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Multi-criteria optimization of traffic signals: Mobility, safety, and environment

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ABSTRACT

Two-dimensional multi-objective optimizations have been used for decades for the problems in traffic engineering although only few times so far in the optimization of signal timings. While the other engineering and science disciplines have utilized visualization of 3-dimensional Pareto fronts in the optimization studies, we have not seen many of those concepts applied to traffic signal optimization problems. To bridge the gap in the existing knowledge this study presents a methodology where 3-dimensional Pareto Fronts of signal timings, which are expressed through mobility, (surrogate) safety, and environmental factors, are optimized by use of an evolutionary algorithm. The study uses a segment of 5 signalized intersections in West Valley City, Utah, to test signal timings which provide a balance between mobility, safety and environment. In addition, a set of previous developed signal timing scenarios, including some of the Connected Vehicle technologies such as GLOSA, were conducted to evaluate the quality of the 3-dimensional Pareto front solutions. The results show success of 3-dimensinal Pareto fronts moving towards optimality. The resulting signal timing plans do not show large differences between themselves but all improve on the signal timings from the field, significantly. The commonly used optimization of standard single-objective functions shows robust solutions. The new set of Connected Vehicle technologies also shows promising benefits, especially in the area of reducing inter-vehicular friction. The resulting timing plans from two optimization sets (constrained and unconstrained) show that environmental and safe signal timings coincide but somewhat contradict mobility. Further research is needed to apply similar concepts on a variety of networks and traffic conditions before generalizing findings.

1. Introduction

Externality is defined, in economics, as the cost or benefit that affects a party who did not choose to incur that cost or benefit. We can also think of externalities, as positive or negative by-products of certain processes. In transportation, and more specifically roadway traffic, examples of negative externalities are safety incidents/crashes, air pollution, noise, etc. Although by-products of human activity to move people and freight around, which is a broad definition of transportation,

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these externalities are not less important than the mobility metrics (e.g. travel time, delay, speed, number of completed trips) that we usually use to qualify success of a transportation system/process.

In traffic engineering design, and more specifically in the operations of signalized intersections, some of these externalities (e.g. fuel consumption which is directly related to environment/air pollution), have been used to decide how to meaningfully tradeoff between mobility performance metrics such as delay and number of stops (Robertson et al., 1980). Since development of externality metrics (e.g. fuel consumed or potential conflicts created) requires methodology that usually goes beyond capabilities of most of the driver-behavior-based traffic simulation models, integration of simulation models and outside externality models have been a natural way to include externalities in the traffic engineering optimization processes (Stevanovic et al., 2009).

Logically, since complex stochastic simulation models require evolutionary algorithms to derive (near) optimal solutions (Foy et al., 1992; Park et al., 1999), the field of transportation engineering has seen a significant number of studies where Genetic Algorithms (GAs), and other evolutionary processes, are embedded in the optimization framework to reduce negative mobility and externality performance metrics (Oda et al., 2004; Tan et al., 2012). The next step were multi-objective optimization studies, where firstly competing multiple objectives were integrated in the single objective function, followed by an outburst of studies where Pareto Fronts (2-dimensional objective functions) were developed to address optimization of mobility and externality performance metrics (Li et al., 2004; Kwak et al., 2012; Ma, 2012). While the other engineering science disciplines went a step further to utilize (and visualize), 3-dimensional Pareto fronts, we have not seen many of those concepts in transportation and specifically not applied to traffic signal optimization problems.

To summarize the gap in the existing studies – there has not been a study that presents 3-dimensional optimization of traffic signals (signal timings) based on their influence on mobility, safety, and environmental factors. Objective of this article is to present such an approach where 3-dimensional Pareto fronts of signal timing solutions, which are expressed through throughputs (measure of mobility), conflicts (surrogate measure of safety), and fuel consumption (measure of environmental impacts), are optimized by use of an evolutionary algorithm in the stochastic optimization environment.

This study builds upon similar 2-dimensional optimization studies (Chen and Yu, 2007; Ma, 2012; Stevanovic et al., 2013a; etc.) and proposes a novel approach to integrating the evaluation of mobility metrics, surrogate measures of safety, fuel consumption, and stochastic optimization of signal timings. VISSIM microsimulation software (PTV, 2010), Surrogate Safety Assessment Model (SSAM) (Gettman et al., 2008), Comprehensive Modal Emission Model (CMEM) (Barth et al., 2000), and VISSIM-based Genetic Algorithm for Optimization of Signal Timings (VISGAOST) (Stevanovic et al., 2007) have been integrated in a framework to optimize performance of traffic signals by taking in consideration 3-dimensioanl nature of traffic operations (mobility, safety, and environment). The optimization process moves through the 3-dimensional space and generates surfaces which improve always at least one of the objective criteria, without worsening the other two.

The final result is a 3-dimenisonal Pareto front surface that gives system users a chance to select between points (signal timing plans) on the surface, understanding that a sacrifice that has to be made (by preferring improvement in a particular objective criterion over the other two) is the smallest that one can get (assuming that the optimization process led to a (near) optimal solution). The optimization experiments are divided into two parts, where the first part explores a variety of solutions in a non-constrained approach, thus representing a more theoretical approach to the problem. The second part constraints mobility metrics in such a way that derived solutions do not impede mobility of the system by much, thus representing more of a practical approach to the retiming of traffic signals. The authors investigate also how few common single-objective-optimization scenarios compare to the derived 3-dimensional Pareto front surfaces.

2. Literature review

Research described in this paper includes a variety of concepts and methods that have been previously addressed in the work of others, including: integration of safety and environmental measures within signal timing processes, evolutionary algorithms, stochastic optimizations, multi-criteria optimizations and others. To fairly summarize findings from variety of previous studies on these subjects, the authors divide the literature review section into several subsections. It should be noted that the list of the studies cited is not inclusive and it presents a summary of some of the most notable studies in each category. The authors pay special attention to 3-dimensional (3-D) multi-criteria optimizations, with potential 3-D visualizations, because such studies were not previously conducted in the area of traffic signal optimization.

One should note that this research study does not consider the re-routing of vehicles due to optimization of signal timing settings; routes are assumed from ‘a priori’ static route assignment. However, integration of dynamic re-routing and signal optimization problem is a very relevant approach to investigate realistic externalities of traffic signal operations. A reader should, for example, see work of Gartner and Al-Malik (1996) who investigated the problem of traffic flow re-routing induced by traffic signal optimization. Also, Chen and Ben-Akiva (1998), considered the interaction of dynamic traffic control and dynamic traffic assignment and proposed a theoretical game method as the solution for a combined dynamic traffic control-assignment problem. More recently, Paz and Chiu (2011) proposed a practical and efficient solution in the form of an adaptive traffic control model. In a single-loop algorithmic structure dynamic assignment flows and demand-responsive signal timing settings were generated simultaneously, at every iteration of the solution algorithm.

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