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Region-based prescriptive route guidance for travelers of multiple classes

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ABSTRACT

The performance and complicated interactions of different classes of travelers on regional urban networks are presented and analyzed. A new multi-class extension of a regional dynamic traffic model, the Network Transmission Model is proposed. The classes in question correspond to travelers using autonomous vehicles, conventional vehicles, equipped with Route Guidance and Information Systems, and unequipped vehicles. Each class is represented by a different routing method. Incremental Route Planning, an innovative predictive simulation-based routing method, Proxy Regret Matching, a non-predictive strategic learning-based method and Multinomial Logit-based Routing for 1st, 2nd and 3rd class respectively. All routing methods include a Public Transit Diversion mechanism and are assumed to provide prescriptive route guidance, with pre-trip information dissemination for every departing vehicle. We consider the possibility of non-compliance for conventional vehicles equipped with Route Guidance and Information Systems. We also consider 2 possible scenarios for autonomous vehicles that affect their travel time prediction accuracy. We simulate regional traffic dynamics for simultaneous application of all aforementioned routing methods, employing a market penetration scheme for each class of travelers. We analyze results regarding the overall network performance for various combinations of traveler class market penetration rates and non-compliance rates. We come to the conclusion that autonomous vehicles will not only provide benefits for 1st class travelers, but for all traveler classes on the network.

1. Introduction

Quality of life in cities, especially for vehicle passengers, can be directly attributed to the delay they experience daily, as a consequence of congestion. Traffic congestion can be caused by temporary deterioration of network performance, in case of an incident. There can also be recurrent congestion, whereby the travel demand bound for certain regions within the urban traffic network exceeds the capacity of said regions, for specific time periods. Due to limited space availability in modern urban areas, costs associated with infrastructure upgrade and extension are prohibitive. Optimizing the supply of existing infrastructure resources, through use of traffic light control (Papageorgiou et al., 2003; Kuyer et al., 2008; Aboudolas et al., 2009; Haddad et al., 2013), route guidance (Garcia et al., 2000; Knoop et al., 2012; Hajiahmadi et al., 2013; Yildirimoglu et al., 2015), as well as restricting network travel demand through toll pricing (Geroliminis and Levinson, 2009; Zheng et al., 2012, 2016; Simoni et al., 2015), at different degrees of granularity (individual network links, subnetworks), can help alleviate congestion phenomena. Integration of intelligent sensor technologies, such as RSU (Road Side Unites) with DSRC (Dedicated Short Range Communications) capability, to the network infrastructure can help increase the performance of the methods used to increase network capacity or restrict network travel demand,

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especially during peak hour.

In the not-so-distant future, self-driving cars are expected to comprise a significant portion of the vehicle population in metropolitan areas, more concretely, experts are forecasting a 70% market penetration rate for autonomous vehicles by 2040 (IEEE, 2012). One of the main driving forces behind autonomous vehicle technology adoption is the improvement of passenger safety through elimination of human error. Human error accounts for 94% of road accidents (Dingus et al., 2016), which in turn account for 10–30% of delays due to congestion (Skabardonis et al., 2003). One of the main obstacles facing the adoption of autonomous vehicles is the uncertainty regarding their successful integration in human driver-populated traffic networks. Conventional vehicles equipped with navigation devices are able to receive several types of guidance. Descriptive guidance involves prevailing traffic conditions, predicted travel times and incident information. Prescriptive guidance involves specific shortest route information provision. Route guidance can provide user-oriented benefits. Given that vehicles remain compliant to their prescribed routes (Hoogendoorn and Bovy, 1998), route guidance can also lead to system-wide near-optimal network performance. Autonomous vehicles are expected to always maintain compliance, and through coordination with traffic control centers, can lead to system-wide benefits. Past research into the adoption and potential impact of autonomous vehicles has prioritized highly detailed dynamic modeling and simulation (Fagnant and Kockelman (2014), Katrakazas et al. (2015), Talebpour and Mahmassani (2016), Wang et al. (2017)). Region-based routing can be considered as routing at an aggregated level. Any large urban traffic network can be appropriately partitioned into regions (Ji and Geroliminis, 2012; Lentzakis et al., 2014; Etemadnia et al., 2014; Saeedmanesh and Geroliminis, 2016, 2017). Region-based routing then presents a set of region sequences that drivers can follow from their origin region to their desired destination region. This has been shown to lead to significant decrease of total vehicle travel time and better utilization of available resources, i.e. the regions of the urban traffic network, in our previous work (Lentzakis et al., 2016). In transportation economics literature, travelers are classified into certain broad categories, according to their value of time, type of activity (commuting to work, leisure) or other criteria and are given the option of changing their desired departure times, which becomes an additional control parameter (Small and Verhoef, 2007). However, this classification introduces additional complexity and stochasticity to the route selection process. In addition, many studies fail to consider the bounded rationality of travelers as decision makers (van Essen et al., 2016). A public transit diversion mechanism, as integrated to each routing method presented in this paper, can be considered as an alternative route choice which does not compromise travelers' departure time preferences. This feature would not be as readily justifiable in a link-by-link routing approach, where the destination location might be a considerable distance away from a public transit station.

1.1. Background on macroscopic fundamental diagram

Godfrey (1969) first proposed the existence of a Macroscopic Fundamental Diagram representing the relationship between vehicle density (veh/km) and space-mean flow (veh/h) for urban regions. Herman and Prigogine (1979) defined a Two Fluid Kinetic model later improved upon by Herman and Ardekani (1984) that stated that the average speed in urban network traffic is a function of the ratio of stopped vehicles, which can be represented as a power function of network link density. Daganzo (2007) defined a relationship between urban network output, representing the number of trips ending inside or outside of the network, and number of vehicles present at the network, or accumulation. This relationship should be valid under the condition that congestion is distributed in a homogeneous fashion throughout the network and as long as external conditions are varying at a slow rate. Geroliminis and Daganzo (2007) posited that the Macroscopic Fundamental Diagram can also exist for urban areas. The Macroscopic Fundamental Diagram, MFD for brevity, has been a staple of freeway traffic modeling and applications, but it's accuracy, as regards freeway networks, has recently been called into question (Mahmassani and Saberi, 2013; Geroliminis and Sun, 2011a; Knoop and Hoogendoorn, 2013). The MFD has been shown to be a suitable modeling tool for urban network regions, characterized by low intra-regional link density variability. The Urban-scale MFD can relate the number of vehicles within a certain region, called accumulation, to the product of average network flow and length, called production. The Urban-scale MFD presents in the shape of a asymmetric unimodal concave function, where for a critical accumulation value, network production is at capacity. For accumulation values below the critical value, network is considered to be under free flow conditions, while for accumulation values above the critical value, network is considered to be congested, ranging from lightly congested, all the way to gridlock. A well-defined Urban-scale MFD can only exist under homogeneous distribution of congestion. The traffic modeling of a network partitioned to several regions each represented with a MFD is first developed in Geroliminis et al. (2013). Geroliminis and Sun (2011b), Mazloumian et al. (2010) and Daganzo et al. (2011) have demonstrated the importance of network link density variability in acquiring a well-defined Urban-scale MFD. Additionally, work from de Jong et al. (2013), Leclercq and Geroliminis (2013), Knoop et al. (2014), Gayah et al. (2014) indicates that network topology, traffic signal settings, route distribution and demand can actually affect the total output of a region. Leclercq et al. (2015) posited that MFD shape will change when for the same network, different route distribution is applied and proposed a framework whereby all routes within a region would be grouped into macroscopic route clusters. Keyvan-Ekbatani et al. (2016) found that the integration of adaptive traffic control and network gating leads to higher network throughput as well as shorter queues on the boundary expanding work by Gayah et al. (2014). There are two approaches in mitigating these effects. One approach is to incorporate link density variability, a measure of congestion heterogeneity, in the relationship defined by the Urban-scale MFD, deriving an MFD dependent not only on the accumulation, but also link density variability, as in Simoni et al. (2015), Ramezani et al. (2015), Yildirimoglu et al. (2015). Another approach is to partition the urban traffic network into homogeneously congested regions with well-defined Urban-scale MFDs. Examples of different partitioning schemes resulting in homogeneously congested regions can be found in Ji and Geroliminis (2012), Lentzakis et al. (2014), Ji et al. (2014), Saeedmanesh and Geroliminis (2016). One of several regional dynamic traffic models used to describe region-based traffic dynamics, the Network Transmission Model, NTM for short, was originally developed by Knoop and Hoogendoorn (2014, 2015) and later implemented in a real-world application by Knoop et al.