Moving Horizon Optimization Algorithm for Cooperative Adaptive Cruise Control Systems at Intersections

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1. Introduction

Every year in the United States, about six million traffic accidents occur on US roads where driver behavior is considered to be the leading cause of more than 90 percent of all accidents [1]. Consequently, the idea of an automated driving environment has been studied for decades to reduce the number of crashes and enhance mobility.

One of the expected features for the automated vehicles of the near future is the Cooperative Adaptive Cruise Control (CACC) framework. CACC is a considered the third generation form of the very familiar cruise control and the Adaptive Cruise Control (ACC) system. The CACC is one of the main applications for the connected vehicles initiative of the USDOT for providing better connectivity, safety and efficient mobility in transportation.

Very limited research efforts have studied the impact of CACC systems at intersections. There has been little research on developing dynamic optimal speed advising algorithms on the vehicle side rather than modifying the design of the signal timing controller at the traffic signal side [2, 3]. As an application of using connected vehicles technology, Malakorn and Park (2010) explored the difference between intelligent traffic signal cooperated with CACC system and traditional intersection control [4]. The ultimate goal of the system was to reduce the environmental impacts of driving at intersections by minimizing vehicle acceleration levels using the VT micro-model [5]. A review of the literature revealed that none of the previous approaches used an explicit optimization algorithm to minimize the intersection delay.

2. Study Objective

The purpose of this study is to develop an optimization algorithm for controlling the movement of vehicles equipped with CACC systems at intersections. The research assumes that some vehicles have some form of communication with the intersection controller to replace traditional traffic control systems at intersections (traffic signals, stop signs, yield signs, etc.). Non equipped vehicles have to come to a complete stop before proceeding through the intersection. To accomplish the research objectives mentioned above, a new optimization/simulation tool is presented in order to develop an optimal control strategy entitled "iCACC". Each vehicle is modeled as a unique entity with its own goals and behavioral characteristics. The tool uses a moving horizon optimization framework to compute the optimal control strategy that ensures no collisions occur while at the same time minimizing the total intersection delay.

3. Proposed Optimization-Simulation Concept

In general, the main objective of the "iCACC" tool is to compute the optimum vehicle trajectory that enssures no conflicts occur while at the same time minimizes the total intersection delay. Figure 1 shows a screen shot of the visualization interface for the iCACC optimization-simulation tool.

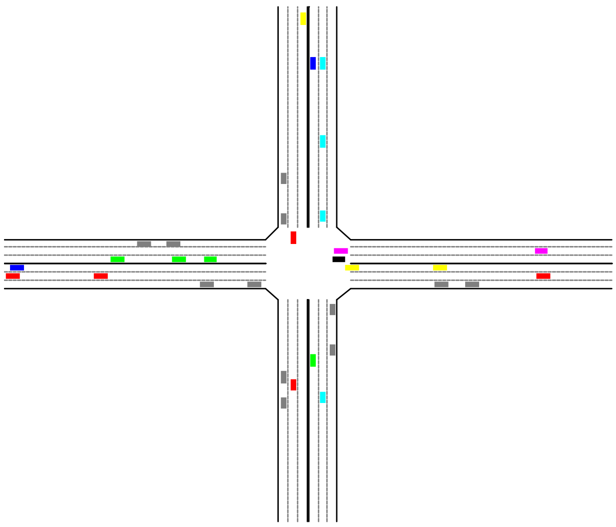

Figure 1: A screen shot from the iCACC used for simulating automated vehicles

The optimization-simulation tool seeks the efficiency of vehicle flow through the intersection by controlling the arrival time of vehicles at the intersection while minimizing the stop-and-go actions. It should be mentioned that a vehicle dynamics (acceleration and deceleration) model is incorporated in the optimization-simulation tool. The iCACC tool's optimization process could be summarized as follows:

1- Based on the entry speed and acceleration for each vehicle to the intersection coverage area, the arrival time for each vehicle at the intersection is estimated.
2- For each vehicle, the arrival and occupancy time for each conflict point is calculated.
3- The tool begins to search for the unsafe conflict points; in other words, the points where the time difference between two crossing vehicles is less than the minimum safety interval.
4- Last, the tool tunes the arrival time value for each vehicle (triggered as unsafe arrival time) to the intersection and determines the optimum trajectory.

4. Numerical Application of iCACC

The proposed simulation tool was tested by simulating a single 4-legged intersection with 3-lane approaches (as shown in Figure 1). The iCACC system operation was compared to a base case where a signal controlled intersection was simulated. A total of 13 scenarios of major and minor street volumes were tested by varying the volume-to-capacity ratio from 0.2 to 0.8. The lane-width was assumed to be 3.5 meters and the approach speed limits were assumed to be 35 mph (approximately 16 m/s). The intersection was assumed to be on level terrain. In order to calibrate the vehicle dynamics model, characteristics of a Toyota Prius 2010 model (similar to the tested vehicle in Google Driverless experiment [6]) was used. The vehicle has an engine power of 134 Horse Power (Hp).

For both scenarios, the entrance time, entrance speed and acceleration level of each vehicle to the Intersection Zone (IZ) is randomly selected. For signal control scenario, the intersection is simulated using the commercial software Synchro 6 where the cycle length is optimized to accommodate the different volume cases.

Thereafter, in order to compare the impact of different traffic control scenarios on the operation efficiency of the intersection, the average delay per vehicle is computed. For each volume combination case, the average delay for each vehicle was calculated (Figure 2).

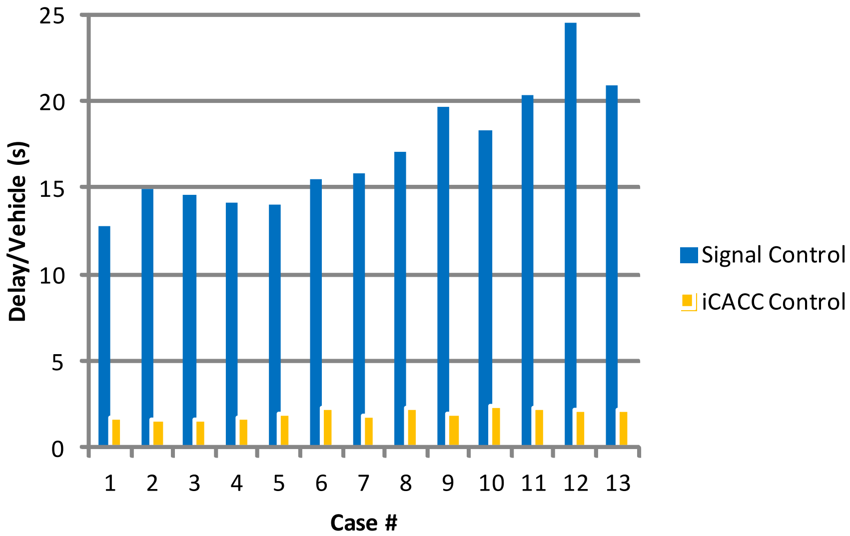

Figure 2: Delay per Vehicle (s) comparison between Signal control and the proposed iCACC control

The results demonstrate that for all volume cases, the proposed framework produces less delay per vehicle compared to the signal control scenario. These results clearly demonastrate that the iCACC approach produces significant benefits over traditional traffic signal control.

5. Summary and Conclusions

The research presents an innovative approach for optimizing the movements of vehicles equipped with CACC at intersections. The proposed tool can deal with partial of full deployment of vehicle-to-infrastructure communication technology. Vehicles without CACC technology would require some form of technology to identify their locations (e.g. video detection or GPS technology).

The iCACC was built to overcome some of the previous research drawbacks in optimizing and simulating automated vehicles. Specifically, the iCACC has the capability to capture the physical characteristics of each vehicle (e.g. acceleration/deceleration behavior), different weather conditions (e.g. dry, rain, snow, ice), different movements at intersections, shared lanes, and different levels of system deployment levels. The iCACC uses a moving horizon concept in optimizing the movements of vehicles and thus can be applied in a real-time field experiment.

In testing the proposed system, two traffic control strategies were considered: traditional traffic signal control and the proposed iCACC controller. The results demonstrate that the iCACC strategy can produce significant reductions in the average delay for each vehicle relative to the traditional traffic signal control for volume to capacity ratios up to 0.8. It is anticipated that this research will contribute in the future of intelligent transportation system (ITS), connected vehicle technology systems, and driverless vehicle applications.

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