Transportation Research Part C xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Transportation Research Part C

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

Stability analysis on a dynamical model of route choice in a connected vehicle environment☆

Seungjae Lee[a], Benjamin G. Heydecker[b], Jooyoung Kim[c,*], Sangung Park[d]

[a] University of Seoul, Room 523, 21st hall, University of Seoul, 163 Seoulsiripdaero, Dongdaemun-gu, Seoul 02504, Republic of Korea
[b] University College London, Centre for Transport Studies, London WC1E 6BT, United Kingdom
[c] University of Seoul, Room 533, 21st hall, University of Seoul, 163 Seoulsiripdaero, Dongdaemun-gu, Seoul 02504, Republic of Korea
[d] The Seoul Institute, Nambusunhwan-ro 340-gil, Seocho-gu, Seoul 02504, Republic of Korea

ARTICLE INFO

Keywords:
Dynamical model
Route choice
Lyapunov stability
String stability
V2X
Connected vehicle

ABSTRACT

Research on connected vehicle environment has been growing rapidly to investigate the effects of real-time exchange of kinetic information between vehicles and road condition information from the infrastructure through radio communication technologies. A fully connected vehicle environment can substantially reduce the latency in response caused by human perception-reaction time with the prospect of improving both safety and comfort. This study presents a dynamical model of route choice under a connected vehicle environment. We analyze the stability of headways by perturbing various factors in the microscopic traffic flow model and traffic flow dynamics in the car-following model and dynamical model of route choice. The advantage of this approach is that it complements the macroscopic traffic assignment model of route choice with microscopic elements that represent the important features of connected vehicles. The gaps between cars can be decreased and stabilized even in the presence of perturbations caused by incidents. The reduction in gaps will be helpful to optimize the traffic flow dynamics more easily with safe and stable conditions. The results show that the dynamics under the connected vehicle environment have equilibria. The approach presented in this study will be helpful to identify the important properties of a connected vehicle environment and to evaluate its benefits.

1. Introduction

Normal traffic flows can suffer from unexpected congestion due to an abrupt speed reduction or an incident. In such cases, perturbations cause dynamic increases in subsequent travel times. Traffic engineers and researchers argued that a connected vehicle (CV) environment leads to conditions with stabilized traffic flows and more predictable travel times. The CV environment will enable other vehicles, RSUs (Road Side Units), the infrastructure, and driver devices to send and receive real-time traffic information. It also offers the prospect of reducing accidents caused by driver errors and phantom traffic jams in the form of stop-and-go waves caused by perception-reaction lags and geometric design (Knorr et al., 2012).

The CV environment includes several emerging technologies such as sensor, mapping, recognition/decision, and radio communication. Previous research on CV environment significantly improved the technologies in these related fields. Among these technologies, researchers have focused on vehicle control strategies, communication with other vehicles (Jin and Orosz, 2014), vehicle management, and connection to other advanced technologies (Qin and Orosz, 2017). Traffic engineers, however, focused on

☆ This article belongs to the Special Issue on International Symposium on Transportation and Traffic Theory.

* Corresponding author.
E-mail address: trafficplan@naver.com (J. Kim).

https://doi.org/10.1016/j.trc.2017.10.019
Received 29 August 2017; Received in revised form 12 October 2017; Accepted 15 October 2017
0968-090X/

Nomenclature

Δ_{rs}	route swap vector from r to s
Δt	time step
δ	time-varying communication delay
$\dot{C}_i$	relative speed between vehicle i and the preceding one
γ_i	positive control parameters of $i = 1,2$
$\mathscr{C}$	the set of origin-destination(OD) pairs (p,q), $\mathscr{C} \subset \mathscr{N} \times \mathscr{N}$
$\mathscr{G}$	a directed graph, $\mathscr{G} = (\mathscr{N},\mathscr{L})$
$\mathscr{L}$	a set of links
$\mathscr{N}$	a set of nodes
$\mathscr{R}$	the set of routes $r \in \mathscr{R}_{pq},(p,q) \in \mathscr{C}$
$\Phi(X)$	differentiate function of X
τ	desired time gap between a vehicle and the preceding one
a_i	acceleration of vehicle i
C_d	desired gap between a vehicle and the preceding one
C_i	real gap between vehicle i and the preceding one
$C_s(X)$	link travel cost of link l
d	vector-valued demand function of the least travel costs $d = g(\pi)$
L_l	length of link l
s_i	position of vehicle i
SSD	stopping sight distance
$V(X)$	Lyapunov function of X
v_e	equilibrium speed
v_i	speed of vehicle i
$v_l(t)$	average speed of vehicles in link l
v_{safe}	safe speed
$X(t)$	number of vehicles at time step t
x_i	the sum of the real position and ideal position of vehicle i, $x_i = s_i + i \times v_i \times \tau$
X_l^{cap}	link capacity at link l

appropriately revised microscopic traffic flow or lane-changing models to reflect the CV environment (Becker et al., 1994; Ge et al., 2014; Jia and Ngoduy, 2016;Talebpour and Mahmassani, 2016). Researchers were also interested in the accuracy, privacy, and effectiveness of radio communication between vehicles or high occupancy vehicles (HOV) such as bus or truck as well as connection with traffic signal controller using V2I (Dey et al., 2016; Hu et al., 2015; Khondaker and Kattan, 2015; Bauza and Gozalvez, 2013;Knorr et al., 2012). Traffic engineers indicated that a CV environment provides detailed information about driving conditions and can also improve road efficiency and safety(Liu and Khattak, 2016). As a result, saturation flow can increase and traffic congestion be reduced.

In this study, we consider a microscopic traffic flow model to evaluate network stability because it is difficult to depict connected vehicles behavior in a macroscopic dynamical model of route choice due to the limitation of low-resolution data. Unlike the microscopic traffic flow model, the conventional macroscopic dynamical model of route choice will not explain the effect of real connected vehicles. Thus, a microscopic car-following model is used to depict CV environment accurately. For each time step, car-following models calculate the speed of a vehicle to maintain a relative gap between each vehicle and the preceding one. Gipps model and Intelligent Driver Model (IDM) are examples of car-following models (Treiber and Kesting, 2013). In the CV environment, the reaction time and hence safe gap can be decreases progressively by using Adaptive Cruise Control (ACC) (Hoedemaeker and Brookhuis, 1998) and then Cooperative Adaptive Cruise Control (CACC) technologies(Lioris et al., 2017).

Researchers has recently considered network performance under the CV environment (Mahmassani, 2016;Fountoulakis et al., 2017). Although this plays an important role in traffic flow prediction, only few paper considered route choice process in the CV environment. de Almeida Correia and van Arem (2016) integrated traffic assignment and the parking strategy process considering automated vehicles into the user optimum privately owned automated vehicles assignment problem (UO-POAVAP). To measure the effectiveness of CV environment and reduce travel times under such road conditions require the study of traffic assignment considering CV environment.

The conventional mesoscopic traffic assignment process does not usually represent signals or intersections in detail. Previously, researchers just understood traffic assignment as a problem of finding the equilibrium pattern over a given urban transportation network (Gartner, 1976; Sheffi, 1985; Cascetta, 2009). Smith (1979a,b), Allsop (1974), and Bentley and Lambe (1980) were the first to combine models of route choice and traffic signal control to find optimal controls taking account of routing reactions. Recently, Liu and Smith (2015), Smith (2015) investigated the combined traffic assignment model taking into account the route choice and traffic signal control at the same time. Specifically, Liu and Smith (2015) introduced a new combined traffic assignment process known as the restricted proportional adjustment process (RPAP). The signal control model may be regarded as a model of a system periodically updated either by an operator or by an automatic system. Smith (2015) showed how route choice and signal control work simultaneously. Initially, green times give rise to travel times that influence travelers choice of route. After intersection and road delay are modified according to the assigned traffic flow, the control policy is recalculated to update signal green times. Thereafter, a revised control policy is adapted again. Finally, the process ends when the control policy and traveler route choice become mutually consistent.

In this study, the microscopic and macroscopic models are used simultaneously to test stability to evaluate macroscopic traffic assignment processes. Many studies proved that the dynamical model of route choice is globally stable. In the field of dynamical model of route choice, Smith (1984) applied the Lyapunov theorem (Lyapunov, 1907), the stability tests at the fixed points of a nonlinear system, to prove the global stability of combined traffic assignment for the first time. He showed that in the dynamical model of route choice, traffic flowflows converge to the set of Wardrop equilibria with time, and proved that the global stability of traffic assignment is stable if path costs are differentiable and monotone. Subsequently, Lee (1995), Ghali and Smith (1995), Meneguzzer (1995), He et al. (2010), Liu and Smith (2015), Smith (2015), Smith and Watling (2016), and other numerous