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Heterogeneous traffic flow modelling using second-order macroscopic continuum model

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ABSTRACT

Modelling heterogeneous traffic flow lacking in lane discipline is one of the emerging research areas in the past few years. The two main challenges in modelling are: capturing the effect of varying size of vehicles, and the lack in lane discipline, both of which together lead to the ‘gap filling’ behaviour of vehicles. The same section length of the road can be occupied by different types of vehicles at the same time, and the conventional measure of traffic concentration, density (vehicles per lane per unit length), is not a good measure for heterogeneous traffic modelling. First aim of this paper is to have a parsimonious model of heterogeneous traffic that can capture the unique phenomena of gap filling. Second aim is to emphasize the suitability of higher-order models for modelling heterogeneous traffic. Third, the paper aims to suggest area occupancy as concentration measure of heterogeneous traffic lacking in lane discipline. The above mentioned two main challenges of heterogeneous traffic flow are addressed by extending an existing second-order continuum model of traffic flow, using area occupancy for traffic concentration instead of density. The extended model is calibrated and validated with field data from an arterial road in Chennai city, and the results are compared with those from few existing generalized multi-class models.

1. Introduction

Modelling heterogeneous traffic flow lacking in lane discipline is one of the emerging research areas in the past few years. The two main challenges in modelling are: capturing the effect of varying size of vehicles, and the lack in lane discipline, both of which together lead to the ‘gap filling’ behaviour (a phenomenon of congested traffic where vehicles try to percolate through the available gaps in the road section ahead). Ref. [1] proposed a non-lane based lattice hydrodynamic model of traffic flow incorporating the effect of lateral separation of lane width in homogeneous traffic. Simplified versions of hydrodynamic models are the continuum models. Existing conventional continuum type traffic flow models are well suited for developed countries with homogeneous traffic and perfect lane discipline. In fact, even in the so called homogeneous traffic, the vehicles’ sizes may vary. Ref. [2] considered a follow-the-leader approximation of the ARZ model [3,4] of traffic flow in a multi-population formulation. Frequent lateral/lane changing movements in heterogeneous traffic force modelling approaches to consider the entire road width as a whole instead of multiple lanes. The gap filling behaviour makes the road capacity much higher when compared to homogeneous traffic. Thus, the conventional measure of traffic concentration, the density which is measured as vehicles per unit length, is not a good choice for heterogeneous traffic. Recently, Refs. [5] and [6] introduced the concept of *area occupancy* for measuring heterogeneous traffic concentration. This paper addresses the above mentioned two challenges, extending the macroscopic model presented in [4], using area occupancy for traffic concentration instead of density. The paper aims to have a parsimonious model, at macroscopic level, of heterogeneous traffic flow that can capture the unique phenomena of gap filling. The paper suggests area occupancy could be used as traffic concentration measure for modelling heterogeneous traffic. Also, the suitability of higher-order models for modelling heterogeneous traffic is emphasized in the paper. For this, the extended model along with few other existing generalized macroscopic multi-class models is calibrated and validated using data from an arterial section in Chennai City, India. It is shown that in a heterogeneous traffic scenario, the extended second-order model with area occupancy as the traffic concentration measure could better predict flow parameters and congestion propagation than the existing generalized macroscopic multi-class models that rely on density.

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Macroscopic continuum models of traffic flow started with the first-order LWR model by [7] and [8] where the traffic is assumed to be always in steady state equilibrium condition. The model consists of the flow conservation equation, an equilibrium speed–density relationship and the fundamental equation of traffic flow. Though the model proved its ability to capture the traffic shockwave formation explicitly, because of the presence of instantaneous speed–density relationship, it failed to explain few well-known traffic phenomena such as hysteresis, stop and go waves, and platoon dispersion [9]. Realizing that the model's performance can be improved by including the inertial effect in the dynamics of velocity and driver's anticipation to the traffic ahead, Ref. [7] proposed a higher-order extension of this model. Higher-order models remained under-explored until the introduction of macroscopic models by [10,11] which are derived from the microscopic car following logic. Along with the flow conservation and fundamental traffic flow equations, these models express the dynamics of velocity using the relaxation and anticipation terms borrowed from Newtonian physics. The relaxation term shows how the vehicle adjusts to its equilibrium velocity in some relaxation time and hence contributes to the inertial effect of speed. The anticipation term includes a pressure term and considers drivers' reaction to the spatially changing traffic condition ahead. Ref. [12] criticized this model stating the dissimilarities between the infinitely small particle flow in fluid and the finite size vehicle flow in the traffic. The paper also mentioned the 'negative speed' experienced by vehicles in the tails of the congestion region. The higher-order models developed after [11] model tried to resolve the limitation of negative speeds modifying the anticipation term [13,14,4,15]. There also exist models that consider drivers' attribution to the traffic ahead [16–19] and bottleneck effects [20,21]. Literature for higher-order traffic flow models is still vast and only few of them are highlighted above. A comprehensive review of macroscopic traffic flow models is given in [22].

Extension of macroscopic continuum models to heterogeneous traffic has been widely reported in literature [14,23,24,9,25–36]. These extensions include first-order or higher-order equations/models developed in Lagrangian or Eulerian coordinates. First-order models assume the speed of vehicles to be in equilibrium and the main equation is the flow conservation equation. Higher-order models include separate equation for vehicles' speed dynamics along with the flow conservation equation. Since heterogeneous traffic consists of varying vehicle types with varying speeds, higher-order models could be a better choice for its modelling. Few other higher-order models developed for heterogeneous traffic are by [37–40,27,28,41,42]. However, the above models hold limitations of restriction of vehicle categories, inability to capture the gap filling phenomena, or lack of validation with field traffic data.

This paper concentrates on the macroscopic second-order continuum model by [4], well known as AR model. The model uses the convective derivative instead of the spatial derivative, of traffic pressure in the velocity dynamics of [11] model. Thus unlike Payne type models, a driver need not have to decelerate seeing a stopped traffic or a faster moving high density ahead. There exists comprehensive literature as analysis or modification to the AR model [43–50]. This paper extends AR model, for heterogeneous traffic using area occupancy [6], observes the qualitative properties of the extended model, checks the validity using field traffic data, and compares the result with that from two other existing generalized multi-class models.

The paper is organized as follows. The next section briefly reviews the AR model for homogeneous traffic and also the traffic concentration measure Area Occupancy (AO). In the third section, the extended AR model is presented and its qualitative properties are analysed. Calibration of the extended model and two other multi-class models is given in the fourth section and the fifth section validates and compares the results from these models. The last section draws conclusion on the paper.

2. Model background

2.1. AR model of traffic flow

The flaws [12] in the well-known [11] model of traffic flow lead [4] to the formulation of a new model modifying the velocity dynamics equation. The velocity dynamics equation in [11] model is given as:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \frac{u_e(k) - u}{\tau} - \frac{1}{k}\frac{\partial p}{\partial x} \tag{1}$$

where u is the velocity of vehicles, $u_e(k)$ and p respectively are the equilibrium speed and traffic pressure expressed as a function of density, and x and t denote space and time respectively. When solving the above equation along with the flow conservation, the characteristic speeds from the model are given by $u\frac{dp}{dk}$. The speed $u + \frac{dp}{dk}$ indicates that some part of the information always travels faster than the velocity u of cars and hence causes negative speeds of vehicles at some part of the congested region. It can be avoided by using a convective derivative of the pressure instead of the spatial derivative. Thus, the equation system of AR model is given by

$$\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = 0 \tag{2}$$

$$\frac{\partial\,(u + p(k))}{\partial t} + u\frac{\partial\,(u + p(k))}{\partial x} = \frac{u_e(k) - u}{\tau} \tag{3}$$

The traffic pressure $p(k)$ can be expressed as an increasing function of density and is given by $p(k) = {C_0}^2 k^\gamma$ where γ is a dimensionless parameter ($\gamma > 0$) and C_0 is a constant that equals 1. For choosing the pressure function, the two qualitatively important conditions to be satisfied are: the strict convexity of the function $kp(k)$ and $p(k) \sim {C_0}^2 k^\gamma$, near $k = 0$. The two characteristic speeds from equations (2) and (3) are $\lambda_1 = u$ and $\lambda_2 = u - k\frac{dp}{dk}$ indicating that the information will travel with speed at most equal to that of the vehicles.

For traffic lacking lane following discipline, the same section length may be occupied by different vehicle types at the same time depending on the space availability. Hence the traffic pressure in terms of density is valid only for homogeneous traffic condition where clear lane and queue discipline exist. For heterogeneous traffic conditions in Asian countries where the concept of lane based movement is not strictly followed, traffic concentration can be better expressed in terms of AO.

2.2. Area occupancy for heterogeneous traffic

Traffic density is defined as the number of vehicles occupying unit length of roadway at any instant of time. It is usually measured as vehicles per lane per km length of the road neglecting individual vehicle speed and dimensions and hence more suitable for homogeneous, lane disciplined traffic. In order to account for vehicles' varying speeds and dimensions even under homogeneous traffic condition, a new measure of concentration, occupancy [51,52] is introduced which is a dimensionless variable, measured directly by the amount of time a particular point of the roadway is occupied by all the vehicles. Even though occupancy is mentioned as a point measurement, based on practical consideration, it is defined as the percentage of time a detection zone is occupied by vehicles. Hence this measure varies with change in detection zone length even for the same site with identical traffic. Thus it is