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Urban transportation emissions mitigation: Coupling high-resolution vehicular emissions and traffic models for traffic signal optimization

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A R T I C L E   I N F O

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A B S T R A C T

This paper proposes a methodology that allows high-resolution traffic and emissions models, known as microscopic simulation models, to be efficiently used to address transportation optimization problems that account for complex environmental metrics. The methodology consists of a metamodel simulation-based optimization (SO) approach. The metamodel combines traffic and emissions information from high-resolution microscopic simulators with information from lower-resolution analytical macroscopic models. This paper formulates and uses an analytical and differentiable macroscopic approximation of the non-differentiable simulation-based microscopic emissions model. A differentiable macroscopic traffic model is also used.

This paper shows that the analytical structural information provided by macroscopic analytical emissions models can contribute, despite their lower-resolution, to enhance the computational efficiency of algorithms that embed higher-resolution inefficient emissions models. The proposed algorithm is computationally efficient, i.e., it can identify points with improved performance within few simulation runs. More generally, the results of this paper highlight the added value of embedding analytical structural information within SO algorithms to address complex SO problems.

A traffic signal control case study is carried out. The proposed metamodel identifies signal plans that improve travel time and various emissions metrics. We present the corresponding monetary savings that can be achieved.

This optimization framework enables practitioners to use high-resolution microscopic traffic and emissions models to systematically design transportation schemes that account directly, in the design process, for environmental metrics. Hence, the use of such high-resolution models is no longer limited to the environmental evaluation of a small set of predetermined schemes. The tight computational budgets used in this paper show that such complex problems can be addressed in a computationally efficient manner.

1. Introduction

Nations around the world have adopted increasingly stringent regulations to monitor and control urban traffic emissions. In the US, federal regulations such as the Clean Air Act and the Surface Transportation Efficiency Act place increasing

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responsibility on transportation agencies to account for and achieve their environmental targets. By increasing accountability and using past performance as a metric for the procurement of future federal funding, these regulations also build incentive for agencies to design and operate their networks in a more sustainable manner.

Transportation agencies currently design transportation schemes (e.g., network design, traffic management) with a focus on improving traditional traffic metrics (e.g., travel times, throughput), they then evaluate the environmental impact of a small set of pre-determined schemes. There is a lack of practical, computationally efficient, optimization techniques that enable them to design the schemes while directly accounting for complex environmental metrics. This paper addresses this challenge.

The efficient design of such schemes involves coupling urban traffic models with vehicle emissions models, and embedding the integrated models within efficient optimization algorithms. Traffic models are usually classified as either macroscopic, mesoscopic or microscopic. For a recent review, see Barceló (2010). Macroscopic models are aggregate, flow-based models that are often computationally tractable and scalable yet fail to account for vehicle-specific attributes or detailed traffic dynamics. Microscopic models represent individual vehicles and individual travelers, they can account for the heterogeneity of driver, and more generally traveler, behavior; yet are often stochastic and computationally costly to run, this makes their efficient use for transportation optimization a challenge. Mesoscopic models combine ideas from both macroscopic and microscopic models.

Similarly, emissions models can be classified as either macroscopic or microscopic. For reviews see Rakha et al. (2003), Cappiello (2002), and Williams et al. (2001). Macroscopic emissions models are usually based on laboratory drive cycle tests conducted over a given average speed (CARB, 2008; EPA, 1994). Once the emissions rates are established for a given average speed, the emissions at other speeds are estimated by using multiplicative speed correction factors (SCFs). SCFs are based on inputs of vehicle-specific characteristics such as age and operating conditions. Macroscopic models do not account for time-variations in speed, let alone in acceleration, which significantly impact emissions (Rakha et al., 2000).

Microscopic emissions models, on the other hand, are based on vehicle-specific instantaneous (e.g., second by second) speed and acceleration information. Other inputs include vehicle-specific information (e.g., type, age) and road information (e.g., road-grade). Microscopic emissions models provide a higher-resolution description of emissions compared to their macroscopic counterparts, yet are more data-intensive and hence their use is mostly limited to the analysis of small urban areas (e.g., a corridor segment).

This paper proposes an optimization framework that can address a variety of urban transportation problems while directly accounting for both instantaneous vehicular emissions metrics and traditional congestion metrics (e.g., travel times). The framework considers continuous generally constrained simulation-based optimization problems. A variety of sustainable urban traffic management problems can hence be addressed with this framework.

As is detailed in Section 1.1, there is extensive work that couples vehicular emissions and vehicular traffic models. Nonetheless, the majority of the work uses the coupled models to evaluate a small set of predetermined transportation strategies (e.g., traffic management strategies). This paper uses the coupled models for optimization. It proposes an optimization framework that allows transportation strategies with improved emissions performance to be systematically designed.

To illustrate the approach, we consider a traffic signal control problem. The mapping of signal plans to network-wide vehicular emissions depends in an intricate way on individual vehicle technologies, instantaneous driver behavior and prevailing local traffic conditions. Hence, it is a nonlinear and high-variance function with numerous local minima. This makes the use of instantaneous emissions metrics for network-wide optimization an intricate problem. The proposed optimization method addresses this problem: it embeds high-resolution instantaneous emissions models and identifies traffic signal plans that improve network-wide congestion and emissions metrics.

The proposed optimization framework is computationally efficient, i.e., strategies with improved performance can be identified within few simulation runs. This is of interest for practitioners. In order to achieve computational efficiency, this paper formulates a macroscopic analytical and differentiable emissions model that approximates the non-differentiable microscopic simulation-based emissions model. Information from both the macroscopic and the microscopic models is combined within a simulation-based optimization algorithm. This allows the algorithm to use both high-resolution information (from the microscopic model) and analytical computationally efficient information (from the macroscopic model). It is this combination that allows the inefficient microscopic simulator to be used efficiently for optimization.

Section 1.1 reviews work that has coupled vehicular traffic and emissions models to address various transportation problems. Section 1.2 details how this paper contributes to the simulation-based optimization literature.

1.1. Coupling of vehicular traffic and emissions models for transportation analysis

A summary of this review is given in Table 1. This table lists for each work the type of traffic and emissions model used, and whether the coupled models are used for the what-if analysis of a small set of predetermined transportation strategies or for optimization. The last line considers the method presented in this paper.

The works of Li et al. (2004) and of Williams et al. (2001) couple macroscopic traffic models and macroscopic emissions models of carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x). They use the coupled models to evaluate the impact on delays, fuel consumption and emissions of various traffic signal plan parameters. Li et al. (2004) consider a case study of one intersection in the Chinese city of Nanjing. Williams et al. (2001) study hypothetical networks with up to two