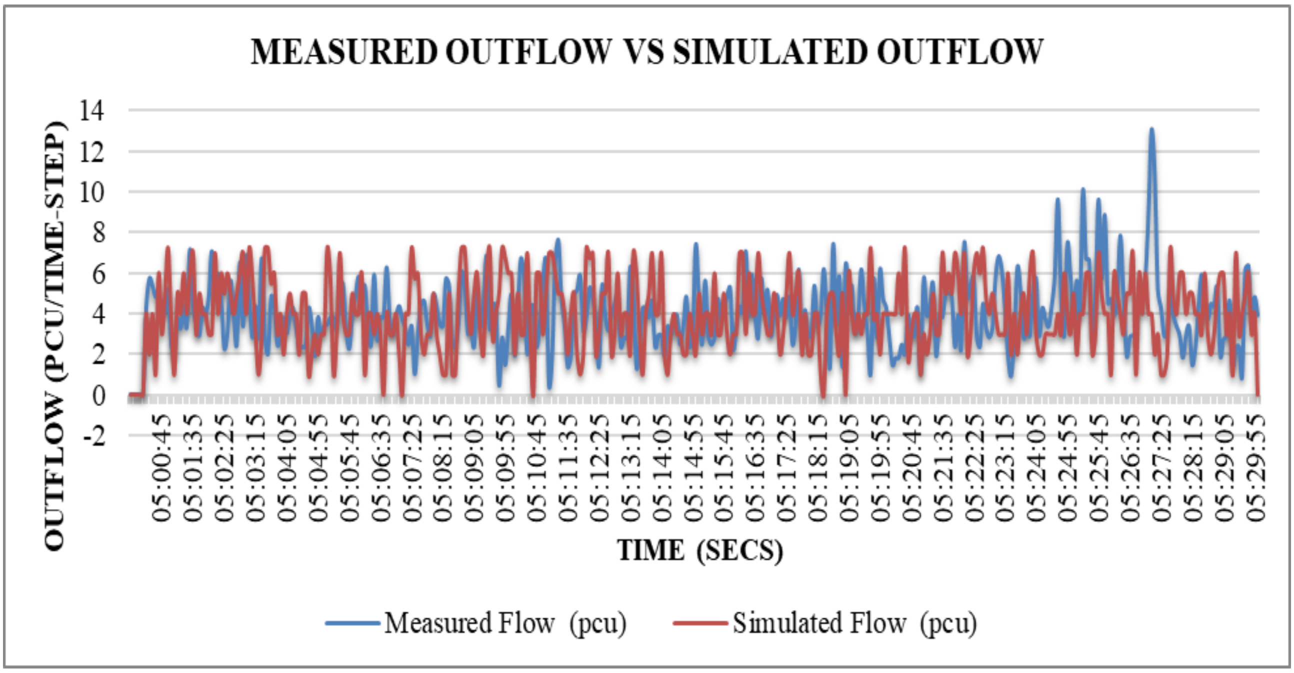

Fig. 4. Comparison of measured and simulated flow

5. Conclusion

This research is focused on calibration of the Cell Transmission Model through the development of a flow-density fundamental diagram. Traffic data collected from various arterial roads of Karachi was used to develop the fundamental diagram. This fundamental traffic flow diagram was used to extract the values of traffic flow parameters, which were utilized to calibrate CTM. Almost 4700 data points collected from various arterial roads in Karachi were used for the development of this diagram. The calibrated CTM was tested with another road and the validation results are showing a close correlation with the observed traffic flows.

This research highlights that macroscopic traffic flow models, such as CTM can be extremely useful to model heterogeneous and undisciplined traffic systems, where it is complicated to calibrate simulation packages based on microscopic traffic flow models. In comparison with microscopic simulation packages, which need calibration of multiple parameters, the CTM can be easily calibrated by developing fundamental traffic flow diagram for given conditions. The calibrated CTM can be useful in simulating the traffic network using traffic simulation packages such as TRANSYT, DISCO, CTMSIM and SIGMIX.

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