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Network-based model for predicting the effect of fuel price on transit ridership and greenhouse gas emissions

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A B S T R A C T

As fuel prices increase, drivers may make travel choices to minimize not only travel time, but also fuel consumption. Consideration of fuel consumption would affect route choice and influence trip frequency and mode choice. For instance, travelers may elect to live closer to their workplace, or use public transit to avoid fuel consumption and the associated costs. To incorporate network characteristics into predictions of the effects of fuel prices, we develop a multi-class combined elastic demand, mode choice, and user equilibrium model using a generalized cost function of travel time and fuel consumption with a combined solution algorithm. The algorithm is implemented in a custom software package, and a case study application on the Austin, Texas network is presented. We evaluate the fuel-price sensitivity of key variables such as drive-alone and transit class proportions, person-miles traveled, link-level traffic flow and per capita fuel consumption and emissions. These effects are examined across a heterogeneous demand set, with multiple user-classes categorized based on their value of travel time. The highest relative transit elasticities against fuel price are observed among low value of time classes, as expected. Although total personal vehicle travel decreases, congestion increases on some roads due to the generalized cost function. Reductions in system-wide fuel consumption and greenhouse gas emissions are observed as well. The study uncovers the combined interactions among fuel prices, multi-modal choice behavior, travel performance, and resultant environmental impacts, all of which dictate the urban travel market. It also equips agencies with motivation to tailor emissions reduction and transit-ridership stimulus policies around the most responsive user classes.

1. Introduction

Fuel consumption and greenhouse gas emissions have become an increasing concern in recent years, and transportation accounted for 28% of total U.S. emissions in 2011 as reported by the EPA. A promising solution for the future is fuel efficient or battery electric vehicles (BEVs). However, improving the fuel efficiency of vehicles does not necessarily make travel less costly. Indeed, it can cause more vehicle-miles traveled and more fuel to be used. This is called the 'rebound effect' and has been studied in different sources (Allan et al., 2009; Small and Van Dender, 2007).

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The behavior of users in selecting the type of vehicle, the mode for transportation, route, etc. has great impacts on fuel consumption and pollution. As traffic congestion increases, increasing attention has been given to demand management policies. Past studies show that fuel price policies, as a major factor affecting the travel behavior, are particularly promising for demand management (Huang and Burris, 2015; Wang and Chen, 2012). Also, price mechanisms can generate funds for public and private sectors and ensure that external costs of pollution are paid by those who cause them. As fuel prices rise, so does the cost of personal vehicle trips, particularly for repeated travel such as home to work trips. Travel demand elasticities are stronger for long-term travel decisions than short-term (Goodwin et al., 2004; Graham and Glaister, 2004), and are highly sensitive to household income (Wadud et al., 2009). Intuitively, demand elasticities should also depend on the quality of trip and mode alternatives, and depend on specific origins and destinations. However, previous work has relied on regression models (Gillingham, 2014) that do not capture the effects of network structure and characteristics.

This paper develops a novel network-based model to improve predictions of how fuel price affects trip, mode, and route choice. To that end, we present a multiclass four-step planning model incorporating the effects of fuel consumption and pricing. Traveler behavior is based on a generalized cost function with components of travel time, tolls, and fuel cost, with different values-of-time for each traveler class. Although these planning steps have been traditionally separated into an iterative feedback process (Boyce et al., 1994)—the four-step planning model (McNally, 2007)—this paper presents a combined formulation in the spirit of Bar-Gera and Boyce (2003). Although monotonicity of the cost function cannot be proven due to the multiclass formulation, empirical results suggest that an equilibrium is achieved through a diagonalization heuristic. (The monotonicity of the generalized cost function admits a convex programming formulation when there is a single class).

Variation in system metrics with respect to changing fuel costs are analyzed on the downtown Austin city network. Our model demonstrates that effects of fuel prices on mode choice, overall travel performance, and environmental-impact reduction are highly non-uniform across demand and links. We show that disaggregate link-level traffic impacts resulting from fuel prices and mode-choice variations cannot always be extrapolated from higher-level observations. In particular, increases in fuel prices, although associated with decreases in overall demand, nevertheless caused increases in congestion on several links due to changes in route and trip choices. Although overall changes in transit ridership, demand, and the environmental impact with respect to fuel price followed expected trends, network analyses nevertheless improve the accuracy of such predictions.

The remainder of this paper is organized as follows: a literature review is given in Section 2. The combined trip, mode, and route choice formulation is presented in Section 3. Section 4 shows the results of applying the proposed algorithm on an urban study area in Austin, Texas. Section 5 concludes the paper and discusses the implications on policy and practice.

2. Literature review

The importance of fuel consumption, pollution, and efficiency has inspired much research on the effect of fuel price on different aspects of a transportation system, especially traffic demand. The impact of fuel policy on demand behavior can range from mode-destination choice to vehicle purchases. Many past studies have explored the change in different traffic related variables such as: customers' vehicle choice (high-consumption vehicles vs. gas-efficient cars) (Jeihani and Sibdari, 2010); toll facilities (Huang and Burris, 2015); carpooling (Bento et al., 2013); and highway travel demand (Kwon and Lee, 2014). Readers may refer to Graham and Glaister (2004) and Goodwin et al. (2004) for more detail on elasticities of traffic demand with respect to prices and incomes. Winebrake et al. (2015) most recently evaluated nation-wide fuel price elasticities in combination truck operations from 1970 to 2012. A recent study by Mishalani et al. (2014) reported that population density, transit share, freeway lane-miles per capita, private vehicle occupancy, and average travel time have a statistically significant explanatory effect on passenger travel related carbon dioxide emissions. As regards alternative fueled vehicles, Ewing and Sarigöllü (1998) reported that a large shift of demand to cleaner and zero-emission vehicles is possible provided their cost and performance came within an acceptable range of conventional vehicles.

The impact of fuel price on transit ridership is one major focus of this paper. In order to maintain system viability and meet service goals, it is necessary to anticipate changes to public transportation demand. The price elasticity of public transit has been studied by many researchers including Currie and Phung (1992), Litman (2004), and A.P.T. Association et al. (2008) which summarizes a survey of U.S. transit agencies. Haire and Machemehl (1992) found a statistically significant correlation between the fuel price and transit ridership. A study by Gallo (2011) on the effect of fuel policy surcharges on demand behavior in Italy found that people are willing to switch to more fuel-efficient vehicles in response to the surcharge policy rather than using public transit. The author stressed that the findings hold mainly for Italy and might be different for other countries. Hammadou and Papaix (2015) implemented an "urban mobility policy package" in Lille, France including a combination of carbon tax, congestion charging, parking charges, and public transportation service improvements, which resulted in a change in the modal split.

Sensitivity to fuel price as it pertains to gasoline demand is also affected by household income (Wang and Chen, 2012; Dahl, 2012). Wadud et al. (2009) found that the lowest and highest income groups respond most strongly to higher fuel prices, while households falling into mid-range income groups react less strongly. A more attractive and flexible approach than income is value of time (VOT). Since the effect of fuel price on people's behavior can vary across population, it is necessary to divide people into different VOT classes. The VOTs can either be from a discrete set or modeled by a continuous