



Technologies for Safe & Efficient Transportation

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What do autonomous vehicles mean to
traffic congestion and crash?
Network traffic flow modeling and
simulation for autonomous vehicles

FINAL RESEARCH REPORT

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Problem statement

Transportation infrastructure is quickly moving towards revolutionary changes to accommodate the deployment of AVs. On the other hand, the transition to new vehicle technologies will be shaped in large part by changes in performance of roadway infrastructure. This research aims at understanding the relationship between AV technology and infrastructure performance, which leads to revolutionary change in transportation infrastructure design in the both short and long term.

For nearly a century, traffic flow in the roadway networks is operated purely by human beings. Human's reactions to preceding vehicles and side vehicles almost dominate the driving behavior, which is to be replaced by vehicle automation/communication in the future. The technology for autonomous and connected vehicles is rapidly approaching the point of commercial implementation. AVs are cars that can be fully controlled by computers, instead of people, relying upon on-board advanced sensors and computers to observe and interpret road conditions and determine a safe course of action. Connected vehicles, on the other hand, receive data from other vehicles, or a central system, that then instructs them how to operate safely. Generally there is a significant developmental overlap between the two, with future autonomous connected vehicles able to receive data from itself, other cars and systems, and capable of driving themselves or accepting control from external systems. With an assigned time and path, these lightweight, self-guided cars would proceed steadily through crowded infrastructure without all the stop-and-go that chokes roadways and saps fuel efficiency. Many of the enabling technologies, such as adaptive cruise control and lane departure warning systems, already exist. We envision that the pathways of AV and connected vehicle development are likely to converge in the long run. This research uses 'autonomous vehicle (AV)' to represent 'autonomous connected vehicle'.

To assess the vehicular technology impact to the traffic flow, two of the most important questions we attempt to tackle in this research are,

- 1) How would vehicle automation/communication, with different sensing and control specifications, change the vehicle speed and headway under various traffic conditions, and therefore change traffic congestion and crash patterns in the network?
- 2) How would the vehicular technology change the flow capacity of the roadway infrastructure network, under different crash rates that are expected to be achieved by different vehicular control strategies? How does the change vary at different levels of AV penetration rates?

This project primarily addresses the mobility concerns of AVs, while establishing a modeling framework that allows future extensions to assess both mobility and

safety. In particular, this research proposes a multi-class traffic flow model that captures the car-following behavior of both regular vehicles and AVs. The research helps determine the impact of vehicle automation on the effective road capacity and operating efficiency of transportation networks. It also provides insights for design of the vehicle control strategies targeting mobility and safety. With the traffic flow model mixing both AV and regular vehicles, future research will be devoted to address knowledge gaps related to the operations of automated vehicles and the existing road infrastructure, and the policy implications for transportation planning, system design, and the economy.

Approach

One key idea of modeling heterogeneous flow is that, rather than an aggregated flow-density relation of mixed flow as treated in the well-known LWR model, we approximate the mixed flow by considering the interactions of several classes of traffic streams. 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. In this paper, still within this general framework, we develop a generic, yet simple, class-specific capacity allocation and flux scheme to capture inter-class flow interactions. This method has several distinct features,

Data-driven framework. We propose several flow propagation and interaction rules that are consistent with the flow physics and can be easily calibrated using real-world data. Unlike the LWR model whose only empirical input is the aggregated fundamental diagram, class-specific fundamental diagrams and interaction rules of the proposed multi-class model can be simultaneously tuned to best reflect empirical truth, analogous to classical data mining models. The data-driven approach can ensure the model fit the reality in an optimal fashion and produce reliable estimation and prediction. Though in reality, virtually every single car possesses different behavior and their respective attributes are unknown, it is possible to approximate the actual flow attributes by several representative classes and tuning them properly with data.

Realistic class-specific travel time computation. Traversal times of a roadway segment can vary significantly among flow classes. An important advantage of this multi-class model is to estimate or predict the travel time for each class in the dynamic transportation network, a necessity for multi-class Dynamic Traffic Assignment. A general phenomena is that under severe congestion, the travel speed of all classes tends to converge, while each class can follow its respective free-flow speed in very light traffic. The travel time plays an important role in travelers' route choice, departure time choice and modal choice in the network, and therefore should be distinguished among classes.

Model flexibility. Traffic flow can be distinguished by many factors, such as vehicle size (e.g., trucks versus standard passenger cars), drivers' reaction time (aggressive drivers versus conservative drivers), vehicle maximum speeds (luxury cars versus regular cars), and vehicle automation (automated vehicles versus human-driving vehicles). Each of those factors, if significant in flow, can be captured in the fundamental diagram of a representative class. For instance, aggressive drivers' class leads to higher free-flow speed and slower shockwave speed. Truck's class leads to lower free-flow speed and much lower jam density. If sufficient field data are available, approximating the flow attributes using sufficient amount of representative classes is always possible.

Computational efficiency for large-scale networks. Multi-class flow models often require intensive computations, which hinders its application to large-scale dynamic network models. A simple and pragmatic flow propagation model enables efficient modeling of heterogeneous travelers in large-scale networks.

Methodology

This research approximates traffic flow by two vehicle classes each of which is assumed to possess homogeneous car-following behavior and vehicle size. An intuitive computational procedure is proposed to capture mixed vehicular flow propagation and shock formation phenomena. The car-following behavior and vehicle size are assumed to be homogeneous for both regular vehicles and AVs, represented by a deterministic fundamental diagram. Both classes of vehicles experience identical traffic state, but each class perceived the effect of other classes differently. We propose the concept of perceived equivalent density for each class. Perceived density for class m is the equivalent density of vehicles in class m that a class m would perceive by converting other classes into class m . Both lateral and longitudinal cross-class interactions are modeled. The lateral cross-class intersections are captured through α , namely the fraction of lateral road space utilized by class m traffic. Oftentimes, microscopic data are unavailable or not sufficient to identify such fractions precisely. Therefore, a pragmatic scheme is proposed in such a way that the lateral road capacity is utilized most efficiently and the space allocation is consistent with the flow phenomena.

The research methodology has been reported in a paper titled, Modeling Heterogeneous Traffic Flow: A Pragmatic Approach, and under review for publication in Transportation Research Part B.

Findings and Conclusions

Our multi-class flow model is shown to be consistent with the single class CTM model and has the ability to capture shockwave of multiple classes. The multi-class models has been extensively tested in numerical experiments and the NGSIM I-80

data set (obtained through). They can produce realistic congestion propagation for two classes in various scenarios including flow perturbation and incident-induced bottleneck. The new model also computes realistic time-varying travel time for each class, which cannot be obtained from the conventional single class model.

The new multi-class flow model inherently enables a data-driven approach to further calibrate and verify the underlying behavior models. If refined traffic data are available (e.g., vehicle trajectory data similar to the NGSIM or time-varying density/counts), then road space allocations and fundamental diagrams of each representative vehicle class can be determined such that all those tuning parameters together produce estimation of spatiotemporal flow closest to the real observation. This is analogous to Rank-M approximation of data in the data mining literature.

Our future work will first collect traffic data in more sites and further validate the multi-class model. We will generalize our classification. Traffic flow can be categorized by vehicle size (e.g., trucks versus standard passenger cars), drivers' reaction time (aggressive drivers versus conservative drivers), vehicle maximum speeds (luxury cars versus regular cars), and vehicle automation (automated vehicles versus human-driving vehicles). Different vehicle classification methods can be examined to better approximate the real traffic flow. In addition to modeling flow in a stretch of highway, we will also extend our model to merge and diverge junctions. A pragmatic model will be proposed to model merge and diverge for multiple classes, which requires field test and data validation. Another goal is to apply the multi-class model to general network models so that route, mode and departure time choices of heterogeneous users in the network can be properly modeled.