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Development and Preliminary Field Testing of an In-Vehicle Eco-Speed Control System in the Vicinity of Signalized Intersections

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Abstract: This paper develops and addresses the implementation issues associated with the field application of an Eco-Speed Control (ESC) system that computes and recommends a fuel-efficient trajectory to drivers using signal timing and phasing data received from downstream-signalized intersections. From an algorithmic standpoint, the proposed process addresses the possible scenarios that a driver may encounter while approaching a signalized intersection. Alternatively, from an implementation standpoint the paper overcomes the challenges associated with communication latency, data errors, real-time computation, and smoothness of the drive in developing the system. The Virginia Smart Road connected vehicle controlled facility at the Virginia Tech Transportation Institute (VTTI) was used to conduct a preliminary proof-of-concept testing of the proposed ESC system. The testing included driving on downhill and uphill approaches for four red indication offset values. In total 192 trips were conducted using four different participants. The analyzed data indicate that the proposed system is very promising, producing an average reduction in fuel consumption levels and travel times in the range of 17.4 and 8.4 percent, respectively.

Keywords: Eco-Speed Control; Connected Vehicle; Fuel Consumption; Vehicle Dynamics Model; Signalized Intersection.

1. INTRODUCTION

With the development of information and communication technology, connectivity between vehicles and between vehicles and transportation infrastructure was made possible. For instance, information of signal phasing and timing (SPaT), location and speed of vehicles could be easily transmitted and exploited for any application. Studies showed that vehicle fuel consumption levels in the vicinity of signalized intersections are dramatically increased due to vehicles' deceleration and acceleration (Barth et al., 2008; H. Rakha et al., 2003). During the past decades, many studies have focused on changing traffic signal timings to optimize vehicles' delay and fuel levels (Li et al., 2004; Stevanovic et al., 2009). Recently, researchers attempted to use connected vehicles and infrastructure technologies to develop eco-driving strategies that are more fuel-efficient. One of such applications is the Eco-Speed Control (ESC) which was developed to optimize individual vehicle fuel consumption by recommending a fuel-efficient trajectory using advanced information from surrounding vehicles and upcoming signalized intersections (Rakha et al., 2012).

Various ESC algorithms were developed in recent years. Malakorn and Park proposed a cooperative adaptive cruise control system by using SPaT to minimize absolute acceleration levels of vehicles and reduce fuel consumption level (Malakorn et al., 2010). Kamalanathsharma and Rakha developed a dynamic programming based fuel-optimization strategy using recursive path-finding principles, and evaluated the developed strategy using an agent-based modelling approach (R. Kamalanathsharma et al., 2014). Asadi and Vahidi proposed a schedule optimization algorithm to allocate "green-windows" for vehicles to pass through a series of consecutive signalized intersections (Asadi et al., 2011).

Most of ESC algorithms are developed and tested in a traffic simulation environment where vehicles are forced to follow the recommended speed as calculated by the ESC algorithms. However, many problems that are not treated in simulation software need to be solved in order to implement ESC in the field, such as communication latency, system malfunction, data collection error, driver perception/reaction delay, driver distraction resulting from following posted recommended speed, etc. Few studies attempted to investigate the potentials of implementing ESC in the field. For instance, Barth and Xia developed a dynamic eco-driving system and conducted a field test on arterial roads (Barth et al., 2011; Xia, 2014). However, vehicle fuel consumption is not explicitly considered in their algorithm objective function. Instead, their algorithm attempts to optimize vehicle acceleration and deceleration profiles to minimize the total tractive power demand and the idling time so that the fuel consumption levels are also reduced (Barth et al., 2011).

This paper describes the preliminary field-controlled tests of an ESC algorithm developed to provide a "fuel-optimized" speed profile from upstream to downstream of a signalized intersection. In the tested algorithm, minimizing the fuel consumption level from upstream to downstream of the intersection is set as the objective function, and various constraints are constructed using the relationship between

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vehicle speed, acceleration, deceleration, and travelled distance. Dynamic programming is used to solve the optimization problem and provide the optimum speed profile. The remainder of this paper is organized as follows. The proposed ESC algorithm and the discussion of its field implementation are presented in the following section. Thereafter, the test environment are described the test results are provided to investigate the benefits of using ESC. Finally, the conclusions and some recommendations for future research are provided.

2. METHODOLOGY

2.1 Definitions and Assumptions

Given that both upstream and downstream vehicle speed profiles are considered in the ESC algorithm, a control region in the vicinity of signalized intersections should be defined. Considering the communication range of Dedicated Short Range Communications (DSRC), ESC algorithm is activated at a distance of d_{up} upstream of the intersection to a distance of d_{down} downstream of the intersection. Note that the distance is calculated from the vehicle location to the intersection stop line. The value of d_{down} is defined to ensure that the vehicle has enough downstream distance to accelerate from zero speed to the limit speed with a low throttle level (e.g. 0.3).

The Eco-speed Control algorithm described in this paper produces the optimum speed profile from upstream to downstream of a signalized intersection, by incorporating vehicle dynamics and fuel consumption models. It should be noted that the impacts from neighboring vehicles such as car following and/or lane changing are not considered in the current algorithm. The developed algorithm treats eco-speed control under light traffic conditions. It can be easily implemented for the controlled-test conditions used in this study since only one vehicle is used during the test. The developed ESC algorithm could be refined for more complicated traffic conditions by considering the calculated optimum speed profile as the variable speed limit as demonstrated in (R. K. Kamalanathsharma et al., 2015). Therefore, a general solution of ESC can be achieved by constraining the vehicle speed by the variable speed limit produced by the algorithm as well as other common traffic flow constraints such as car following model, gap acceptance, collision avoidance, etc.

When a vehicle approaches a signalized intersection, the vehicle may accelerate, decelerate, or cruise (keep its current speed) depending on its speed, distance to the intersection, signal timing, etc. Considering that the vehicle may or may not need to decelerate when approaching the traffic signal, two cases are considered to develop the ESC strategies:

Case 1: vehicle is able to pass the intersection on green phase without deceleration (either keeping a constant speed, or accelerating to a higher speed and then keeping that speed).

Case 2: vehicle needs to decelerate to a lower speed, and then keep that speed to pass the intersection on green phase.

The above two cases describe the vehicle's optimum trajectory in order to minimize fuel consumption while traversing the intersection. After the vehicle passes the stop line, the vehicle tries to reach the speed limit, which describes the vehicle's maneuver downstream of the intersection. More details of optimum speed profiles during various situations have been discussed in (R. K. Kamalanathsharma, 2014; Xia, 2014). Fig. 1 demonstrates the optimum speed profile when vehicle passes a signalized intersection, and the ESC algorithm helps to find the best acceleration/deceleration levels. The sample speed profiles (initial speed u_1 and u_2) for case 1 are highlighted in blue, and the sample speed profile (initial speed u_3) for case 2 is represented in maroon. u_f denotes road speed limit. Note that the samples in Fig. 1 happens at the red phase when vehicle passes the upstream distance d_{up}. The same classification of case 1 and 2 also exist for the situation of green phase. Considering the simplicity to explain the proposed algorithm, the initial red phase is assumed for the following sections.

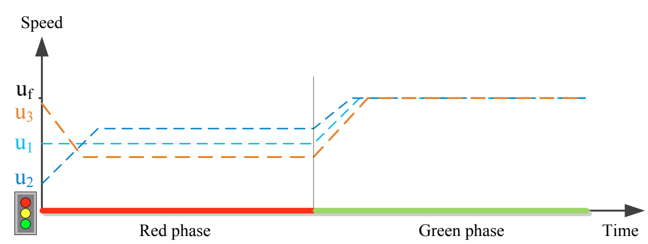

Fig. 1. Samples of optimum speed profile when vehicle approaches the signalized intersection.

In the proposed ESC algorithm, the deceleration is assumed constant for case 2. In case 1, the vehicle acceleration follows the vehicle dynamics model developed in (H. Rakha et al., 2002). In this model, the acceleration value depends on vehicle speed and throttle level. Given that the throttle level is typically around 0.6 as obtained from field studies (R. K. Kamalanathsharma, 2014), a constant throttle level of 0.6 is assumed in the vehicle dynamic model to simplify the calculations in the ESC algorithm for case 1. In case 2, the throttle level ranges between 0.4 to 0.8, and the optimum throttle level can be located by the minimum fuel consumption level. The vehicle dynamics model is summarized by (1) to (3).

$$u(t+\Delta t)=u(t)+3.6\frac{F(t)-R(t)}{m}\Delta t \tag{1}$$

$$F=\min\left(3600 f_p \beta \eta_d \frac{P}{u}, m_{ta} g \mu\right) \tag{2}$$

$$R=\frac{\rho}{25.92}C_d C_h A_f u^2+mg\frac{c_{r0}}{1000}\left(c_{r1}u+c_{r2}\right)+mgG \tag{3}$$

where F is the vehicle tractive effort; R represents the resultant of the resistance forces, including aerodynamic,