Traffic Flow of Connected and Automated Vehicles: Challenges and Opportunities

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Abstract Significant progress has been observed in recent years in the development of connected and automated vehicles (CAVs). Such progress has been publicized through the latest products/applications being released or announced by the industry. However, there is a limited knowledge on the impact of CAV technologies on surface transportation network performance. In particular, the technological specifications associated with CAVs and the response of drivers to such technologies are not well integrated into traffic flow models. These models are needed to assess and evaluate the safety and mobility impact on our roadway conditions. Accordingly, a more elaborate discussion is needed between three entities: (1) the industry partners leading the efforts in developing CAVs; (2) the academic traffic flow modeling community researching the impact of CAVs on traffic flow

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performance; and (3) the public/government agencies devising the standards and the rules to regulate the deployment of CAVs on our roadway network. This chapter summarizes the presentations of speakers from these three entities during the Automated Vehicles Symposium 2016 (AVS16) held in San Francisco, California on July 19–21, 2016. These speakers participated in the break-out session titled "Traffic Flow of Connected and Automated Vehicles". The corresponding discussion and recommendation are presented in terms of the lessons learned and the future research direction to be adopted. This session was organized by the AHB45 (3) Subcommittee on Traffic Flow Modeling for Connected and Automated Vehicles.

Keywords Traffic flow modeling · CAV · Deployment · CACC · Urban networks · Research needs

1 Introduction

As the deployment of connected and automated vehicles (CAVs) is being advocated for by different industry stakeholders, it is important to understand the implications of CAV technologies on the traffic flow dynamics at both the local link level and the network level. Such implications will not be understood without studying two dimensions: the technology dimension and the human dimension. In terms of the technology dimension, the communication, the vehicle dynamics and the sensing specification of CAVs should be identified and should be translated into traffic flow models. In terms of the human dimension, the responsiveness of drivers to CAV technologies should be measured and tested through elaborate experiments especially that CAVs have different types of connectivity and different levels of automation.

Towards studying the technological and human dimensions mentioned earlier, the Transportation Research Board (TRB) AHB45(3) subcommittee on "Traffic Flow Modeling for Connected and Automated Vehicles" organized a breakout

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session at the Automated Vehicles Symposium 2016 (AVS16)—held in San Francisco, California, on July 19–21, 2016. The breakout session titled "Traffic Flow of Connected and Automated Vehicles" brought together five scholars from academia, the industry and the public sector (Federal Highway Administration). These scholars presented their latest work in the CAV field. Following the presentations, a panel consisting of the five invited speakers had extensive discussions with the audience. This chapter summarizes 4 out of the 5 presentations made while identifying the key challenges in this research area and the corresponding efforts made to incorporate both the technological CAV specifications and the corresponding human behavioral response in traffic flow models.

The remaining sections of this chapter are organized as follows: Sect. 2 presents the summary of four out of the 5 invited presentations and Sect. 3 introduces the key results from the panel discussion.

2 Challenges and Research Opportunities on Connected and Automated Traffic Flow

This section presents a summary of four out of the five invited talks, which addressed the research challenges, opportunities and existing efforts in translating Connected and Automated Vehicles (CAVs) characteristics into traffic flow models. The summary includes the motivation and the contributions associated with the presented research, the main conclusions, and the future research directions.

2.1 Challenges of Automated Vehicles for Traffic Flow Modelling

The[1] development of automated vehicles (AVs) has been a long one that has been going on for many decades (Shladover 2007; Tsugawa 2008). The recent developments in the field are in response to a level of maturity in vehicle automation that has reached the stage that vehicles with lower level of automation [SAE L1 and L2 (SAE 2014)] are now present on roads and testing is in full flow for higher levels of automation (Ibañez-Guzman et al. 2012). At the same time, there are still many unknowns in relation to the physical performance of AVs in traffic and in interaction with other vehicles (Calvert et al. 2016). For a safe transition from the current state of affairs to the one where AVs are commonplace, much research is still required. This is the case for the deployment of these vehicles and therefore all the more for the modelling of the effects of the vehicles when deployed.

[1]By Simeon Calvert, Delft University of Technology (Netherlands).

Modelling AVs in traffic requires accurate models. Firstly, the movement of conventional vehicles needs to be more accurate than in regular traffic, as the interaction with AVs is subtler. Secondly, the different levels of AV's need to be considered and accurately captured, from vehicles with driving assistance (SAE L1), right up to fully autonomous vehicles (SAE L5). And thirdly, the interaction between conventional vehicles and the different levels of AV needs to be correct. These requirements are far from trivial, especially as we have not yet even considered the influence of vehicle cooperation and connectivity, and the fact that each automated system will perform differently, even for identical levels of automation. An SAE L2 vehicle from manufacturer A, will undoubtedly be programmed differently one from manufacturer B and therefore will drive differently.

Currently, traffic flow simulation for longitudinal driving generally performs well, however often lacks for the lateral modelling of conventional traffic (Schakel 2015). This is a major issue when it comes to simulation. Empirical research is already ongoing in relation to SAE L1 AVs, and some level 2 systems, which should give good insights into their dynamics and performance in traffic. However, ground truths for higher levels of automation and especially for the interaction between AVs and conventional traffic are scarce. There are a number of challenges that vehicle manufacturers need to consider that also need to be considered for AV simulation. Five of the main challenges relate to: anticipatory capabilities of AVs, situation and behaviour recognition, flexibility of (safety) protocols, consideration of other vehicles and the extent to which AVs are considered equal to conventional vehicles in traffic flow.

There is much to be done in understanding AV dynamics and being able to model these, however the outlook is not bleak. There is a need to focus on acquiring greater ground truths for the performance of AVs in real traffic, that goes beyond what can be achieved from theory. Furthermore, a solid reference with accurate conventional driving models is imperative. There must also be an awareness that AVs will also create new stochastic dynamics in traffic flow, stemming from the interaction with other vehicles and due to differences in vehicle and system design and capabilities. These aspects will need to be continuously addressed as the deployment of vehicle automation advances and should lead to greater capabilities to perform forecasting with the next generation of traffic simulation models.

2.2 Network Level Modeling and Applications of CAV Technologies: Strategic Level

This[2] summary is based on a recent survey article that examines the flow and operational considerations of autonomous and connected vehicles (Mahmassani 2016a); additional discussion of these issues can be found in that document.

[2]By Hani S. Mahmassani, Northwestern University, U.S.A.

The impacts of autonomous vehicles may be far-reaching on several levels. They entail changes on (1) the demand and behavior side, (2) the supply of mobility services, and (3) network and facility operational performance. For individuals and households, it becomes simpler to share the use of vehicles among household members, relieving the need for parents to chauffeur dependent household members, or to tightly synchronize joint travel. This may eventually provide households (and businesses) with the equivalent of a robotic assistant that could perform small errands and pick-up and delivery chores. These benefits, along with the perceptions of safety and reliability of the technology, will play a major role in the adoption equation for autonomous technologies (Mahmassani 2014). Autonomous capabilities may also reduce the need to own multiple vehicles, and some researchers have argued that it would preclude individual vehicle ownership altogether in favor of shared mobility fleets (Fagnant and Kockelman 2015).

The second point is that driverless vehicles will enable new forms of mobility supply. By eliminating the cost and performance limitations of human drivers, and increasing the ease of communicating instructions to both vehicles and travelers, autonomous vehicle fleets can be operated efficiently to deliver dynamically scheduled services to individuals riding privately or in shared vehicles. As such, new forms of car sharing with greater convenience may reduce the motivation for individual ownership. With driverless cars, vehicle availability in sharing services is not limited to fixed locations as vehicles can be repositioned dynamically (Hyland and Mahmassani 2017). Likewise, ride and car sharing marketplaces will likely expand with driverless vehicles, building on platforms developed by ride-hailing app companies like Uber and Lyft. This would contribute to reducing the cost and uncertainty of the sharing model by increasing the supply pool and enabling rapid dispatch of driverless vehicles. More generally, the realm between personal transportation and public mobility can widen considerably to include various hybrid forms. With transit companies adopting a broader portfolio of services, possibly in conjunction with third parties, one could envision disappearance of conventional fixed-route, fixed-schedule bus service in most lower-density communities, supplanted by driverless, personalized service at low density, and shared hybrid forms at medium densities; and greater focus on frequent rapid service along dedicated right of way (rail and/or BRT) in higher-density travel corridors (Mahmassani 2016b).

The potential changes in the supply of transportation and mobility at the urban scale are difficult to predict and characterize for the purpose of developing specific planning tools, and forecasting the demand for these services over time.

These changes in demand patterns, coupled with potentially far-reaching changes in the supply of mobility services, place considerably different loads on transportation networks than under the current situation. The net result is likely to be more, not less, travel, given the additional capacity, flexibility and convenience introduced by autonomous features and the mobility business models devised to leverage them. Actual performance at the network level will reflect these new patterns, and will be greatly affected by the specific routing and scheduling algorithms developed for both individual autonomous vehicles and for vehicle fleets.

These problems share many features of vehicle routing problem (VRP) variants, though coordination for network control purposes introduces features unique to the autonomous vehicle context. Several of the standard assumptions routinely made in predicting flows in networks, such as the prevalence of a user (Nash) equilibrium (UE) in how drivers route themselves through networks are likely to be challenged. For instance, repositioning or return trips, when driverless vehicles are not carrying any passengers (the equivalent of deadhead trips), could be routed on paths that are optimal for the system, i.e. that minimize marginal cost instead the vehicle's average cost. The formulation presented by Peeta and Mahmassani (1995) in the early days of advanced traveler information systems, for multiclass users that include UE, SO along with bounded rational users would be applicable in this case.

The most direct impact on network performance will result from the operational performance characteristics of the vehicles in the traffic stream, and the control algorithms enabled by and deployed with varying degrees of V2 V and V2I connectivity as vehicles navigate through the network's links and junctions. While greatly dependent on decisions made in the commercial marketplace and in the regulatory arena, understanding and modeling these impacts under a given set of assumptions about technological features, deployment scenarios and control measures is somewhat less speculative than the preceding two aspects (behavior, mobility supply models) because it lies mostly in the realm of traffic physics. Accordingly, there are already existing studies in the literature that have attempted to address some of these questions, particularly with regard to throughput and flow stability (Talebpour and Mahmassani 2014, 2016; Talebpour et al. 2016, 2017). A summary of these is found in Mahmassani (2016a).

2.3 CACC—V2X Solutions to ACC Challenges

The[3] CAMP V2I Consortium is a consortium of nine light-vehicle and one heavy-duty truck manufacturers, collaboratively working on Vehicle to Infrastructure applications. The consortium is conducting the CACC Small-Scale Test project that is aiming to understand the necessary technical steps and potential challenges to implement CACC in vehicles.

The project studied the behavior of conventional ACC systems when they are operated in strings of vehicles following each other. These tests were conducted by implementing a prototype ACC system into four vehicles from different manufacturers and then characterizing them on a test track. The test results showed that during deceleration maneuvers, the reaction time from vehicle to vehicle was 1.5 s. Around 0.8 s of those can be attributed to the detection of the previous vehicle's maneuver and the remaining 0.7 s can be attributed to the reaction of the host vehicle to the computed desired reaction. Due to these latencies, the vehicles would

[3]By Jan-Niklas Meier, CAMP V2I Consortium.

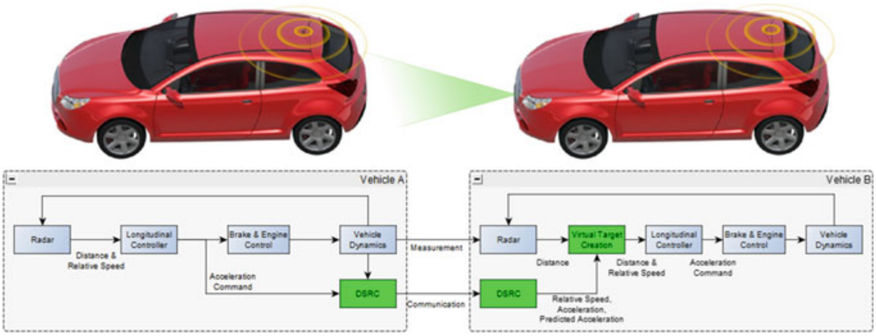

Fig. 1 CACC control diagram

operate in an undesired manner, amplifying decelerations from vehicle to vehicle which could lead to increased traffic perturbations or even so-called phantom traffic jams.

Since the reaction time of the host vehicle likely can't be improved without significant modifications in the vehicle's brake and engine control systems, they are assumed to stay. The project instead focused on implementing a CACC system that aims to reduce or remove the initial detection time. This is done by introducing Dedicated Short-Range Communications (DSRC) to the vehicles. Through this communication channel, the vehicles receive the current acceleration from the preceding vehicle. Most importantly, the vehicles also transmit and receive a predicted acceleration of the preceding vehicle, giving them an indication of how that vehicle will be acting in $\sim$0.5 s into the future. This would effectively turn a 0.8 s detection disadvantage into a −0.5 s prediction advantage. Using this information, the project hopes to design a CACC system that can stabilize traffic flow instead of increasing perturbations. For the design of the system, the project team chose to keep most components of the existing ACC longitudinal control system unmodified but instead modifying the inputs to that system through the new module "virtual target creation". If successful, this would allow for a relatively simple modification to improve ACC systems or other longitudinal control systems (e.g. found in automated vehicles) using DSRC (Fig. 1).

The project team built a simulation environment including a traffic simulator, Radar and DSRC models, and a vehicle dynamics model to test out the developed system. This was necessary since the goal is to execute the same algorithms that would be executed in the vehicle in the simulation environment.

The project is still ongoing and will implement different algorithms for CACC and then characterize them using the built simulation environment to assess the potential benefits. Additionally, a functional safety analysis will be conducted, assessing necessary modifications when using DSRC data in addition to Radar data when computing vehicle control commands. When the project is completed, it will show, if CACC can be implemented as an extension to ACC and what the estimated benefits of mixed make and model CACC strings are.

2.4 Connected Vehicles Can Increase Throughput and Decrease Delay on Urban Roads

Intersections[4] are the bottlenecks of the urban road system because an intersection's capacity is only a fraction of the flows that the roads connecting to the intersection can carry. Consider an intersection with four approaches, each with one through and one left-turn lane, so these approaches can accommodate eight movements. But the intersection can only permit two non-conflicting movements at any time. So, the intersection's capacity is one-quarter that of the approaches.

Therefore, the throughput of the urban road system can be increased only if vehicles can cross the intersections in platoons rather than one by one as they do today. Platoon formation is enabled by connected vehicle technology. This talk assesses the potential mobility benefits of platooning. It argues that saturation flow rates, and hence intersection capacity, can be increased by a factor C in the range 1.7–2.0.

The queuing analysis and the simulations reveal that a signalized network with fixed time control will support an increase in demand by a factor C if all saturation flows are increased by the same factor, with no change in the control. Furthermore, despite the increased demand vehicles will experience the same delay and travel time. The same scaling improvement is achieved when the fixed time control is replaced by the max pressure adaptive control. However, the queue lengths will also increase by C, which may lead to saturation. But part of the capacity increase can alternatively be used to reduce queue lengths and the associated queuing delay by decreasing the cycle time. Impediments to the control of connected vehicles to achieve platooning at intersections appear to be small.

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 from the industry and the public sector.

As a first step, the traffic flow modeling community can offer insights into the propagation of disturbances along different traffic steams with different types of vehicles involved. The resulting traffic dynamics are a function of the vehicle/driver behavior reaction latency and the technological specifications to be adopted and regulated by the industry stakeholders and the public agencies respectively.

[4]By Pravin Varaiya with J. Lioris, F. Yildiz, R. Pedarsani, D. Farias, A. Kurzhanski, A. Askari (UC Berkeley, USA).

The research findings from the traffic flow modeling community will pave the way to improved inter-vehicular interactions. Such contribution is essential since added CAV technologies is not synonymous to improved driving conditions.

In particular, researchers can analyze existing CAV applications including ACC and their role in reducing reaction time at signalized intersections. Additional methodological contributions may be through offering quantifiable traffic performance measures associated with the introduction of CAVs in a traffic stream. Such measures may include safety measures, throughput measures (capacity), stability measures (local versus global stability), reliability measures, emission and sustainability measures. Moreover, traffic flow simulation models may be seen as an economically feasible way to analyze the traffic worthiness of CAVs manufactured by the industry. Simulation models may create different congestion dynamics and may serve as a virtual environment to test if a vehicle with specific specifications will function properly. Although these simulation models require field experiments and ground truth data for calibration and validation purposes, they remain an essential feasibility medium before deploying vehicles in the real-world.

The second set of recommendations made in this break-out session is related to the technological specifications of CAVs. In particular, it is important at this stage to finalize the testing of CACC with the collaboration of the different entities mentioned in the abstract. Once the CACC research is deployed, the focus should be on the CAV applications associated with lateral movement. For example, lane-changing and merging CAV applications (for example: gap identification and lane usage per type of vehicle) need to be studied. Finally, the communication between vehicles remains the main feature to be analyzed in traffic simulation models. These models should recognize the potential errors in communication, the reliability dependence on the surrounding weather and infrastructure conditions, the cybersecurity related threats and the storage limitation given the amount of data transferred between vehicles.

In summary, the future research needs identified by the audience/presenters can be classified into three groups.

Data needs: even though the US Department of Transportation and the Federal Highway Administration are managing multiple CAV deployment testbeds, there is a lack of communication of the findings with the research community. Moreover, the data being collected/stored do not answer the research needs of the traffic flow modelers who need to calibrate/validate different assumptions when formulation/expanding on simulation modeling paradigms. On the other hand, the data produced by the industry is proprietary in nature and is not made public for further analysis. In response to such lack of data, researchers are attempting to conduct their own field (expensive) experiments in order to collect ground truth data.

Technological needs: the CAV market needs cheap and accurate positioning technology for implementing different CAV applications, including CACC. Such technology is not yet available especially given the lack of the full utilization of the DSRC channels, while having to rely on the more expensive but more reliable LiDAR technology. In addition, GPS resolution should be taken into consideration when modeling traffic in a connected driving environment.

Application needs: the objective of translating technological specifications and human behavioral responses in CAV-enabled traffic flow models is to devise improved CAV applications, including CACC. Accordingly, it might be useful to test variant CAV applications by: (1) studying scenarios when CACC platoons are broken by regular vehicles; (2) testing various combinations of CAV, CV, AV and regular vehicles; (3) investigating the impact of heterogeneous vehicles (e.g., trucks and passenger cars) on CAV-penetrated traffic flow; (4) capturing the impact of infrastructure and weather characteristics on the performance of different types of vehicles (including CAV, CV, AV and regular vehicles); (5) considering the role of electric cars in reducing congestion and emission/pollution in a connected and automated traffic environment.

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 communities (if feasible) will be very beneficial.

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