Integrated Traffic Flow Models and Analysis for Automated Vehicles

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Abstract With the emergence of connected and automated vehicle (CAV) technologies, research on traffic flow modeling and analysis will play a very important role in improving our understanding of the fundamental characteristics of traffic flow. The frontier of studies on CAV systems have examined the impacts of CAVs on freeway bottleneck capacity, and macroscopic traffic flow, CAV

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G. Meyer and S. Beiker (eds.), *Road Vehicle Automation 3*,
Lecture Notes in Mobility, DOI 10.1007/978-3-319-40503-2_20

applications on optimization of individual vehicle trajectories, potentials of CAV in traffic signal control, and applications of CAV in network routing. For current and future research initiatives, the greatest challenge lies in the potential inconsistencies between user, operator, and manufacturer goals. Specific research needs were identified on data collection and analysis on CAV behavior and applications. This paper summarizes the presentations and discussions during the Automated Vehicles Symposium 2015 (AVS15) held in Ypsilanti, Michigan, on July 20–23, 2015.

Keywords Traffic flow model · CAV behavior · Data collection · Research needs

1 Introduction

As connected and automated vehicle (CAV) technologies emerge in road transportation systems, it is critical to bring together the wireless communication, vehicle dynamics and traffic flow communities to better understand the fundamental characteristics of traffic flow with varying level of connectivity and automation and identify research needs to develop models to assess the implications of CAV in various aspects, including mobility, safety, and the environment.

This paper summarizes the presentations and discussions and presentations during the breakout session on Integrated Traffic Flow Models and Analysis for Automated Vehicles at the Automated Vehicles Symposium 2015 (AVS15) held in Ypsilanti, Michigan, on July 20–23, 2015. In the breakout section five scholars were invited to present their frontier research on CAV from different perspectives. Following the presentations, a panel consisting of the five invited speakers had extensive discussions with the audience to identify the key challenges in this research area define and further research needs.

The remaining sections of this paper are organized as follows: Sect. 2 presents the summary of the invited presentations and Sect. 3 introduces the key results from the panel discussion. References are also provided at the end.

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2 Frontier Research on CAV Traffic Flow Modeling and Control

This section presents a summary of the invited talks, which addressed the research frontier from various aspects. The summary includes the background and significance of the research, the main conclusions, and also directions for future research.

2.1 Modeling Traffic Flow with Automated Vehicles at Highway Bottlenecks[1]

Automated vehicles are believed to help resolve congestion in motorway networks. Back of the envelope pipeline capacity calculations based on short distance platooning indeed easily yield capacity estimates up to 6,000 veh/h, which by far exceeds traditional capacity estimates that are around 2200 veh/h as can be found in the Highway Capacity Manual [1]. As a consequence it has been argued that automated vehicles could triple roadway capacity. Shladover et al. [2] have shown lane capacities to increase from (approximately) 2,065–3,970 veh/h using more realistic models for the behaviour of manual and cooperative adaptive cruise control (CACC) equipped vehicles. In real freeway networks, however, congestion typically occurs at bottleneck locations such as lane drops, on-ramps, weaving sections or other discontinuities in the road geometry. Bertini and Hoogendoorn [3] argue that congestion can be resolved by improving outflow from and reducing inflow into road segments, preventing spill backs and spreading traffic over different alternatives.

van Driel and van Arem [4] focused on the impacts of a congestion assistant on a high traffic demand motorway stretch with a 4–3 lane drop scenario. The congestion assistant was assumed to help a driver to slow down by an active gas pedal when approaching congestion and provided full longitudinal automation in congested traffic. Using traffic flow simulations, they have shown that around 30 % delay saving could be achieved at low CAV penetration rates such as 10 %. The delay savings are particularly caused by increased outflow of the congested area. The free flow bottleneck roadway capacity did not change significantly.

van Arem et al. [5] studied a special lane where vehicles equipped with CACC can drive at short intra platoon distances, again at a motorway stretch with a 4–3 lane drop. The motivation to study a special lane for CACC platoon was to explore whether this could help reduce congestion at a high traffic demand level. The problem was studied using traffic flow simulation. The experiments showed again that increased outflow results in higher throughput. Notably, it was also found that the mandatory lane changes of manual vehicles moving out of the CACC-only lane

[1]By Bart van Arem, Delft University of Technology (Netherlands).

caused detrimental impacts on traffic efficiency. Therefore, the geometric design involving a dedicated lane only beneficial at a specific range of CACC penetration.

The results of the studies outlined above and others [6] suggest that the contribution of automated vehicles to reducing traffic congestion depends substantially on how automated vehicles perform at bottleneck locations compared with human drivers. The current literature also suggests that aiming to improve outflow of congestion by automated vehicles (and reducing capacity drop) can yield early benefits at low penetration rates. In addition, there is a need to develop coordination strategies of automated vehicles in complex road geometries such as weaving areas and to manage transitions between manual and automated driving and between general purpose and dedicated lanes. A recently started project conducted by UC Berkeley PATH and TU Delft on behalf of the Federal Highway Administration (FHWA) [7] is focusing on active platoon formation strategies, supported by road side systems and dedicated lanes. The project includes traffic flow simulations of a 21-km SR-99 freeway stretch with high occupancy vehicle (HOV) lanes near Sacramento.

2.2 *Impacts of Connected and Automated Vehicles on the Macroscopic Fundamental Diagram*[2]

The fundamental diagram (FD) (Fig. 1) shows the relationships between traffic flow, speed, and density on freeways and arterial links. Traditionally, these relationships have been used in traffic modeling, control, and operation assessments. The fundamental diagram can be used for queue estimation and control (e.g., platoon progression) at signalized intersections, and it defines the main building blocks of traffic flow theory. The FD is primarily used on freeways to model the steady-state relationship between density and flow [8]. Temporary changes in traffic flow and/or capacity on a link usually result in shockwaves where conditions change rapidly. Collecting data in such dynamic situations typically results in a cloud of data points, and consequently, a non-unique FD.

Recent developments in traffic flow and network modeling gave rise to what is now widely known as the macroscopic fundamental diagram (MFD). The MFD has been defined as a relationship between average network flow and accumulation. This concept attempts to establish an FD-like relationship at the network level. It requires averaging of all network flows and density over small time periods, and plotting their relationship [9, 10] for the purpose of establishing large-scale network state estimation and control [9]. Recent work indicated that the level of heterogeneity in the network characteristics affects the degree of data scatter and maximum flow of an MFD. Researchers recommended constructing the MFD for

[2]By Montasir M. Abbas, Virginia Tech.

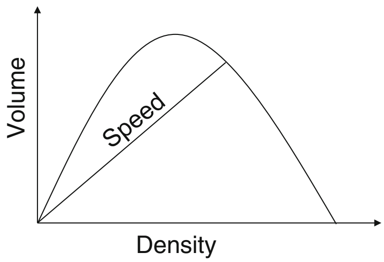

Fig. 1 Fundamental diagram

homogeneous networks with low link density variance to reduce the scatter [11, 12].

The introduction of connected and automated vehicles into the traffic stream is bound to change the shape and form of the fundamental diagram. To model future connected and automated vehicles, a novel multi-agent reservation system was developed where vehicles reserve space tiles and time slots at signalized intersections in a priority-stratified first-come first-served way (Fig. 2). However, higher priority vehicles can revoke the reservation of lower priority vehicles, forcing them to re-reserve later time slots.

In contrast to the MFD, a new concept was defined that aims to explore the heterogeneity of the FD relationship associated with each priority level. This may allow one to separate FDs associated with different priorities from. This concept is called aggregated fundamental diagram (AFD) and aim to define a class of service (COS) for each data set. Vehicles with priorities that fall onto a higher capacity AFD experience a higher COS. One could expect links that suffer from spillback, low capacities, or suboptimal control to fall onto lower AFD and lower COS.

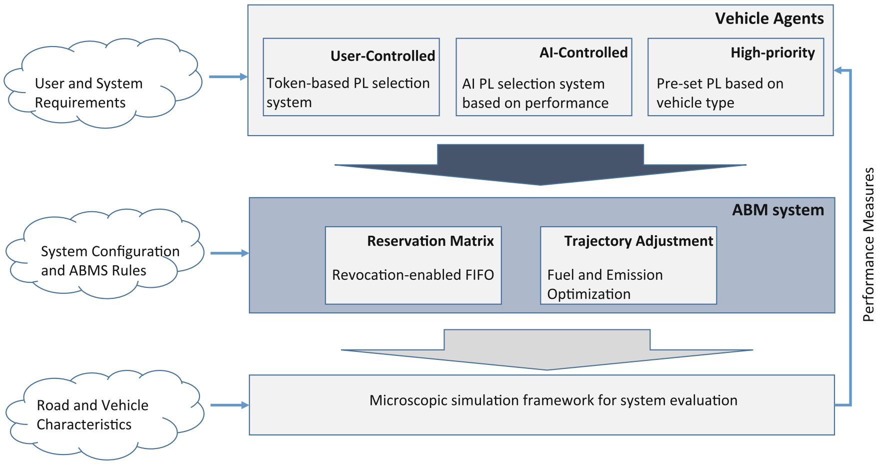

Fig. 2 Reservation multi-agent system (MAS)

A future objective may be to observe and analyze the impact of the introduction of high priority connected and automated vehicles on the fundamental diagram and develop control applications.

The proposed agent-based framework was implemented using the VISSIM traffic simulation software [13]. An experiment was conducted for modeling agents' self-organization ability by setting different priorities for agents according to their associated movement phases. Through movements on the main approaches were given the highest priorities, followed by through movements on the minor approaches, then the left turners. Conflict resolution was handled by the MAS reservation system (Fig. 2) and without signalized intersection operation.

No models were fitted to the data to avoid extrapolation issues, but it is clear that different priority levels are falling onto different FDs. It is therefore concluded that:

- AFDs can be used for characterization and improvement of network performance.
- Agent-based modeling and simulation provides a suitable framework for analysis of automated and connected vehicles.
- Movements with different priorities exhibit different traffic flow relationships. The framework illustrated here removes the necessity to assign higher priorities (and hence a higher classes of service) to approaches. This allows the redefinition of "major" and "minor" movements to align with individual user's needs and urgency levels regardless of the approach/phase they are in.

2.3 *Automated Vehicle Trajectory Control Versus Classical Traffic Flow Theories*[3]

One can anticipate that future connected and automated vehicle technologies will enable vehicles to be driven by customizable computer programs instead of human beings with obvious behavioral defects and constraints. With these technologies, we can potentially control vehicle trajectories to optimize both the individual experience and the overall traffic performance. As transportation researchers, do we just focus on modifying the current infrastructure to accommodate automated vehicles designed by the auto industry or should we participate in the research agenda of designing and optimizing vehicle driving rules? The answer to this question may shift the scope of future transportation research and change the impacts of these emerging technologies to our society.

The author's opinion on this question is that we should participate in designing or modifying vehicle driving rules in conjunction with thinking about corresponding changes of the infrastructure. We shall get into the very depth of the vehicle trajectory design, which ultimately determines each individual driver's

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[3]By Xiaopeng Li, University of South Florida.

experience as well as the collective traffic performance. Only by allowing infrastructure interacting with vehicle trajectory control, can we maximize the overall benefit of these emerging technologies while minimizing each individual's cost on transportation.

As one of the pioneering attempts, a novel shooting heuristic (SH) was proposed for optimizing CAV trajectories, considering realistic constraints including vehicle kinematic limits, traffic arrival patterns, and car-following safety [14]. In particular, the relationships between SH results and those obtained from classic traffic theories were investigated. The time geography theory was generalized to investigate the theoretical properties of SH. It was found that SH can be viewed as a generalization of a number of classic traffic flow models (e.g., kinematic wave model and Newell's simplified car-following model). Numerical examples were conducted to illustrate these theoretical findings. This study reveals commonalities and connections between emerging trajectory optimization approaches and classic traffic flow theories and it lays a solid foundation for devising holistic control strategies for future transportation systems with emerging technologies.

Three directions are worth investigation for future research: (a) vehicle trajectory optimization, (b) next generation infrastructure design, and (c) interaction between automated vehicles and human drivers.

2.4 Automated and Connected Vehicles on Traffic Signal Control[4]

The contribution examines the question of what is new in a connected and automated environment for traffic signal control. Traffic signal control evolves from the efficiency-oriented design to the collective fashion considering multi-model efficiency/safety as well as quality of service. There seem to be enormous application potentials, particularly in four major aspects:

1. Reducing the start-up lost time using signal phase and timing data (SPaT) information and cooperative adaptive cruise control (CACC) control.
2. Reducing the change period lost time by replacing yellow interval with green clearance interval and eliminating red clearance. This can be achieved by using SPaT data to accurately compute the Go or No Go decision for every vehicle.
3. Reducing the saturation headway of CACC vehicle to increase the utilization of green time (saturation flow period).
4. Increasing system capacity by forming self-organized platoons (e.g., using CACC technology).

There are some key research questions in this area that need to be addressed, including (a) what's what are the requirements for CACC on signalized roadways?

[4]By Larry Head, University of Arizona.

(b) How to improve traffic signal efficiency under different market penetrations? And (c) how to provide incentives to form self-organizing platoons?

2.5 Connected and Automated Vehicles on Space-Phase-Time (SPT) Hyper-Network[5]

Emerging automated vehicle technology technologies will allow for route guidance for individual vehicles and have the potential for close coordination between vehicles and the infrastructure. In practice, these possible benefits also create new challenges. As an example, in urban areas, it is critical to provide individual vehicles with guided paths and optimize related traffic signals together so as to maximize both traffic safety and mobility. This problem is referred to as simultaneous route guidance and traffic signal optimization problem (RGTSO). In this contribution, the RGTSO problem is was formulated using the time-dependent space-time network coupled with a new type of network traffic signal control representation, referred to as phase-time network. The new formulation of RGTSO can guarantee the RGTSO problem's linearity. The RGTSO problem is then decomposed into two sub-problems: the route guidance (RG) problem and the traffic signal optimization (TSO) problem. The solution to the TSO sub-problem provides time-dependent link capacity constraints for the RG sub-problem whereas the dual prices of the RG sub-problem indicate search directions for the TSO sub-problem. Both the RG and TSO sub-problems can be solved using a computationally efficient finite-horizon dynamic programming framework, enhanced by scalable parallel computing techniques. Two numerical experiments demonstrated that the system optimum of the RGTSO problem can be quickly reached with relatively small duality gap for medium-size urban networks.

3 Discussion

The panel discussion (including audience interaction) identified the key challenges in traffic flow research in the connected-automated environment and outlined the future research needs, which not only help to advance research on traffic flow modeling of CAV but also to promote the collaboration and coordination of the traffic flow research community with other communities, including vehicle automation, cyber-physical systems, and human factors.

It was concluded that the *biggest challenge* lies in the potential inconsistency in user, operator, and manufacturer goals. In particular, users are most likely interested in benefits at the individual level, such as improving safety, reducing travel time,

[5]By Xuesong Zhou, Arizona State University.

and enhancing travel convenience and comfort. In contrast, traffic and transportation system operators mostly prioritize the system-wide benefits. Finally, manufacturers are indeed driven by vehicle sales. Therefore, the interests of these key stakeholders are not always well aligned, which could severely impede the technology implementation and application.

For example, traffic operators are quite interested in the appealing benefits of CACC vehicles to improve roadway capacity and mitigate congestion (i.e., positive societal benefits), which require drivers to form short-space platoons. As a user, however, there is no obvious benefit to motivate such platooning maneuver. From the manufacturer's perspective, user acceptance is a key factor to decide further investment. Therefore, it's critical to understand and align the interests of the different stakeholders. The research community can play a key role in this process. For example, control/management strategies can be designed that will benefit both users and the system and thus connect the user, operator, and manufacturers. To enable this, the research community needs to understand the operational opportunities and challenges of CAV, which requires operational data, most specifically operational constraints of CAV. This will need the cooperation particularly from the manufacturers. In addition, it is important to recognize that the introduction of CAV technologies will occur incrementally, so for the foreseeable future there will always be a mix of vehicle types and technologies on our roadways. Research aimed at assessing the potential benefits of a range of vehicle types is also important.

Based on the discussion, future research needs can be classified into two groups.

1. Data collection and analysis. It's important to collect data and study (a) changes in driver behavior (especially in non-automated vehicles), (b) CAV operational capabilities and constraints, (c) interactions of drivers with CAV capabilities, and (d) benefits of CAV to consumers (especially linked to applications). Detailed trajectory data are needed.
2. CAV applications. Research is needed to (a) analyze the traffic impacts of CAV on corridor and network level operations under various market penetration rates, and (b) investigate trajectory control and vehicle cooperation strategies at freeway bottlenecks (e.g., merge and weave bottlenecks) and traffic signals, especially under multiple objectives/constraints (e.g., safety, environment, time, comfort, driver acceptance).

It was agreed by the breakout session participants that traffic flow related research plays a critical role in advancing and implementing the CAV technologies, and that collaboration with other research communities, such as vehicle automation and cyber-physical systems, will be very beneficial.

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