Research Needs

Autonomous driving technology is expected to bring dramatic societal, environmental, and economic benefits due to its potential for improving traffic safety, vehicle fuel economy, road capacity, travel speed, and driver productivity (Fagnant and Kockelman, 2015; Chen et al., 2016). In the United States, a fifty percent market share of autonomous driving vehicles will result in an estimated 1.88 million fewer crashes, 9,600 lives saved, 1.68 billion hours of travel time savings, 224 million gallons of fuel savings, and $102.2 billion in economic cost savings every year (Fagnant and Kockelman, 2015).

Currently the development of autonomous driving is focusing on autonomous vehicle (AV) technology and is mainly led by the private sector, which includes technology companies such as Google and Baidu, automakers such as Audi, Toyota, Ford, and Volvo, and transportation network companies such as Uber, Lyft, and DiDi. As of July 2018, Google’s AV fleet has self-driven more than eight million miles on public roads (Waymo, 2018), and numerous manufacturers, including BMW, Nissan, Ford, General Motors, Tesla, Mercedes-Benz, and Bosch, have begun testing their prototype AVs (Wang, 2018).

However, focusing on AV technology alone may potentially slow the penetration of AVs and consequently slow the realization of societal benefits from AVs. In order to safely drive itself in various road environments, an AV needs to be equipped with expensive sensor systems and additional hardware and software. The high cost of AVs can be a significant barrier to their broad adoption (Fagnant and Kockelman, 2015; Jun and Markel, 2017). Moreover, if autonomous driving relies exclusively on AVs, AV manufacturers will be saddled with both the responsibility and liabilities associated with the traditional capabilities of the vehicles as well as those associated with functions that human beings routinely perform (Gopalswamy and
Rathinam, 2018). The liability threats associated with AVs will be an important and potentially limiting consideration for AV manufacturers and possibly present a significant deterrent to the development of AVs (Marchant and Lindor, 2012).

Integrating transportation infrastructure enhancement into the realization of autonomous driving can potentially promote the development and adoption of AVs (Rebsamen et al., 2012; Horst et al., 2016; Jun and Markel, 2017; Sanchez et al., 2016; Ran, 2018). Sanchez et al. (2016) indicated that cooperative technologies, which enable cooperation among vehicles, vulnerable road users, and infrastructure, will be vital to the development of highly autonomous vehicles operating in complex urban environments. Based on simulation and field experiment results, Rebsamen et al. (2012) argued that utilizing infrastructure sensors can improve the operation safety and reduce the on-board sensor cost of AVs. Jun and Markel (2017) proposed a data-sharing strategy in which the expensive AV component, the light detection and ranging (LiDAR) sensors, is moved from vehicles to the infrastructure to be used as shared sensors by all vehicles within the vicinity. They argued that the infrastructure-based strategy will reduce the cost of automobiles and can accelerate the introduction of AVs. More recently, Gopalswamy and Rathinam (2018) introduced a concept of infrastructure-enabled autonomy (IEA), in which autonomous driving is enabled only on certain corridors equipped with the necessary sensing, computing and communicating devices; outside these corridors, vehicles will be driven by human drivers. Under the IEA concept, autonomous driving can be treated as a service jointly provided by automakers, infrastructure players, and third-party players; consequently, the responsibility and liability associated with autonomous driving can be shared by these players rather than undertaken primarily by automakers. The authors concluded that the redistribution of the responsibility and liability associated with autonomous driving would incentivize the ecosystem of businesses to accelerate the deployment of AVs. Ran et al. (2018) and Ran (2018) defined a connected automated vehicle highway (CAVH) system, which integrates connected and automated vehicle (CAV) technology and automated highway system (AHS) (Congress, 1994) to dramatically promote the development and adoption of AVs. Ran (2018) pointed out that the majority of the sensor functions can be achieved using sensor systems on highway infrastructure while the majority of the vehicle operation and control functions can be achieved via the cooperation of control systems on highway infrastructure and vehicle. Based on an implementation cost analysis in the area of Southern Wisconsin and Northern Illinois, Ran (2018) showed that the return on investment (ROI) of the CAVH-based approach for autonomous driving is more than two thousand times that of a vehicle-only approach. In summary, the infrastructure-enabled autonomous driving system or the CAVH 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 manufacturers; (3) it is a cost-effective way for society to implement autonomous driving; and (4) it endows transportation agencies with a more active role in the realization of autonomous driving.

In this study, we will explore the potential impacts of the infrastructure-based or infrastructure-enabled autonomous driving system and focus on developing a modeling framework for the planning and evaluation of such a system. We envision that there will be 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 call
the vehicles that are fully autonomous on ordinary public roads IIAVs. Google’s self-driving cars can be treated as IIAVs. Equipped with roadside sensing as well as computing and communicating devices, ordinary roads can be upgraded to automated roads providing autonomous driving service to vehicles (Gopalswamy and Rathinam, 2018). We define IEAVs as vehicles that are normally driven by human drivers on ordinary roads but are equipped with appropriate on-board devices and can be driven autonomously 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. Automated roads can be provided by the government or implemented through a public–private partnership scheme.

To the best of our knowledge, this study is the first in the literature to develop a modeling framework for the planning and evaluation of the infrastructure-enabled autonomous driving system in a general transportation network.

Research Objectives

This project proposes a modeling framework for the planning and evaluation of an infrastructure-enabled autonomous driving system. The proposed project will accomplish the following two objectives:

1. Develop a new network equilibrium model to describe road users’ vehicle type and route choice behaviors in a transportation network with automated roads.

2. Investigate the strategic planning of automated roads in a general transportation network.

Research Methods

For the new network equilibrium model, user equilibrium (UE) conditions will first be proposed to describe the route choice behaviors of HVs, IEAVs, and IIAVs in a transportation network with automated roads. The model considers two special characteristics of IEAVs: (1) IEAVs are driven by human drivers on regular roads and will be driven autonomously on automated roads; and (2) IEAV users will experience different value of travel time on regular and automated roads (Le Vine et al., 2015; van den Berg and Verhoef, 2016; Noruzoliæe et al., 2018). For road users, vehicle prices and the corresponding travel costs are the primary concern when making their vehicle type and route choices. A multinomial logit model will then be adopted to model road users’ vehicle type choice behaviors. A variational inequality model will be formulated to simultaneously capture the route choice and vehicle type choice behaviors of road users. The new network equilibrium model can be used as a tool for transportation agencies to evaluate their infrastructure investment of deploying automated roads.

Based on the proposed network equilibrium model, we will further propose a general mathematical model to help government agencies optimally deploy automated roads. The proposed model is structured as a Stackelberg leader–follower game, in which the government is the leader and road users are followers. As the leader, the government determines the deployment of automated roads with the goal of maximizing all road users’ benefit. Given the deployment of automated roads and the prices for different types of vehicles, road users choose their vehicle types and routes to finish their trips. The deployment model will be formulated as a mathematical program with complementarity constraints (MPCC) and solved by an efficient algorithm.
We will then conduct numerical studies to evaluate the performance of the proposed methodology and sensitivity analyses to identify the impacts of different factors on the market share of autonomous vehicles.

**Expected Outcomes**

This project is expected to produce an advanced modeling framework for the planning and evaluation of an infrastructure-enabled autonomous driving system. The research findings will have theoretical significance as well as offer policy implications of government investment in the infrastructure-enabled autonomous driving system. This study will provide an infrastructure-based alternative solution to promote autonomous driving. The results may facilitate practitioners’ efforts to further the ongoing discussions of the government’s involvement in promoting autonomous driving. The end product will be useful for transportation agencies evaluating their infrastructure investment of deploying automated roads.

**Relevance to Strategic Goals**

The proposed project contributes to two strategic goals of the Mountain-Plains Consortium—namely, economic competitiveness and livable communities. The primary goal addressed by this proposed project is economic competitiveness. Through their use of vehicle communication and automated control technologies, AVs can improve road traffic capacity by reducing time headways between consecutive vehicles. Results from both simulation and analytical modeling analyses have demonstrated that road traffic capacity increases significantly with an increase in the proportion of AVs on the road. Deploying automated roads has great potential in promoting the adoption of autonomous driving technology. As a result, the proposed modeling framework can help transportation agencies mitigate traffic congestion and support regional economic competitiveness. Furthermore, the proposed project has the potential to make communities more livable. Studies have demonstrated that AVs are expected to generate safety benefits and increased driver productivity, which are critical indicators of livable communities.

**Educational Benefits**

One graduate student will be involved in the research and receive training in transportation network modeling, optimization, and transportation automation. The research results will provide fresh materials and case studies to expand the transportation curricula at USU.

**Technology Transfer**

Research results will be disseminated through publication in peer-reviewed professional journals and presentations at state and national meetings and conferences. All data collected from the research project will be stored in a repository such that the information will be easily retrievable should anyone wish to use it. Research results will also be incorporated into a wide variety of education, training, outreach, and workforce development activities.
**Work Plan**

The proposed research will be conducted over an 18-month period according to the following schedule:

Task 1: Literature review (2 months). We will conduct a thorough literature review on transportation modeling work related to AVs.

Task 2: Formulation of a new network equilibrium model (4 months). We will formulate a new network equilibrium model that describes road users’ vehicle type and route choice behaviors in a transportation network with automated roads.

Task 3: Formulation of a strategic planning problem (3 months). We will propose a general mathematical model that helps government agencies optimally deploy automated roads.

Task 4: Solution algorithm development (3 months). We plan to explore and compare solution algorithms that are the most efficient for the proposed mathematical models.

Task 5: Numerical study (4 months). We will conduct several numerical studies to demonstrate the proposed methodology. Sensitivity analyses will be conducted to assess the impact of different factors on the market share of AVs.

Task 6: Report writing (2 months).

**Project Cost**

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**References**


