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Exploration of correlation between environmental factors and mobility at signalized intersections

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ABSTRACT

Characterizing the relationship between environmental factors and mobility is critical for developing a sustainable traffic signal control system. In this study, the authors investigate the correlation of the environmental impacts of transport and mobility measurements at signalized intersections. A metamodeling-based method involving experimental design, simulations, and regression analysis was developed. The simulations, involving microscopic traffic modeling and emission estimation with an emerging emission estimator, provide the flexibility of generating cases with various intersection types, vehicle types, and other parameters such as driver behavior, fuel types, and meteorological factors. A multivariate multiple linear regression (MMLR) analysis was applied to determine the relationship between environmental and mobility measurements. Given the limitations of using the built-in emissions modules within current traffic simulation and signal optimization tools, the metamodeling-based approach presented in this paper makes a methodological contribution. The findings of this study set up the base for extensive application of simulation optimization to sustainable traffic operations and management. Moreover, the comparison of outputs from an advanced estimator with those from the current tool recommend improving the emissions module for more accurate analysis (e.g., benefit-cost analysis) in practical signal retiming projects.

Introduction

Transportation is a major contributor to energy consumption, greenhouse gas (GHG) emissions, and other environmental pollutants that can cause serious human health issues. For instance, transportation accounts between 20 and 25% of the total energy being consumed among developed countries (WEC, 2007) and it accounts for 27% of GHG emissions in the U.S., which is the second largest source after electricity generation (34%) (EPA, 2013; DOT, 2013). Traditionally, transport planning and operations mainly aim to improve access, mitigate traffic congestion, and smooth traffic flows, but they rarely consider the environmental impacts of transport for sustainable development explicitly. Among many elements of the surface transportation system, signalized intersections along urban arterials are often "hot spots" for fuel consumption and air pollution because of higher traffic density, longer vehicle idling time, and deceleration and acceleration of the driving cycles through the intersections. Existing signal timing optimization tools, including fixed-time, coordinated actuated, traffic responsive, and adaptive control (FHWA, 2008), mainly focus on capturing an optimal cycle length and green-time split to improve mobility (i.e., reducing delays and stops) (Sun et al., 2003; Lv, 2012). Although some of these tools have built-in emission

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estimation modules when calculating measurements of effectiveness, they are imprecisely estimated by assuming a drive cycle that consists of constant fractions of free-flow and congestion conditions rather than realistic traffic characteristics. To better understand the environmental factors associated with different traffic conditions and control strategies, the ability to adequately model and quantify fuel consumption and emissions at a microscopic level is of high importance.

The built-in emission estimation modules within current traffic simulations and signal optimization tools are relatively under-developed and have a very limited function. The available macroscopic optimization software for traffic signal timing includes Synchro (Husch and Albeck, 2006), TRANSYT-7F (Hale, 2008), PASSER (Chaudhary and Messer, 1993) and SIDRA INTERSECTION (Akçelik and Besley, 1984). Delay and its derivatives are commonly used as objective functions in most optimization software. For example, Synchro optimizes signal settings using a percentile delay, which considers cycle-by-cycle traffic variations. TRANSYT-7F optimizes signal settings using a disutility index, which is based on a combination of delay and stops (Hale, 2008). However, mobility-based optimization is usually insufficient to characterize the fuel consumption and emission levels of real-world driving behavior due to the nature of the macroscopic simulation model. Estimation of fuel consumption in Synchro and TRANSYT-7F is a linear combination of total travel distance, total delay, and total stops, without explicit considerations such as traffic congestion, vehicle type mix, and geometric and environmental factors. Only three types of emissions (i.e., carbon monoxide [CO], nitrogen oxides [NO_x], and Volatile Organic Compounds [VOCs]) in Synchro are roughly estimated based only on fuel consumption with fixed rates. There is no component of emission estimation in TRANSYT-7F. Besides macroscopic optimization tools, microscopic traffic simulation tools such as TSIS-CORSIM, VISSIM, and Transportation Analysis and Simulation System (TRANSIMS) have been developed to model and evaluate transportation networks in various traffic conditions (PTV AG, 2011; Stevanovic et al., 2009). Microscopic simulation modeling is a faster, safer, and cheaper way to test actual field implementations. Basic input parameters for microscopic simulation models, such as geometry, number of cars, and traffic signal setting, are easily obtained. However, similar to signal optimization tools, microscopic simulation software cannot adequately estimate environmental impacts of a traffic network. Although VISSIM has an add-on module related to emissions, the estimation method of the emission module is simplified without detailed considerations.

As air pollution problems attract more and more attention around the world, many researchers have attempted to incorporate traffic emission factors into traffic control strategies. Dating back to the 1970s, concerns with energy considerations and emissions at intersections were proposed (EPA, 1975; Christian, 1975), and there have been many studies on intersection emissions since then (Patterson, 1976; Tarnoff and Parsonson, 1979; EPA, 1992; Rouphail et al., 2001; Frey et al., 2001). The major limitation of most of these early studies is the lack of a sophisticated way of estimating energy consumption and emissions. Recently, several advanced emission estimation models have been developed, such as Comprehensive Modal Emission Model (CMEM) (Barth et al., 1999), the VT-Micro model (Ahn et al., 2002), and Motor Vehicle Emission Simulator (MOVES) (EPA, 2012). These microscopic models estimate vehicle pollutants at a second-by-second level of resolution using either vehicle engine or vehicle speed/acceleration data. In particular, the emerging model MOVES surpasses previous emission estimation tools. This new emission modeling system is the most sophisticated to date and is being applied at a number of different modeling scales, from the micro-scale (project-level, e.g., parking lot) to the macro-scale, where national-scale inventories are being generated for precursor, criteria, and GHG pollutants from on-road mobile sources (EPA, 2012). The embedded database and project level emission analysis in MOVES provide great opportunities for more accurate emission estimations in the traffic performance analysis.

Recent research and studies also have noted the importance of integrating traffic simulation modeling and advanced emission estimators (Li et al., 2004a,b; Chen and Yu, 2007). For example, Coelho et al. (2005a,b, 2009) explored the relative impact of traffic interruptions (e.g., pay tolls, roundabouts, and traffic signals within the corridor) on traffic performance and emissions (in terms of ratios or percentages). In their study, the research priority was given to relative values of emissions based on European driving behaviors of vehicle fleets. Park et al. (2009) proposed an optimization approach by integrating a CORSIM microscopic traffic simulation, the VT-Micro model, and a Genetic Algorithm (GA). Their study demonstrated that the proposed framework is effective in minimizing fuel consumption and emission with moderate trade-offs in delay and stops. Similarly, Stevanovic et al. (2009) presented an integration of VISSIM, CMEM, and VISGAOST to optimize signal timings. Findings of these studies show that a formula commonly used to estimate fuel consumption in traffic simulation tools inadequately estimates fuel consumption and cannot be used as a reliable objective function in signal timing optimizations. Kwak et al. (2012) quantified the impact of direct traffic signal timing optimization aimed at minimizing fuel consumption based on TRANSIMS, the VT-Micro emission estimator, and a GA-based traffic signal optimizer. Although the GA worked well in these studies, the GA-based optimization consumed significant time and computational loads. More efficient computational techniques should be sought and implemented in the direct optimization way. Lately, Lv (2012) investigated the relationship between emissions and control delay to formulate the optimization problem. Although his study demonstrated the air quality benefit by reducing vehicle emissions under different scenarios, the dataset of vehicle trajectories is quite small, and he considered only control delay as mobility measurement when exploring the relationship between mobility and emissions, with the selection of the parabolic function. Similarly, Zhang et al. (2013) and Osorio and Nanduri (2014) developed a surrogate model or metamode for the traffic signal optimization with environmental concerns. However, there is short of studies investigating the comprehensive relationship between different objectives (e.g., environmental factors and traffic metrics) at different intersections and different relations for various types of emissions.

Given the limitations of current practice and gaps in existing research, this study aims to explore how the environmental impacts of transport are related to mobility measurements at signalized intersections based on microscopic simulation and multivariate regression analysis. By developing two comparable intersection types, this study also investigated the role of