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Impact of transition between signal timing plans in social cost based in delay, fuel consumption and air emissions

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ABSTRACT

Significant effects of traffic congestion include the cost associated with extra travel time, fuel consumption, and gas emissions. This paper develops a mathematical function to quantify the monetary impact of transition designs between signal timing plans on users and the environment. This function offers an approach to reduce problems such as excessive travel time, pollution emissions and fuel consumption. The proposed social cost function is evaluated for various transition plans to assess the impact of the number of steps required to adjust signal timing. The relationships between delay, fuel consumption and gas emissions and the number of steps needed to achieve the transition are also analysed.

Introduction

Traffic intersections are designated areas for vehicles to turn in different directions and are generally subject to traffic control policies such as traffic lights and stop signs. Traffic intersection users may be exposed to traffic signal delays, queue formation and speed change cycles due to different levels of congestion throughout the day.

According to the 2011 Urban Mobility Report, traffic congestion levels have increased in America's urban areas over the past 28 years, and have worsened in regions of all sizes Schrank et al. (2011). In 2010, the total delay for all travellers in urban areas of the United States reached 4.8 billion hours or four times the total delay in 1982. A more significant effect of traffic congestion is the cost associated with extra travel time, fuel consumption, and gas emissions. The amount of fuel wasted due to congestion was 1.9 billion gallons, and the total congestion cost reached $101 billion in 2010.

Transportation is also an important contributor to total greenhouse gas (GHG) emissions. The transportation sector contributes 29% of the total U.S. and over 5% of world GHG emissions (U.S. Department of Transportation, 2010). The largest sources of transportation greenhouse gases in 2010 were passenger cars (43%), light duty trucks, including sport utility vehicles, pickup trucks, and minivans (19%), freight trucks (22%) and commercial aircraft (6%). The primary driver of transportation-related emissions was the CO_2 produced by fossil fuel combustion, which increased by 17% from 1990 to 2010 and led to a 19% increase in overall emissions from transportation activities EPA (2012).

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These statistics show that, despite the efforts made thus far, work is still required to solve or alleviate transportation-related problems. The design of traffic control policies for the movement of users at a specific intersection should be accomplished in a way that benefits all modes of travel, improving not only measurements of traffic flow but also influencing factors as the reduction of gas emissions and fuel consumption.

Therefore, when designing traffic control policies, it is necessary that coordinated signals operate optimally at all times, even during transition phases between timing plans Selekwa et al. (2003). Indeed, improvements to the transition phase could lead to considerable reductions in delay times, gas emissions and fuel consumption.

Several authors such as Shelby et al. (2006), Yun et al. (2008), McShane and Roess (2011), and Lee and Williams (2012) have addressed the potentially negative and lasting effects of severe disruptions caused by transitioning from one timing plan to another. However, there is a gap in the literature in terms of the implementation of mathematical approaches to address transitions between timing plans and the need to apply functions that can simultaneously optimise multiple objectives.

The few articles that fall into this category are simple models with limited optimisation objectives. For example, Lieberman and Wicks (1974) have presented an algorithm (RAST) designed to minimise the duration of a transition period, while Chang (1987) has reviewed a transition procedure in which the optimal parameter is computed to minimise the sum of squares of the differences between the current and past offsets. Abbas et al. (2001) have presented a traffic signal offset transitioning algorithm as an integrated optimisation approach and Selekwa et al. (2003) have proposed a methodology to optimise traffic flow based on cost based on dynamic quadratic optimisation. Lee and Williams (2012) have presented a nonlinear mathematical model that provides constrained delay minimisation.

In summary, more complex mathematical functions capable of evaluating existing conditions during transition periods more accurately are needed. Consequently, this paper proposes a multiple objective function to reduce delays, gas emissions and fuel consumption. The overall objective is to minimise social costs, which are understood as costs to society, including users and the environment. The social cost function is evaluated with various transitions plans to assess the impact of the number of steps needed to adjust signal-timing plans. The relationships between the number of steps to reach transition and delays, fuel consumption and gas emissions are also analysed. This research seeks to achieve the following objectives to support these needs.

1. Develop a mathematical function to minimise social costs in terms of three components that correspond to delays, fuel consumption and air emission costs.
2. Design a heuristic method to determine transition signal timing plans with different numbers of steps to adjust signal timing.
3. Assess the impact of the number of steps needed to adjust signal timing on the social cost function through a case study.

Literature review

The purpose of this section is to review and analyse information found in the literature regarding delays, fuel consumption and gas emission models and current research efforts in these areas.

Delay models

Delay is one of the most commonly used measurements of efficiency in traffic control and can be described as the amount of time spent traversing an intersection, from vehicle arrival until vehicle departure. Delay measurements can be taken for a single vehicle, as an average for all vehicles over a specified time period or as an aggregate value for all vehicles over a specified time period.

The problems in estimating delay at signalised intersections have been widely studied in the literature. Beckmann et al. (1956) was the first to estimate the expected delay at fixed-time signals. Another delay model has been presented by Webster (1958), in which a systematic approach based on deterministic queuing analysis is used for delay estimations at pre-timed intersections, and this basic model has supported all subsequent delay functions.

The Webster (1958), Highway Capacity Manual (HCM) (2010) and Akcelik (1981) delay models are preferred by traffic engineers for estimating delay. The HCM and Akçelik formulas can give more reasonable results than the Webster method, but the estimations of these two models do not include delays due to oversaturation because of unclear parameters in the problem, such as driver behaviour, age, education, arrival type, and others Murat and Baskan (2006).

Other delay models are described briefly as follows. McNeil (1968) has derived a formula for expected signal delay assuming a general arrival process and constant departure time. Michalopoulos and Pisharody (1981) have developed a traffic control algorithm to minimise total delay at isolated intersections based on shock wave theory. Olszewski (1993) has developed a numerical method of calculating average delay and the time-dependant distribution of average cyclic delay, while Han (1996) has presented an alternative approach to the problem of optimising fixed-time traffic signal settings at an isolated junction for a single time period, in which the degree of saturation for each traffic stream can be greater than one or less than one. Fu and Hellinga (2000) have developed an analytical model to estimate the variance of overall delay, including the variance of both uniform and random delays. Chang and Lin (2000) has developed a delay model for signalised intersections under saturation traffic and they established a real-time control parameter optimisation model for minimising delay.