Transportation Research Part C 90 (2018) 114–133

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Dynamic traffic assignment of cooperative adaptive cruise control

Christopher L. Melson[a,*], Michael W. Levin[b], Britton E. Hammit[c], Stephen D. Boyles[d]

[a] Department of Construction Management, Louisiana State University, United States
[b] Department of Civil, Environmental, and Geo-engineering, University of Minnesota, United States
[c] Department of Civil and Architectural Engineering, University of Wyoming, United States
[d] Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin, United States

ARTICLE INFO

Keywords:
Cooperative adaptive cruise control
Connected vehicles
Dynamic traffic assignment
Link transmission model

ABSTRACT

Advances in connected and automated vehicle technologies have resulted in new vehicle applications, such as cooperative adaptive cruise control (CACC). Microsimulation models have shown significant increases in capacity and stability due to CACC, but most previous work has relied on microsimulation. To study the effects of CACC on larger networks and with user equilibrium route choice, we incorporate CACC into the link transmission model (LTM) for dynamic network loading. First, we derive the flow-density relationship from the MIXIC car-following model of CACC (at 100% CACC market penetration). The flow-density relationship has an unusual shape; part of the congested regime has an infinite congested wave speed. However, we verify that the flow predictions match observations from MIXIC modeled in VISSIM. Then, we use the flow-density relationship from MIXIC in LTM. Although the independence of separate links restricts the maximum congested wave speed, for common freeway link lengths the congested wave speed is sufficiently high to fit the observed flows from MIXIC. Results on a freeway and regional networks (with CACC-exclusive lanes) indicate that CACC could reduce freeway congestion, but naïve deployment of CACC-exclusive lanes could cause an increase in total system travel time.

1. Introduction

Connected and automated vehicle (CAV) technologies offer potentially transformative traffic impacts, including significant mobility, safety, and environmental benefits. The United States Department of Transportation has led a major effort in the development, research, standards making, and deployment of these technologies. Several promising CAV applications have grown in prominence: cooperative adaptive cruise control (CACC), speed harmonization, cooperative merging, among others. These applications require only level 1 automation of the Society of Automotive Engineers automation scale (SAE, 2013). CACC in particular has shown significant increases in throughput (Van Arem et al., 2006; Shladover et al., 2012; Marsden et al., 2001; Kesting et al., 2010).

Numerous modeling studies have been conducted for CACC, but nearly all are limited in scope, modeling small corridors and relying solely on microsimulation capabilities. These models ignore impacts at the corridor's ingress/egress points and any impacts to the surrounding arterial network. Consequently, there is a lack of research investigating more regional, network-wide impacts of CACC. Quantifying these impacts is necessary since the relationship between local changes and global network effects is non-trivial and can be counterintuitive (Braess, 1968; Daganzo, 1998). A mesoscopic-level dynamic network loading model for dynamic traffic assignment (DTA) is necessary for evaluating large-scale impacts. DTA can predict the effects of route choice behavior on traffic

---

[*] Corresponding author.

E-mail addresses: cmelson1@lsu.edu (C.L. Melson), mlevin@umn.edu (M.W. Levin), britton.hammit.ctr@dot.gov (B.E. Hammit), sboyles@mail.utexas.edu (S.D. Boyles).

https://doi.org/10.1016/j.trc.2018.03.002
Received 29 March 2017; Received in revised form 28 February 2018; Accepted 2 March 2018
0968-090X/

congestion over a much larger geographical area than microsimulation.

As most models for CACC have focused on microsimulation, little work exists on mesoscopic models suitable for DTA on large networks. The Braess (1968) and Daganzo (1998) paradoxes demonstrate the potential costs of network improvement without analysis of route choices, and our results show the same for CACC specifically. Therefore, we develop a link transmission model (LTM) of CACC (Yperman et al., 2005; Yperman, 2007). The fundamental diagram for the LTM is constructed (at 100% CACC market penetration) from the equations of the MIXIC car-following model, which has been used in previous work on CACC (Van Arem et al., 2006; Su et al., 2018). Although infinite wave speeds in LTM result in some numerical errors, we believe it is the most appropriate solution method to the kinematic wave theory for CACC. Our model can be used inconjunction with microsimulation to analyze route choice on regional networks, while microsimulation is used for more accurate predictions of smaller segments of CACC-exclusive lanes.

The contributions of this paper are as follows. This paper develops a method to model CACC in DTA. We derive the fundamental diagram (flow-density relationship) from the MIXIC car-following model for CACC (at 100% CACC market penetration). The fundamental diagram has an unusual shape: part of the congested regime has an infinite congested wave speed. We verify the flow predictions of the fundamental diagram using microsimulations from VISSIM. Then, we derive LTM formulas of CACC flow for solving DTA on large networks. A comparison on a subnetwork demonstrates that DTA and VISSIM predict similar patterns of travel time reductions from CACC. DTA results on freeway networks (with CACC-exclusive lanes) indicate that CACC significantly reduces freeway congestion, which is expected due to the capacity improvements of the fundamental diagram. In addition, results on the Round Rock network show implementation of CACC-exclusive lanes could cause an increase in total system travel time, and therefore network analyses and/or network design studies are needed before deploying CACC-exclusive lanes.

The remainder of this paper is organized as follows. We first discuss previous work on CACC modeling and simulations in Section 2. Next, we derive the fundamental diagram from the MIXIC car-following model and validate it using VISSIM in Section 3. Section 4 presents LTM formulas for the CACC fundamental diagram. Section 5 presents results on freeway and city networks, and we discuss conclusions in Section 6.

2. Background

There has been a significant amount of research involving the development of CACC longitudinal control systems, their performance, and modeling their impact on the transportation system. This section focuses on the latter analyses—discussing past modeling studies of CACC at the microscopic, mesoscopic, and macroscopic level.

Nearly all previous modeling studies were conducted in microsimulation using a variety of new/modified car-following logic—typically a simplified representation of CACC controller systems. One of the first studies to estimate CACC's impact on traffic flow was conducted by Shladover et al. (2012). The study developed an error-based control system where CACC car-following behavior was defined by three terms: leading vehicle's acceleration, difference between lead vehicle's velocity and current velocity, and difference between the current distance gap and a "desired" distance gap measure. The study modeled a simple, one-lane test network and results showed significant capacity improvements with high CACC market penetrations. Based on field tests of two CACC-equipped Infiniti FX–45 vehicles (Shladover et al., 2009) and control logic developed in Bu et al. (2010),Shladover et al. (2012) simulated CACC vehicles on a one-lane corridor utilizing a variety of gap settings and mixed-traffic scenarios. Car-following models were based on two separate following modes: speed and gap control (both of which omitted a lead vehicle acceleration term). Results showed quadratic growth in capacity with significant gains only at high market penetrations. If connected vehicles were included, broadcasting position data to CACC-equipped vehicles, results showed a larger, linear growth in capacity. Milanés and Shladover (2014) modeled short vehicle strings (up to 10 vehicles) in a single-lane corridor under various speed variations. Results indicated that CACC overcame the instability issues (amplifying speed changes) of ACC strings. CACC was modeled based on the controller logic developed and field tested on four Infiniti M56 vehicles (Milanés et al., 2014). Building off the structure developed in Shladover et al. (2009), the CACC system involved two main controllers: gap closing controller (controlling speed of a vehicle outside and approaching a platoon) and gap regulation controller (controlling gap of a vehicle once inside a platoon). Utilizing the car-following models developed by Milanés and Shladover (2014), Liu et al. (2018a) modeled the impacts of CACC market penetration, platoon size, and lane-changing on the capacity of a freeway merge area. Based on their simulation results, high CACC market penetration significantly increased capacity (as high as 3,060 vehicles/hour/lane). However, consideration of lane-changing, platoon size, and inter-platoon operations, decreased this potential capacity gain; yet, high CACC market penetration was still shown to increase capacity and traffic flow stability. In a similar study, Liu et al. (2018b) further investigated the impacts of inter-platoon operations and various lane-changing protocols on the capacity of a freeway corridor.

Several previous studies have used the MIXIC car-following model in microsimulation. Van Arem et al. (2006) used MIXIC to model CACC for a freeway merging scenario—a basic network that reduces from four to three lanes. The car-following model used is similar to the model of Vander Werf et al. (2002), containing comparable acceleration, velocity difference, and distance difference terms, albeit more robust. Results showed an improvement in traffic flow stability, slight improvement in throughput, and higher average speeds. Su et al. (2018) used MIXIC to simulate a large-scale implementation of CACC on a 14-mile stretch of I–66 near Washington DC. A managed lane scenario was modeled, and results found that maximum throughput of a dedicate lane can exceed 3800 vehicles/hour/lane (nearly doubling its original capacity).

Talebpour and Mahmassani (2016) conducted a detailed analysis on the impacts of connectivity and automation on traffic flow, throughput, and stability. Unlike the previously mentioned studies, Talebpour and Mahmassani (2016) separated and independently modeled communication and vehicle automation processes. Various market penetrations of manually driven, connected, and