Evaluating the Impacts of Adaptive Cruise Control Systems on Congested Urban Freeways and Emphasizing the Need for New Traffic Control Strategies

Automobile manufacturers, as well as numerous researchers, have been devoting significant efforts to the development of Advanced Driver Assistance Systems (ADAS). The next step in the development of ADAS is to incorporate Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication capabilities representing Connected and Automated Vehicular Systems (CAVS) which would undertake vehicle functions and ease the driving task further. Improved vehicle operation, in terms of enhanced safety and increased passenger convenience, has been the prime motivator behind the CAVS development, in addition to reducing the negative environmental effects of transportation. CAVS are expected to alter the capabilities of individual vehicles within the next decades for the benefit of their own drivers, which may not be beneficial to the overall traffic conditions if these systems are only serving the convenience of their individual users in a myopic way. The introduction of CAVS will, therefore, transform the future of transportation, and there is a need to quantify the effect of such technologies on congested urban transportation systems and potentially steer their effect in a positive direction by implementing appropriate traffic control strategies.

One of the first candidate systems that will affect the traffic flow dynamics is the Adaptive Cruise Control (ACC) system [1], being one of the mature vehicle automation technologies emerging in the market in the past few years. ACC is an extension of the conventional Cruise Control (CC) system which is known to automatically maintain the speed of the vehicle to a certain value set by the driver. The ACC system uses headway sensors to continuously measure the spacing to the vehicle ahead and adjusts the vehicle speed to ensure this headway is maintained close to a desired value. Cooperative Adaptive Cruise Control (CACC) systems represent a more sophisticated form of ACC by incorporating communication such that the equipped vehicles communicate and coordinate their speed changes to one another, resulting in less detection and response delays and permitting closer vehicle following [2]. The use of conservative parameter values for such systems may enhance one's convenience and safety, but at the same time, it would affect the transportation network performance, potentially negatively [3].

While most research is focusing on the technology side of vehicle automation, there is comparatively a smaller number of studies focusing on quantifying the effect of such systems on traffic performance. In this context, literature studies have been divided into studies focusing mainly on the stability of such systems, as in [4], showing that connected and autonomous vehicles can improve the string stability of traffic flow and increase throughput, however, such studies assume minimal reaction times that are only attributable to sensing and mechanical delays as well as minimal headways guaranteeing basic safety, thereby adopting a futuristic best-case scenario. Other studies focus on their effect on speeds and delays without looking into the stability issue such as in [5]-[7] which used microscopic simulation studies to quantify the impact of ACC/CACC on traffic performance under different time headway settings and penetration rates.

Ntousakis et al., [5] have shown that the desired time headway setting in ACC systems has an impact on the roadway capacity since smaller time headway settings led to higher capacity. The study has also shown that as the ACC penetration rate increases, the capacity further increases if the time headway is less than 1.20 sec, while capacity decreases with longer time headways (≥1.2 sec) and increased ACC penetration rates. However, this study [5] assumes operating in ideal conditions in which the network used for simulations is a single lane stretch without any bottlenecks, thereby achieving the maximum capacity of the road for each investigated headway setting, i.e., ~3600 veh/hr for 100% ACC vehicles with 0.8 sec headway. The authors in [6] go a step further by analyzing the effects of ACC on a real freeway stretch, however the scenarios considered in this study are when all ACC users adopt the same headway in addition to assuming small reaction times for such systems and adopting one of the first introduced ACC car following models by Shladover et al. in [7], before introducing their latest ACC model complemented with real field studies. The effects of ACC and CACC-equipped vehicles on highway capacity have been estimated using microscopic simulation in [7]. The time headway settings for the ACC-equipped vehicles ranged from 1.1 sec to 2.2 sec, while it ranged from 0.6 sec to 1.1 sec for the CACC-equipped vehicle systems. The results showed that CACC systems can increase the traffic capacity for moderate to high penetration rates, while ACC systems are unlikely to produce significant improvements to the capacity of highways. Besides the time headway, another parameter that is being overpassed in ACC quantification studies is the reaction time, which is defined as the time it takes a vehicle to react to the speed changes of the preceding vehicle. It is a common assumption that automated vehicles will have negligible reaction time compared to what human drivers can achieve. However, recent studies [8] show that the reaction times of ACC systems range between 0.8-1.2 sec, which is similar to what is commonly found for human drivers.

Considering the above limitations, we aim to address the gaps in the literature **first** by quantifying the effects of ACC systems on the transportation network performance in the context of a long and congested urban freeway corridor in Ontario with multiple bottlenecks and hotspots. **Second**, by adopting different headway settings, i.e., long headways, short headways, and a normally distributed range between both. **Third**, by assuming two different reaction time settings, i.e., human-like reaction time and an optimistic lower reaction time, to quantify the effect of both. **Finally**, by choosing the most suitable car following model for ACC representation from the most commonly used ACC car following models in the literature, all under varying market penetration rates. The adoption of different car following models for ACC representation is mainly done to observe the general performance trends resulting from both models and to highlight the shortcomings of any based on traffic simulations. However, it is worth mentioning that the exact representation of the complex real driving process by a car following equation is a challenging task, and different models have been adopted in the simulation investigations of the ACC-related studies in the literature. Therefore, we picked the two most widely used ACC car following models, i.e., the Intelligent Driver Model (IDM) and the latest Shladover's model in [9], and we moved forward with the latter, first, to overcome the IDM headway error drawback observed in our simulations and reported in the literature, and second, since Shladover's model was formulated based on field experiments and was proven to have a faster response than IDM, hence a better representation of ACC systems and a more accurate quantification of their impacts on the transportation network performance.

Our simulation results show that if the time headway of ACC vehicles is to be left to the recommended value of 2.0 seconds, the freeway performance will deteriorate. As the percentage of ACC vehicles with a 2.0 sec headway increases such deteriorations were found to increase as well. On the other hand, the results of adopting a short 0.8 sec headway or even a range headway setting, i.e., a distribution between the minimum (0.8 sec) and maximum (2.0 sec) ranges considered, show an improvement in performance, and these improvements increase as the penetration rate of ACC vehicle increases. Therefore, if auto manufacturers recommend long time headways, for comfort and convenience reasons, and users abide by such default settings, then the performance will significantly deteriorate. It has also been found that the reaction time contributes to the performance of ACC systems especially with the shorter and the range headway settings since it has been observed that the improvements achieved by adopting such headway settings increase further when the reaction time decreases. This shows that the opportunities that may be offered by ACC systems will not be quite exploitable if their reaction time is within the same order of what humans can achieve. Lastly, it is important to note that ACC systems may vary considerably from one manufacturer to another and that they are mostly proprietary. It is also anticipated that ACC controllers may change in the coming years as auto manufacturers improve their systems to act faster especially in relation to the desired following distances. Nevertheless, the conclusions derived from our simulations complemented with the literature findings provide useful quantitative insights which could be considered as a first good approximation to understand the effect of ACC systems on congested traffic environments based on a generally accepted and utilized car following model reproducing the basic car following behavior.

Therefore, ACC systems have the potential to improve the transportation network performance unless conservative values are set for their parameters which can lead to a deterioration in the transportation network performance. This is a possibility if the recommended desired time headway by automanufacturers is on the longer end or if ACC users prefer to choose conservative headways than those employed in manual driving for safety concerns. This highlights the need for implementing proper control strategies that could guide road authorities for the optimal usage of ACC systems, with regards to traffic management. One way to avoid this deterioration is to have the settings of the ACC vehicles updated dynamically in real time according to the traffic state through the operation of an ACC-based control strategy. ACC control strategies can be implemented to reduce the deteriorations caused by adopting conservative system settings as well as increase the improvements by exploiting the full capabilities of such systems. There are a few studies that address this limitation by adjusting the ACC system settings adaptively in real time according to dynamic traffic conditions such as in [10].

For this, we proposed a simple ACC traffic control strategy which imposes the minimum headway in critical and near critical traffic situations and was found to improve the freeway traffic performance significantly. The improvements resulting from adopting a headway ranging between the minimum and maximum admissible headways were found to further increase with ACC control. Moreover, the significant deteriorations caused by adopting conservative headway settings, turned to improvements by implementing the proposed control strategy. It is worth mentioning that the proposed ACC control strategy imposes the minimum headway only when needed, i.e., in critical and near critical traffic situations, first to maximize the road capacities and avoid traffic breakdown, and second for safety concerns such that the short headways are not imposed for the whole speed range but rather when the speed is around or less than the congestion speed, i.e., equal to or less than 50 km/hr, which is considered a reasonably low speed at which small headways can be imposed without jeopardizing safety. In order to address this limitation, the next step in this context is to develop an ACC traffic control strategy using closed loop optimal control methods with artificial intelligence (AI) techniques such that safety is explicitly taken into consideration in addition to efficiency to investigate the impact of short headways on surrogate safety measures such as time to collision and to impose headways achieving a balance between both objectives, i.e., efficiency and safety.

In conclusion, studying the impact of driving automation in general on the traffic performance should pave the way towards a new era of traffic management research and practice, and the above findings emphasize the importance of implementing new traffic control strategies with the advent of one of these new vehicular technologies, i.e., ACC/CACC systems, especially in their early adoption stages when we are not certain about how users will use such systems and what will be their exact effect on the traffic performance.

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