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Efficient control of fully automated connected vehicles at freeway merge segments

Clark Letter [a,*], Lily Elefteriadou [b]

[a] University of Florida, Department of Civil and Coastal Engineering, 365 Weil Hall, PO Box 116580, Gainesville, FL 32611, United States
[b] University of Florida Transportation Institute (UFTI), University of Florida, 365 Weil Hall, PO Box 116580, Gainesville, FL 32611, United States

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ABSTRACT

This paper presents a longitudinal freeway merging control algorithm for maximizing the average travel speed of fully automated connected vehicles. Communication with a roadside unit allows the computation and transmission of optimized trajectories to the equipped vehicles. These vehicles then carry out the trajectories and resume normal operation once they cease communication with the roadside controller. A tool was developed to simulate and carry out the merging algorithm, while interfacing with the optimization software LINGO. A hypothetical merging segment was simulated to evaluate the effectiveness of the merging algorithm, and its performance is compared to conventional vehicle operation. During uncongested conditions the algorithm is able to reduce travel time, increase average travel speed and improve throughput. The capacity of the merge segment is directly related to the safe time gap selected to run the algorithm. Once capacity is reached, queuing forms on both the ramp and mainline segments upstream of the merge area. The algorithm provides safe merging operations during this congested traffic state.

1. Introduction

As traffic demands continue to increase, new strategies are being developed and implemented to handle traffic operations around bottlenecks. Intelligent Transportation Systems (ITS) are increasingly being deployed to reduce the probability and impacts of traffic flow breakdown. Strategies such as adaptive ramp metering, dynamic pricing, and variable speed limits are being investigated and implemented to relieve congestion on freeway facilities (Papamichail et al., 2008; Yin et al., 2012). While these methodologies have continued to gain support, advanced vehicle technology and communication capabilities have become increasingly available. Automobile manufacturers have announced they are currently developing autonomous vehicles. At the same time, the US DOT has been pursuing communication between vehicles (V2V) as well as between vehicles and the infrastructure (V2I). The availability of these two technologies makes controlling vehicle trajectories feasible. With the advent of V2V and V2I communications along with automated driving, transportation engineers may soon have the means of directly controlling individual vehicle movement. One way to take advantage of this capability and enhance traffic operations is by controlling the flow at key sources of freeway congestion: merging locations at on ramps or lane drops.

The objective of this paper is to develop a merging algorithm that optimizes the performance of connected fully automated vehicles through a freeway merging segment. The algorithm assumes all vehicles on the network are fully automated,

* Corresponding author.
E-mail addresses: clarklet@ufl.edu (C. Letter), elefter@ce.ufl.edu (L. Elefteriadou).

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and equipped with V2I communication capabilities. A tool is developed to simulate the proposed algorithm. A network is created to evaluate the performance of the merging algorithm and conduct sensitivity analysis to compare the impact of traffic demand and minimum time gap settings. Two simulation scenarios are considered. The first is the CORSIM microsimulation which represents a traditional traffic stream consisting of conventional vehicles. This is used as a basis for comparison. The second is a traffic stream consisting of 100% connected fully automated vehicles. The simulation results are reported and comparisons are made based on selected performance measures.

The paper first provides a review of literature related to automated and assisted merging. The merging algorithm is then described in detail. The simulated scenarios are presented, and conclusions and recommendations are made based on the results.

2. Literature review

There are a number of algorithms that have been developed to assist the merging operation of vehicles. Initial merging algorithms were related to automated highway systems (Tan et al., 1998). The system involved the installation of magnetic loops in the pavement to control vehicle movement. The technology was never implemented, but a significant amount of research was performed that is applicable to connected and autonomous vehicle merging behavior. Algorithms developed under that program (Antoniotti et al., 1997; Lu et al., 2004; Ran et al., 1999) were based on data fed to a central controller which provided updated trajectory information and sent it back to the mainline and ramp vehicles. The impacts on traffic performance were shown to be beneficial for these algorithms, especially for low volume conditions. However, some high volume scenarios showed reduced performance and the potential for safety risks including vehicle collisions (Kachroo and Li, 1997).

Recent research has resulted in algorithms relaying specific merging recommendations and advisories that are not mandatory using in-vehicle devices. These algorithms require no vehicle automation. Mainline vehicles are advised through DSRC when to create gaps in the traffic stream (Park et al., 2011; Daamen et al., 2011). Mainline advisories have also been used in conjunction with ramp metering to create gaps for platooning ramp vehicles (Scarinci et al., 2013). Local sensor algorithms have been developed to generate speed and acceleration suggestions to merging ramp vehicles (Sivaraman et al., 2013). The results of driver recommendation algorithms are promising, even for a low percentage of participating vehicles.

Fully autonomous vehicles must have logic designed to handle merging situations without the aid of V2V or V2I communication. Auto manufacturers keep this information proprietary, but researchers have developed merging algorithms to interpret, predict and react to merge behavior (Wei et al., 2013). Milanés et al. (2011a) has used fuzzy logic to govern the merging operations during a congested traffic state, and a longitudinal controller for low speed operations was developed (Milanés et al., 2012). Advancements have been made in vehicle control logic for individual automated vehicles to control lane changing and car following based on cost minimization (Wang et al., 2015).

The most predominant form of research for merging assistance involves the use of V2V and V2I technology in conjunction with CACC systems to facilitate merging operations. This study is focused on the use of a centralized V2I controller to direct automated vehicles safely and efficiently through a freeway merging segment. However, V2V algorithms have used different strategies such as platooning and virtual vehicles to obtain advanced merging operations (Uno et al., 1999). V2V is used to allow cooperation from mainline vehicles when receiving a request from merging ramp vehicles (Xu and Sengupta, 2003). Other algorithms have used a leading vehicle to calculate the merging order of surrounding vehicles (Wang et al., 2007; Awal et al., 2013). V2V has been shown an effective strategy for not only merges, but weaving scenarios and lane drops (Kato et al., 2002; van Arem et al., 2006). Studies have shown V2V capable of increasing throughput (Kanavalli et al., 2008), and that capacity is a function of the allowed headway and speed of traffic (Davis, 2007). Ntousakis et al. (2016) developed a trajectory planning technique to minimize a cost function consisting of the acceleration, jerk, and derivative of jerk to create a smooth merging process. The algorithm is functioning locally in each vehicle and trajectory information relayed from the putative leader through V2V communication. The leader's trajectory is used as an input to the optimization, and results showed an improved merging operation when compared to ACC merging operations.

This study is focused on the use of a centralized V2I controller to direct automated vehicles safely and efficiently through a freeway merging segment. Pueboobpaphan et al. (2010) simulated an algorithm to channel communications through a roadside controller that sent trajectory information to mainline vehicles. The algorithm uses a safety zone around the ramp vehicle dependent on the speed of the mainline vehicle. Acceleration rates are continually relayed to the mainline vehicle to adjust its position to accommodate the ramp vehicle. Average travel time was reduced, and total distance traveled was increased. Marinescu et al. (2012) developed an algorithm that combines V2V communication for mainline vehicles with centralized V2I to direct ramp vehicles into slots for merging. Additionally, mainline vehicles search to move into slots on the adjacent lane to provide more opportunities for merging. The results showed increased throughput and reduced delay. Wang et al. (2013) developed a merging algorithm using V2V and V2I communications to facilitate merging of CACC vehicles. Virtual vehicles are mapped onto both the mainline and ramp to facilitate the merging of single vehicles and platoons. The results displayed the algorithms ability to function, while not providing specifics on network performance. Park et al. (2014) uses anticipated leading and lagging gaps to adjust mainline and ramp vehicle trajectories to create a smoother merge. Simulation results showed improvement in all performance measures, and that a 60% compliance rate and 50% penetration level are needed to achieve benefit.