Analysis of Vehicle Stop-and-Go Driving Behaviors at Signalized Intersections

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ABSTRACT

Vehicle specific power (VSP) has been widely utilized to reveal the impact of vehicle operating conditions on estimations of emissions and energy consumption that are dependent upon speed and acceleration or deceleration based on second-by-second vehicle operation. The analysis of acceleration and deceleration stop-and-go behaviors at intersections is needed for queue simulation and emissions estimation. High-resolution data obtained by driving simulator sensors can provide useful insights into driving behavior at intersections. Hence, aggressive driving behaviors that account for a significant share of vehicle emissions can be identified by data-driven analysis of VSP distribution. Based on the analysis results, an aggregated VSP distribution represents the profile of driving behaviors at signalized intersections.

KEYWORD: vehicle specific power (VSP), aggressive driving, simulator, data-driven.

INTRODUCTION

The modeling of acceleration and deceleration associated with speed change cycles (stop-start and slow down–stop maneuvers) is essential for the analysis of operating cost, fuel consumption, and pollutant emissions, and for determining geometric, stopped and queuing components of overall delay at signalized intersection. The vehicle’s operations, when approaching and leaving an intersection are substantially different from those in the driveway (Minoura et al. 2009). For the stop–go maneuver, the challenges posed for the simulation of queues at a micro-scale level are the acceleration profile of the leading vehicle in the queue (Li et al. 2004), and the headway of the following vehicles (Jin et al. 2009). The car-following dynamic has been studied for decades (Brackstone and McDonald 1999). In contrast, research on acceleration at intersections is underdeveloped. A polynomial model of acceleration and deceleration profiles was derived for estimating instantaneous acceleration and deceleration rates. The model was calibrated using extensive real-life driving data representing general driving conditions, that is, involving a wide range of speed change cycles on different types of roads (Akçelik and Biggs 1987). Wang et al. (2004) assumed that acceleration has a polynomial decreasing relationship with speed. Long (2000) concluded that linearly decreasing acceleration...
rates better represent both maximum vehicle acceleration capabilities and actual motorist behavior.

Deceleration behaviors (slowdown–stop maneuver) at intersections can be categorized into two types: the go–stop maneuver, and the indecision maneuver. The latter refers to the behavior of a motorist who, when presented with a yellow light, is likely to have difficulty deciding whether to stop at the stop line or to proceed through the intersection (Zohdy et al. 2012). This paper focuses on the former. Several studies have been conducted to investigate whether fuel-saving can be achieved by avoiding the need to stop at signalized intersection (Rakha and Kamalanathsharma 2011; De Nunzio et al. 2015). Vehicle operation is also significant for traffic simulation and the modeling of vehicle fuel consumption and emissions, both of which depend on the acceleration–deceleration characteristics of vehicles’ slow down–stop profile. Most vehicle emissions occur at intersection approaches because of the final acceleration to cruising speed and the slow down–stop cycle (EPA 2003). The deceleration and acceleration behaviors at intersections significantly affect emission intensity. The vehicle specific power (VSP) correlates vehicle operation with vehicle emissions. This paper presents a simulator-based method to research vehicle operation status at intersections via VSP analysis.

This study found that data acquisition was the initial and primary challenge: high-resolution and accurately-positioned vehicle trajectory datasets are difficult to obtain in practice. Currently, the two methods used to collect trajectory datasets are through the use of either a vehicle-mounted global positioning system (GPS), or a feature-capture camera (Gordon et al. 2012). The data accuracy of both methods is subject to weather and the surrounding environment which downgrade the reliability of the leading vehicle acceleration behavior. This paper uses the outputs of a vehicle simulator to study the distribution of VSP, with the simulator able to gauge going-stop-going behaviors at intersections. In particular, the paper focuses on two scenarios, namely, the acceleration process of the leading vehicle (vehicle platoon leader) when leaving an intersection, and the deceleration process of the stopping vehicle when approaching a signalized intersection. Two outputs of the simulator, namely speed and acceleration, are used to calculate VSP. And, distributions will be analyzed to identify statistical outliers, aggressive driving in particular.

The paper is organized as follows: Section 2 outlines the methodology used; Section 3 presents the data used in the research and demonstrates the distribution of VSP at intersections; and finally, in Section 4, the paper discusses the main conclusions.

METHODOLOGY

Driving Simulator Experiment

Participants

Forty licensed drivers were selected to participate in this experiment: they ranged in age from 19–77, and comprised a mix of male and female drivers. Drivers completed a demographic questionnaire before they started driving. Participants had four driving runs, which included one practice run to become familiar with the set-up (Kim 2013).

Apparatus and Stimuli

The experiment was conducted using a driving simulator composed of an automatic Holden Commodore vehicle. When seated in the simulator vehicle, the driver was immersed in a virtual
environment which included a 180 degree front field of view comprising three screens, simulated rear-view mirror images on LCD screens, surround sound for engine and environmental noise, and real car cabin and simulated vehicle motion (see Figure 1). The road and environment were developed to create a sense of realistic traffic around the car as it was ‘driven.’

Figure 1. Driving simulator: Centre for Accident Research and Road Safety – Queensland (CARRS-Q).

In this driving simulator, several modules work in coordination. Each module is responsible for one part of the simulation, with the modules comprising:
- An application to create the scenario;
- A module managing the physics (dynamics) of the driven and/or automated vehicle;
- A module to manage traffic;
- A visual module displaying the simulation on the screen;
- A sound module;
- A motion module; and
- An acquisition module to obtain data from the car.

The driving simulator software creates a road network scenario with a combination of straight and curved sections, along with their intersections, as shown in Figure 2. The simulation ran for an hour, during which the participant sat in the driver’s seat, driving the simulator with two pedals (brake and accelerator only), and a force feedback steering wheel. This software records and time stamps data from different devices and different computers, and can synchronize all data collected so the experiment can later be replayed and analyzed (Larue 2013). The experiment included the integration of the VISSIM traffic flow simulation software package with the driving simulator. As VISSIM has the most detailed network and traffic control models, and also considers vehicle widths and lateral movements within and between lanes, it may be a more appropriate tool for modeling networks in which detailed interaction occurs between vehicles (Hidas 2005). In accordance with the simulator configuration, only the leading vehicle behavior needs to be changed, based on what was observed from the driving simulator.
and field data. The following vehicles then need to be moved, based on car-following theory, which is mainly used to control all vehicles in the simulation. The simulated vehicle was the leading vehicle as it drove into an intersection zone with the boundary 200 meters from the stop line. This vehicle’s trajectories at an intersection were collected in increments of 0.05 seconds, with this being the highest sampling rate for the simulator.

![Figure 2. Road Network Scenario on Driving Simulator at CARRS-Q.](image)

**Data collection and vehicle operation classification**

The methods of GPS and video capture have been widely used to research vehicle operations at intersections. Unlike these field technologies, the simulator has full control of the experimental parameters and has several advantages. Initially, the acceleration/deceleration processes can be identified, with an acceleration process defined as a period starting from the idling condition and ending when speed reaches the maximum cruising speed. A deceleration process is defined as the period starting from the maximum cruising speed and ending when the vehicle is idling. The dataset used in the study’s experiment consisted of vehicle speed, acceleration, acceleration pedal movement and brake pedal movement. This paper was therefore able to classify varied operations, as demonstrated in Table 1, with accurate driving behaviors, rather than applying the numeric clustering method (Lin and Niemeier 2003). In comparing our study’s dataset with the dataset collected with a GPS feature-capture camera, other advantages of our study’s dataset were the precise positioning of the vehicle and the zoning bounds. In this simulator experiment, it was planned that the simulated vehicle driven by each participant would stop at signalized intersections (Zohdy et al. 2012). As a further measure, non-compliance driving datasets were removed. Hence, the correlation between driver decision and signal phasing and timing information was excluded in this research. To obtain a homogeneous stop-and-go dataset in terms of driving behaviors, four intersections with straight approach lines, namely, No. 4, 5, 8, and 9, were included in this research.
Figure 3. Selective Speed and Acceleration Profiles at an Intersection: (a) Speed Profile; (b) Acceleration Pedal Movement; (c) Acceleration Phase; (d) Deceleration Phase.

Notes: Acceleration pedal movement ranges from zero to 1. The full movement of the acceleration pedal is displayed as 1, with 0 representing the null value of the acceleration pedal sensor.

This innovative high-resolution data collection is able to reveal driver behavior at a more disaggregated level. The acceleration and deceleration procedures can be extracted from the speed profile with precise datasets of brake pedal and acceleration pedal movements. Figure 3 illustrates two sets of speed profiles from the current study with simultaneous counterparts of
acceleration pedal movement, and an extracted acceleration phase and deceleration phase. Significant variations were observed between the driving behaviors of participants. The acceleration (or deceleration) dispersion did not result simply from how drivers accelerate but from the decisions they made to accelerate (or decelerate), with this decision making the most significant contribution. Therefore, when facing distinctly different speed profiles due to acceleration behavior, the statistical fit is not able to generate any meaningful results. In addition, the Institute of Transportation Engineers (Engineers 1999) recommends 1.26 m/s² and 3.0 m/s² as constant acceleration and deceleration rates. However, the simulator results confirmed the findings of Wang et al. (2004), that the constant acceleration assumption does not reflect realistic driver behavior.

### Table 1. Vehicle operation classification

<table>
<thead>
<tr>
<th>Operation state</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Transition</td>
<td>Brake pedal movement = 0; Acceleration pedal movement = 0 and Speed &gt; 0</td>
</tr>
<tr>
<td>2 Acceleration</td>
<td>Brake pedal movement = 0 and Acceleration pedal movement &gt; 0</td>
</tr>
<tr>
<td>3 Idling</td>
<td>Brake pedal movement = 0; Acceleration pedal movement = 0 and Speed = 0</td>
</tr>
<tr>
<td>4 Braking</td>
<td>Brake pedal movement &gt; 0 and Acceleration pedal movement = 0</td>
</tr>
</tbody>
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### ANALYSIS OF VEHICLE OPERATIONS AT AN INTERSECTION

#### Vehicle Specific Power (VSP)

Vehicle specific power (VSP), as proposed by J. L. Jiménez-Palacios, is an indicator of engine load. It correlates the impact of vehicle operating conditions with estimations of emissions and energy consumption that are dependent upon speed, roadway grade, and acceleration or deceleration based on second-by-second vehicle operation (collected by on-board diagnostics [OBD]) (Jimenez-Palacios 1998). Hence, VSP has been incorporated as a key factor in vehicle emission models, including the Mobile driving simulator and its successor, the Motor Vehicle Emission Simulator [MOVES] (EPA).

By using parameter values for a typical light-duty vehicle, VSP is calculated as follows:

$$VSP = v \left[ 1.1a + 9.81 \frac{r}{100} + 0.132 \right] + 0.000302v^3$$

(1)

Where, $VSP =$ vehicle-specific power, kW/ton;  
$a =$ vehicle acceleration (m/s²);  
$r =$ road grade (%);  
$v =$ vehicle speed (m/s);  
$g =$ acceleration of gravity, 9.81 m/s².

The mass rates of fuel use and emissions are stratified into bins by using a vehicle-specific power (VSP). The binning method is presented in Equation 2:

$$VSP \in [n, n + 1] \; VSP \; Bin = n$$

(2)

Where, $n =$ the integer from -60 to 60.

#### VSP Dataset and Distribution

Previous studies (Song et al. 2011; Song and Yu 2011) have used a VSP range of -20 to 20 kw/ton, with this configuration based on data collected at unrestricted road sections from urban areas, such as Beijing. However, the stop-and-go VSP datasets collected by the driving simulator in the current study show a distinguishing characteristic that is different to the findings in
Figure 4. VSP Distribution at No 4 Intersection: (a) Acceleration Phase; and (b) Deceleration Phase.

Figure 5. VSP Distribution at No 5 Intersection: (a) Acceleration Phase; and (b) Deceleration Phase.
Figure 6. VSP Distribution at No 8 Intersection: (a) Acceleration Phase; and (b) Deceleration Phase.

Figure 7. VSP Distribution at No 9 Intersection: (a) Acceleration Phase; and (b) Deceleration Phase.
previous studies, with this shown in Figures 4, 5, 6, and 7. The stop-and-go VSP distributions at intersections show a high degree of volatility. Moreover, the driving behaviors demonstrate randomness in varied independent datasets obtained at four intersections. In the vehicle acceleration datasets, deceleration behaviors can be identified, while acceleration behaviors can be identified in the deceleration processes. The current study attempted to use the Kolmogorov–Smirnov statistic to fit the empirical distribution function of the sample to distribution function of the reference distributions. However, the fit did not work either in theory or in practice when facing the de facto heterogeneous datasets. Therefore, the study employed the data-driven method to identify aggressive driver behaviors. According to our previous field study, 5% is an appropriate threshold for aggressive behavior identification (Zhao et al. 2015).

Figure 8(a) illustrates the VSP distribution of the acceleration phase, based on an aggregated dataset that consists of driving behavior data obtained at the above-mentioned four intersections. Figure 8(b) illustrates its deceleration phase counterpart. The aggregated VSP dataset consists of 50,723 deceleration phase VSP records and 23,623 acceleration phase VSP records. Based on the large quantity of data samples, it is common to identify acceleration behaviors in the deceleration process. On unrestricted roads, the stop-and-go VSP dataset shows a greater degree of volatility than its counterpart. Based on Figure 8(a) and Figure 8(b), the upper VSP threshold at a signalized intersection is 36 for the leading vehicle, while the lower VSP threshold when approaching a signalized intersection is -42 for a stopping vehicle.

CONCLUSIONS

This paper has focused and on the distribution fitting at intersections. Furthermore, the results have shown that the VSP distribution has a very unique characteristic. The high-
resolution data from the driving simulator demonstrated significant differences in acceleration behavior between participants. The instantaneous emission modeling at intersections is highly dependent on acceleration behaviors (Minocha 2005; Pandian et al. 2009). In addition, the queue estimation procedure can be enhanced (Clement et al. 2004) using the proposed methodology. Compared to other data collection methods used for data acquisition in the field (Lin and Niemeier 2003), the high-resolution driving simulator datasets, including detailed acceleration/brake pedal movements, provide a more reliable operational state classification.

Moreover, current practices in mobile source emission modeling suggest that it is critical that second-by-second vehicle operation data be used for the estimation of emissions in the transportation network. The accurate profiling of high-resolution vehicle dynamics data (i.e. the VSP distribution) eventually will lead to more accurate modeling results and, in particular, the precise identification of aggressive driving.

However, the proposed VSP distribution and thresholds are based on simulator data which may deviate from actual driving conditions (Godley et al. 2002). This research has not taken into consideration turning maneuvers and the influences of traffic management. This study should also investigate the VSP distributions for roadways other than where there is straight movement, such as left-turn and right-turn movements. Improvements to the methodology rely on the collection of vehicle trajectory data at a high level of resolution. For future study, an accelerometer could be used to collect high-resolution data for validation in the field (Bogdanović et al. 2013).

REFERENCES


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