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Research Article

A Methodology to Estimate Capacity Impact due to Connected Vehicle Technology

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Recent development in connected vehicle technology or equivalently vehicular ad hoc networks (VANET) has stimulated tremendous interests among decision makers, practitioners, and researchers due to the potential safety and mobility benefits provided by these technologies. A primary concern regarding the deployment of connected vehicle technology is the degree of market penetration required for effectiveness. This paper proposes a methodology to analyze the benefit of highway capacity gained from connected vehicle technology. To fulfill this purpose, a model incorporating the effects of connected vehicle technology on car following is formulated, building on which a rough estimate of the resulting capacity gain is derived. A simulation study is conducted to verify the model, and an illustrative example is provided to show the application of the methodology. This work provides decision makers and practitioners with a basic tool to understand the mobility benefit obtained from connected vehicle technology and how such benefit varies as market penetration changes.

1. Introduction

Recent development in connected vehicle technology (CVT), formally known as IntelliDrive or vehicle infrastructure integration (VII) in transportation community and as ad hoc networks (VANET) in wireless network community, has stimulated tremendous interests among decision makers, practitioners, and researchers due to the potential safety and mobility benefits provided by these technologies. Supported by the dedicated short range communication (DSRC) standard, connected vehicle technology will enable road vehicles to communicate with each other as well as to roadside infrastructure in the future; see an illustration in Figure 1. Thus, highways and streets will become an environment that encompasses ubiquitous computing and communication. Consequently, a new class of applications can be developed to dramatically increase safety, throughput, and energy efficiency. For example, CVT may serve as an ever-vigilant copilot to watch for potential hazards such as abrupt braking by a leading vehicle, a side vehicle in blind spot, and even a collision from behind. In addition, CVT supports various functionalities to relieve congestion such as notifying downstream congestion, alternative routes, and even parking information. Moreover, CVT opens the door of enroute entertainment such as downloading music and video, checking e-mails, and maintaining social connections like Facebook. All of these possibilities depend on large-scale deployment of connected vehicle technology. However, a deployment decision has to take many factors into consideration. Among others, primary factors are the infrastructure needed for success and the degree of market penetration (i.e., percent of vehicles equipped with connected vehicle technology) required for effectiveness.

The above question is very difficult to answer because of the following: field experiments require a large-scale connected vehicle technology testbed which has yet to be deployed; simulation is unavailable since existing traffic simulation packages are not designed to model traffic enabled by connected vehicle technology; analytical modeling is prohibitive because of the complexity and interdependency involved in connected vehicle systems. To bypass these difficulties, this paper carries a humble goal by following a simplified modeling approach which is complemented by Monte Carlo simulation. In addition, the focus is to explore a feasible approach to conduct preliminary estimation of the mobility

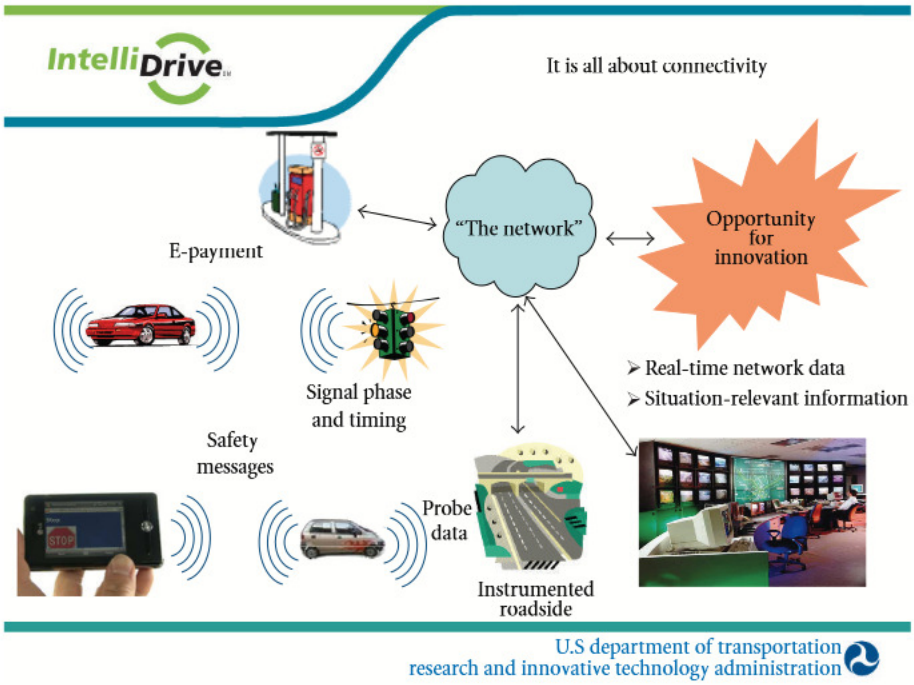

Figure 1: Connected vehicle technology.

benefit of connected vehicle technology, that is, the increase of highway capacity brought about by connected vehicle technology and how the result changes as market penetration varies. There are two building blocks in this approach. The first is to incorporate the effects of connected vehicle technology into driving behavior modeling. For such a purpose, a car-following model was derived based on the classical Gipps' model [1] by attributing the effects of connected vehicle technology to the change in the distribution of drivers' perception-reaction time. Recognizing that connected vehicle technology may bring other profound changes in traffic operations than merely perception-reaction time, the proposed model has to be kept as tractable as possible to make the analysis feasible yet capturing the major effect of connected vehicle technology. For this reason, some aspects of traffic flow, such as lane changing and hysteresis, are not modeled. Based on the proposed model, the second building block is a probabilistic analysis to provide an estimate of highway capacity. In this part, the major tools utilized are Wald's formula in probability theory and a theorem regarding the product moment of stopping time. An analytical approximate formula for capacity is obtained therein. A Monte Carlo simulation study is conducted to provide an alternative to verify this estimate since field tests are not possible at this time. The result obtained in this paper provides decision makers and practitioners with a basic tool to understand mobility benefit resulted from connected vehicle technology and how such a benefit varies as connected vehicle technology market penetration increases. In addition, using the methodology proposed in this paper, researchers can fine tune the assumption about the effects of connected vehicle technology to further investigate its benefits.

The remainder of this paper is organized as follows. In Section 2, relevant studies on this subject are briefly reviewed to provide a context in which the current paper fits. Next, in Section 3, the effects of connected vehicle technology are incorporated into the modeling of driving behavior by rectifying the Gipps' model. Following that, Section 4 is the probabilistic analysis and simulation verification. Section 5 provides an illustrative example to show the application of the methodology. Finally, the findings and results are summarized at the end.

2. Existing Studies

The idea of studying traffic flow benefits due to advanced technologies such as adaptive cruise control (ACC) systems and automated highway systems (AHS) has been addressed in the past. A great deal of studies have been identified which provided insights into highway capacity and traffic stability. A good survey of these studies can be found in [2]. A few additional references that present the necessary context for this study are added here. In their early studies on flow benefits of AHS, authors in [3, 4] investigated how ACC affected traffic flow and found that the improvement in capacity is small. Also focused on ACC, authors in [5] studied the impact of ACC on traffic flow stability and found that car following based on a constant time headway is essentially unstable.

While traffic operation in a separate lane hosting only ACC vehicles represents an ideal condition, analyzing mixed traffic flow consisting of ACC-automated vehicles and manually operated vehicles poses more challenges. Reference [6]

presented such a study. Their simulation results related the capacity trend to mixed ratios of ACC-equipped cars and their market penetration. They found that the capacity benefit became significant when ACC-equipped cars exceeded 50% market penetration. When all cars were equipped with the technology, they found a 33% increase in capacity.

In addition to considering mixed traffic, incorporating inter vehicular communication such as cooperative ACC (CACC) represents a more realistic scenario. Refernce [7] used Monte Carlo simulation to estimate lane capacity under varying proportions of autonomous ACC (AACC) and CACC. They concluded that AACC could only have a small impact on highway capacity (at most a 7% increase), while significant capacity gain could be expected with increased CACC market penetration (potentially more than doubling the capacity). Authors in [8] studied similar subject matter with a focus on the impacts of CACC on a highway-merging scenario. Based on the traffic flow simulation model MIXIC, they found improved traffic stability and a slightly increased capacity compared to the non-AAC-equipped scenario.

In European Union, a simulation study was conducted on cooperative systems deployment impact assessment (CODIA). This study reported reduced average speed and hence increased journey times due to vehicle-infrastructure cooperation, and such an increase exhibited a quadratic "line of best fit" as market penetration varies from 0 to 100 percent [9].

Inspired by these original studies, our work considers a more general scenario which incorporates three types of driving modes enabled by connected vehicle technology (denoted as CVT thereafter), namely non-CVT, CVT assisted, and CVT automated. In the *non-CVT* mode, drivers operate their vehicles without any assistance from connected vehicle technology, just as what a regular driver does. In the *CVT-assisted* mode, drivers receive connected vehicle technology assistances such as driver advisories (e.g., downstream congestion) and safety warnings (e.g., emergency brake), but these drivers still assume full control of their vehicles. The *CVT-automated* mode means that a vehicle is operated by CVT-enabled automatic driving features; however, the driver may break the loop and take over at any time as the need arises. In relation to these modes, existing studies emphasized the CVT-automated mode since ACC, AACC, and CACC can be considered as special cases of this mode. This paper broadens the perspective by also considering the effect due to CVT-enabled assistance to drivers (such as driver advisories and warnings). Moreover, this research takes a probabilistic approach and analytically relates the capacity benefit to the attributes of these driving modes and their varying market penetration rates. It is noted that CVT may result in increased throughput due to reduced accidents and suppressed congestion, and benefit of this nature is typically scenario dependent. As a generic approach, this paper explores the upper bound of such benefit, that is, the increased capacity, given that accidents and congestion have been prevented.

3. Incorporating Connected Vehicle Technology Effects

3.1. Assumptions and Simplifications. Connected vehicle technology can bring about many fundamental changes to transportation systems such as ubiquitous situational awareness, more efficient system control, more advanced safety features and. However, one thing remains the same: drivers will still have full control even though it may be delegated to CVT-enabled systems. Hence, it is reasonable to begin with driver modeling in order to predict the operations of CVT-enabled transportation systems. Among others, the major effects of connected vehicle technology on drivers are changes in the way that information is acquired, processed, and applied. For example, on-board radar can tell the subject driver exactly how far the leading and/or trailing vehicle is and how fast the gap closes, and wireless communication can warn the subject driver of an abrupt braking by the leading vehicle or the approaching of a fast vehicle behind. Given the mix of CVT-enabled and regular vehicles in the traffic, it is likely that rear ends might be resulted due to sudden and unexpected "automated" braking. Hopefully, CVT is able to monitor such hazard and warn the subject driver in advance. On-board computer can synthesize these sources of information and present the subject driver with driver advisories which allow CVT-assisted drivers to have a better understanding of their local and global contexts than drivers without such assistance. As such, assisted drivers may need less time to look out for information (e.g., accident ahead) and could plan accordingly in advance. Thus, they could focus more on understanding the information (e.g., expect emergency brake) and make control decisions. In addition, if a vehicle is so equipped, the information can also be processed before the result is delivered (e.g., a warning to slow down). These assistances may significantly reduce drivers' perception time, and they only need to concentrate on executing decisions which is related to reaction time. Moreover, the reaction time needed to execute decisions can be further shortened if a vehicle is running in the CVT-automated mode.

Therefore, central to driver modeling in CVT-enabled transportation systems is the modeling of driver perception-reaction time. This modeling strategy is further supported by the following two considerations. First, the perception-reaction time is a very, if not the most, significant parameter governing drivers' car-following behavior which directly affects traffic density and highway capacity. Such a parameter is very sensitive to stimuli from drivers' local context (such as in-vehicle assistance systems). This is also evident in various microscopic traffic models, in particular, the Gipps-type model [1] which follows a "safe-distance" argument. Other aspects of driving, such as vehicle handling, are intrinsic characteristics of drivers and less influenced by external information brought by connected vehicle technology. Secondly, connected vehicle technology provides real-time information to drivers. Though field experiments have yet to be conducted to verify this postulation, evidence in psychology literature such as in [10] indicates that perception-reaction time strongly depends on the type and intensity of