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Modeling heterogeneous traffic flow: A pragmatic approach

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ABSTRACT

Modeling dynamics of heterogeneous traffic flow is central to the control and operations of today's increasingly complex transportation systems. We develop a macroscopic heterogeneous traffic flow model. This model considers interplay of multiple vehicle classes, each of which is assumed to possess homogeneous car-following behavior and vehicle attributes. We propose the concepts of road capacity split and perceived equivalent density for each class to model both lateral and longitudinal cross-class interactions across neighboring cells. Rather than leveraging hydrodynamic analogies, it establishes pragmatic cross-class interaction rules aspired by capacity allocation and approximate inter-cell fluxes. This model generalizes the classical Cell Transmission Model (CTM) to three types of traffic regimes in general, i.e. free flow, semi-congestion, and full congestion regimes. This model replicates prominent empirical characteristics exhibited by mixed vehicular flow, including formation and spatio-temporal propagation of shockwaves, vehicle overtaking, as well as oscillatory waves. Those features are validated against numerical experiments and the NGSIM I-80 data. Realistic class-specific travel times can be computed from this model efficiently, which demonstrates the feasibility of applying this multi-class model to large-scale real-world networks.

1. Introduction

Traffic flow dynamics is dictated by competitive traffic streams of different characters, which stem from both heterogeneous vehicle dynamics and driver preferences. For instance, in a multi-modal system, passenger cars, transit fleets and trucks share the right of way. The different vehicle characters necessarily endow them with heterogeneous safety distances, desired speeds, and lanes to travel on. As another example, drivers (including both human and automated robotic drivers) can exhibit heterogeneous driving behavior, e.g., gaps to keep when following the leading vehicles, frequency to apply brakes, and tendency of lane-changing, etc. This further complicates the aggregate traffic dynamics. While heterogeneity is a ubiquitous character of traffic flow in the real world, different studies show that reproducible density-flow relations (i.e. fundamental diagrams) can be reconstructed when is a traffic stream is homogeneous and stationary

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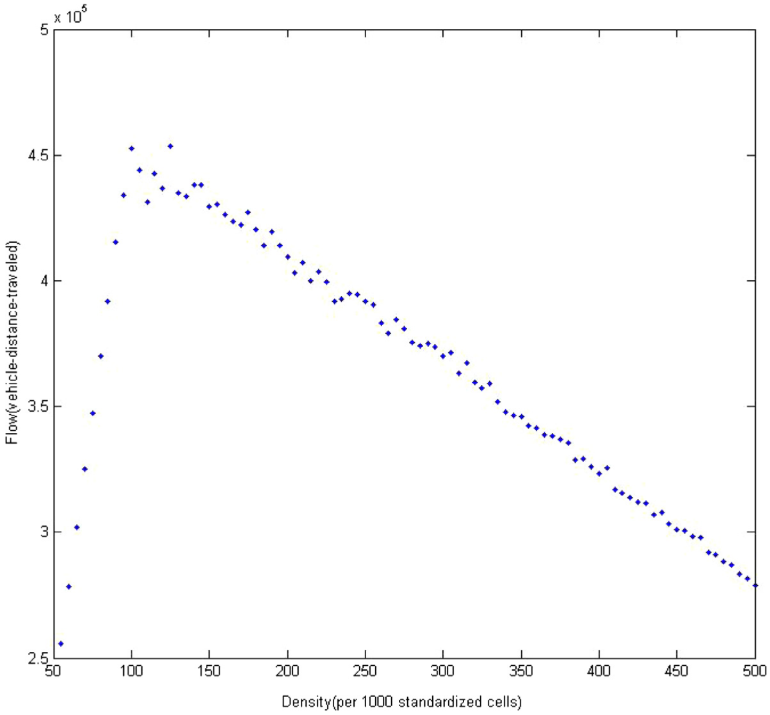

Fig. 1. A fundamental diagram from Nagel–Schreckenberg traffic.

(Cassidy, 1998; Laval and Chilukuri, 2016; Jin, 2017). Therefore, it is reasonable to assume that a homogeneous traffic stream can still be well described by a well-defined (continuous and concave) fundamental diagram.

To further illustrate what the above assumption implies, we consider a traffic stream consisting of vehicles following identical probabilistic car-following rules, which are described by the well-known Nagel–Schreckenberg cellular automaton (CA) model (Nagel and Schreckenberg, 1992; Tian et al., 2016). The resulted flow-density relation is well approximated by a triangle relation, as we show in Fig. 1. This figure depicts the case where we simulate traffic flow in a single-lane loop consisting of in all 1000 cells, with the number of vehicles varying from 50 to 550 vehicles.

Nonetheless, in reality, empirical flow-density fundamental diagrams usually exhibit substantial scatterings, especially near the congestion branch. While other explanations (such as high-order effects, non-stationary behaviors and randomness) to the scatterings also exist (Costeseque and Lebacque, 2014; Mohan and Ramadurai, 2017), how different traffic streams interact obviously influences the aggregate dynamics in a significant way and is one important aspect to look into.

Complications of modeling multi-class flow are primarily due to the unlimited (or unknown) possibilities of interplay between different traffic streams. In mixed traffic flow, the flow-density relation is no longer expected to be a real-valued function. Rather, it is a mapping from multi-dimensional space to multi-dimensional space. Specifications of such relations are challenging in general. Moreover, due to the limited availability of class-specific traffic data, there rarely exists empirical evidence on what the relations should look like.

One natural idea of modeling heterogeneous flow is to approximate the mixed flow by explicitly modeling the interactions of different homogeneous traffic streams, assuming each single traffic stream obeys an equilibrium relation when no other traffic streams are present. Each class possesses identical vehicle attributes and car-following rules, which are encapsulated by a unique well-defined (least requirements usually include continuity and concavity) fundamental diagram. Previous studies provide several significant models from different angles. In light of this, this paper proposes a generalized and parsimonious capacity allocation mechanism to capture inter-class flow interactions. In particular, we design the capacity allocation mechanism based a concept of “perceived equivalent density”. In our model, each vehicle class m treats vehicles of other classes in vicinity as a single class m in an “equivalent” sense, which is determined by impact of other vehicles to the existing capacity. As we will show later on, this model is a natural extension of the classical LWR model (Lighthill and Whitham, 1955; Richards, 1956) and the capacity allocation model defined by Logghe and Immers (2008). We note that our approach differs from classical Passenger Car Unit (PCU) approach (e.g. van Lint et al., 2008). The dynamic PCU is meant to capture the heterogeneity in stopping distance and minimum time headway measured by the same standard class, which stems from different vehicle characteristics. In contrast, our approach of perceived density is defined from a macroscopic perspective for the purpose of capacity allocation along both lateral and longitudinal flux. This difference will be further explained with details in Section 3.5.