Network user equilibrium problems with infrastructure-enabled autonomy

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EXTENDED ABSTRACT

Autonomous driving technology is expected to bring dramatic societal, environmental, and economic benefits due to its potential in improving traffic safety, vehicle fuel economy, road capacity, travel speed, and driver productivity. Currently the development of autonomous driving is focusing on autonomous vehicle (AV) technology and mainly led by the private sector. However, focusing on AV technology alone may potentially slow the penetration of AVs and consequently slowing the realization of societal benefits of AVs. In order to safely drive itself in various road environment, an AV needs to be equipped with expensive sensor systems and additional hardware and software. Integrating transportation infrastructure enhancement into the realization of autonomous driving can potentially promote the development and adoption of AVs. With the development of vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) technologies, researchers have suggested that an infrastructure-enabled or infrastructure-based autonomous driving system provides a promising alternative to the development of autonomous driving. Infrastructure-enabled or infrastructure-based autonomous driving system has the following main advantages: (1) It can promote the adoption of AVs by reducing vehicle cost; (2) It can promote the development of AVs by alleviating the liability threats facing AV makers; (3) It is a cost-effective way for the society to implement autonomous driving; and (4) It endows transportation agencies a more active role in the realization of autonomous driving.

This study aims to develop a modeling framework to evaluate the infrastructure-enabled autonomous driving system at a network level and analyze how this system might affect travelers' behaviors and network-wide congestion. To the best of our knowledge, such a modeling framework is still missing in the literature.

We envision that roadside sensing, computing and communicating devices will be installed along certain roads to convert them into "*automated roads*" that can enable or provide autonomous driving capability for vehicles equipped with necessary on-board sensing, computing, communicating, and control systems. We further envision that there will three major types of vehicles in the market: conventional human-driven vehicles (HVs), infrastructure-independent autonomous vehicles (IIAVs), and infrastructure-enabled autonomous vehicles (IEAVs). We define HVs as vehicles that can only be driven manually by human drivers. We define IIAVs as vehicles that are fully autonomous on any public roads. We define the IEAVs as vehicles that are normally driven by human drivers on ordinary roads but are equipped with necessary on-board devices so that they can switch to autonomous driving mode on automated roads. Although IEAVs' capability for autonomous driving is confined within automated roads, IEAVs can be much cheaper and more affordable to consumers than IIAVs.

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We developed a new user equilibrium (UE) model to describe travelers' route choice behaviors and the resulting equilibrium traffic flow distributions in a road network with automated roads and mixed traffic of HVs, IIAVs, and IEAVs. We proposed to convert mixed traffic flows with HVs, IIAVs, and IEAVs into pure HV flows and then use traditional volume delay functions to characterize link travel times. By doing so, we are able to explicitly consider the impact of mixed traffic on road capacity. Travelers are assumed to minimize their individual travel costs when traveling from their origins to destinations. The travel cost for a HV or IIAV driver is defined as his/her travel time multiplied by his/her value of travel time (VOT). For an IEAV driver, in addition to travel time costs, he/she might also experience service charges of autonomous driving on automated roads and inconvenience costs due to transitions between autonomous driving and manual driving. The service charge on an automated road is determined by the provider of the automated road. The inconvenience cost might capture the delay of driving mode transitions and drivers' anxiety of driving mode change. An IEAV driver might or might not choose to use autonomous driving service on an automated road depending on whether the autonomous driving service leads to lower total travel cost than manual driving. Considering the above unique features associated with IEAV drivers in a network with automated roads, we developed a novel equilibrium sub-model, which is characterized as a set of nonlinear complementarity conditions, to describe IEAV users' driving mode choice behaviors. Finally, the UE model was formulated as a path-based non-linear complementarity problem. The model is solved by a column generation solution procedure embedded with efficient algorithms in iteratively solving shortest path problems.

The contributions of this study are summarized as follows. First, this study makes the first attempt to develop a network equilibrium framework for the evaluation of the infrastructure-enabled autonomous driving system at a network level. A new UE model is developed to describe road users' route choice behaviors in a transportation network with automated roads and mixed traffic of HVs, IIAVs, and IEAVs. Second, the proposed UE model includes a novel equilibrium sub-model to describe the driving mode choice behaviors of IEAV drivers. Third, a column generation solution procedure embedded with efficient shortest path algorithms is proposed to solve the UE model. Fourth, equilibrium solutions of the developed model reveal the potential impacts of the infrastructure-enabled autonomous driving system on network-wide congestion and travel costs of different user groups, laying a theoretical foundation for future planning and operation of the system. Particularly, a paradoxical phenomenon is identified where enabling autonomous driving service on more links might lead to increased travel costs for all user groups.

Keywords: Autonomous vehicles; Infrastructure-enabled autonomous vehicles; Mixed traffic; Automated roads; User equilibrium