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Prediction of Vehicle Activity for Emissions Estimation Under Oversaturated Conditions Along Signalized Arterials

ALEXANDER SKABARDONIS,[1] NIKOLAS GEROLIMINIS,[2] and ELENI CHRISTOFA[1]

[1]Department of Civil and Environmental Engineering and Institute of Transportation Studies, University of California—Berkeley, Berkeley, California, USA
[2]School of Architecture, Civil and Environmental Engineering, Urban Transport Systems Laboratory, École Polytechnique Fédérale de Lausanne (ÉPFL), Lausanne, Switzerland

The traditional methodology for estimating vehicle emissions based on vehicle miles traveled and average speed is not reliable because it does not consider the effects of congestion, control devices, and driving mode (cruise, acceleration, deceleration, and idle). We developed an analytical model to predict vehicle activity on signalized arterials with emphasis on oversaturated traffic conditions. The model depends only on loop detector data and signal settings as inputs and provides estimates of the time spent in each driving mode, which consequently leads to more accurate vehicle emission estimates. The application of the proposed model on a real-world arterial shows that it accurately estimates the time spent and consequently the emissions per driving mode. We also applied the model to evaluate the effectiveness of signal timing optimization in reducing vehicle emissions.

Keywords Driving Activity; Mathematical Models; Traffic Signal Timing Optimization; Vehicle Emissions

INTRODUCTION

Traditionally, the amount of air pollutant emissions from motor vehicles—hydrocarbons, carbon monoxide, and oxides of nitrogen—is estimated from emission factors based on trip and vehicle miles traveled (VMT) and aggregate measures of vehicle activity (e.g., average vehicle speed). Recent research has made it clear that a full understanding of the mobile source emissions burden requires a better representation of the driving modes that produce high emission levels, particularly accelerations (Barth et al., 2000). In light of these developments and the recent requirements for reducing air pollutant emissions worldwide, there is a need to predict vehicle activity by mode of operation, that is, time spent in cruise, acceleration, deceleration, and idle, to obtain improved emission estimates.

On arterial streets controlled by traffic signals, oversaturated conditions cause physical queues to exceed the available link length and departures from the upstream link are blocked, leading the system to restricted mobility and service inefficiency. This in turn causes stop-and-go traffic conditions with high emission levels. It is therefore critical to identify queue spillovers, predict their air quality impacts, and implement mitigation measures. This article presents the development and testing of an analytical model for estimating vehicle activity on signalized arterials with emphasis on oversaturated traffic conditions based on readily available surveillance data from loop detectors. The estimates of vehicle activity obtained by the model are further used along with existing emission factors per driving activity in order to estimate total emissions and evaluate the impact of different signal control strategies on reducing emissions.

Address correspondence to Alexander Skabardonis, Department of Civil and Environmental Engineering and Institute of Transportation Studies, University of California—Berkeley, Berkeley, CA 94720, USA. E-mail: skabardonis@ce.berkeley.edu

The article first briefly describes existing approaches on estimating modal emissions. Next, the formulation of an analytical model that estimates the time spent per driving mode is presented. The site used to test the performance of the analytical model and for the simulation tests is described next. Following, we present the results from the analytical model and the simulation tests and compare them. Next, emission estimates are provided and the impact that optimization of signal settings has on those estimates is investigated. The final section summarizes the study findings along with recommendations for future research.

BACKGROUND

Several studies have addressed the estimation of emissions from motor vehicles based on the time spent and the emission rate per unit time for each driving mode (cruise, acceleration, deceleration, and idling) along signalized arterials (El-Shawarby, Ahn, & Rakha, 2005; Frey, Rouphail, Unal, & Colyar, 2000; Rakha & Ding, 2003; Unal, Rouphail, & Frey, 2003). However, most of the studies just referenced focus on field measurements to quantify emission reductions due to the introduction of traffic management strategies, and not on analysis tools that can predict vehicle emissions based on the amount spent per driving mode.

Microscopic simulation models can readily provide the time spent per driving mode, because they simulate the movements and interactions of individual vehicles; the processing of the simulated vehicle trajectories provides detailed estimates of vehicle activity. Several studies have been conducted to analyze vehicle activity as a function of geometric, traffic, and control conditions (Skabardonis, 1997). However, undertaking microscopic simulations is expensive and time-consuming. Also, simulation results are not easily transferable, given the high number of parameters that need to be calibrated from one site to another.

We have developed an analytical model (Skabardonis & Geroliminis, 2005) to estimate the travel times on arterial streets based on data commonly provided by system loop detectors (flow and occupancy) in each signal cycle and the signal settings (cycle length, green times, and offsets) at each traffic signal. The model is based on the kinematic wave theory (Lighthill & Whitham, 1955), which explicitly considers the temporal and spatial formation of queues at the traffic signals and the signal coordination. The travel time is modeled as the sum of the free flow time and the delay at each traffic signal. The delay at the traffic signal is calculated as the sum of (a) the delay of a single vehicle approaching a signalized intersection without any interaction with other vehicles, (b) the delay because of the queues formed at the intersection, and (c) the oversaturation delay, the additional delay caused when the arrival rate is greater than the service rate at the signal.

The model is straightforward to implement and does not depend on site-specific parameters or short-term traffic flow predictions that make very difficult its transferability to other locations. Recently, the model was extended to explicitly address the issues of queue spillovers that frequently occur on congested arterials in urban areas (Geroliminis & Skabardonis, 2011; Skabardonis & Geroliminis, 2008). The identification of spillovers is based on the observation that the queue discharges at rates smaller than the capacity. The output of the model provides the average travel time in the corridor, the number of vehicles that stopped in the link under consideration, and the maximum length of the queue in that link in each signal cycle. Comparison of the model with empirical and simulated data from several arterial sites shows that they accurately replicate field conditions; the error in the estimated travel times is less than 5% in most cases (Geroliminis & Skabardonis, 2011). However, the existing model can only estimate average travel times and the existence of spillbacks. Therefore, it is not capable of determining how much of the total travel time is attributed to the accelerating, decelerating, cruising, or idling driving modes. Consequently, it cannot be used to estimate emissions or to evaluate traffic management strategies on emissions.

ANALYTICAL MODEL

This section presents the formulation of the analytical model to estimate the time spent per driving mode for a signal cycle based on the extension of the model for signalized arterials described earlier. Time spent cruising has been defined as the time traveled in constant speed and zero acceleration or deceleration; time spent decelerating or accelerating has been defined as any of the states in which the vehicle's deceleration or acceleration is nonzero. Finally, a vehicle is considered idling when its speed is less than 3 mph (5 kph).

First, we estimate the number of times a vehicle stopped during its trip. The average number of stops per vehicle that crossed an arterial link i during cycle C is:

$$\frac{n^i_{s,C}}{q^i_C} \tag{1}$$

where $n^i_{s,C}$ is the number of vehicles stopped in link i during cycle C and q^i_C is the number of vehicles that discharged from link i during cycle C (output).

We can also identify, using the approach in Geroliminis and Skabardonis (2011), the links that experienced spillbacks during cycle C, that is, queues from a downstream link that blocked the upstream departures for a fraction of the green phase. In this case, each delayed vehicle stops more than once, since a spillback can be considered as an intermediate short-duration red phase in the green phase of the upstream link. Thus, the average number of times that a vehicle stopped is

$$N_{s,C} = \sum_i \left(\frac{n^i_{s,C}}{q^i_C} + b^i_C \right) \tag{2}$$

where b^i_C is a binary variable with value equal to 1 if the queue length on link i during cycle C is greater than the 90%

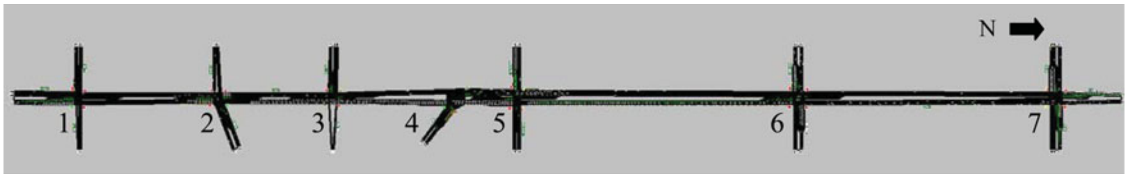

Figure 1 Lincoln Avenue (color figure available online).

of the link length and 0 otherwise. Note that in case a vehicle is delayed for multiple cycles because of spillbacks, the model will identify it as b_C^i equal to 1 for multiple consecutive cycles.

If we now assume that a vehicle that has come to a full stop reaches free-flow speed with constant acceleration rate (or comes to a stop from free-flow speed with constant deceleration rate), then the distance traveled in acceleration (deceleration) during one stop is

$$\frac{1}{2}\gamma_k t_k^2 = \frac{1}{2} v_f t_k \tag{3}$$

where $k = 1$ for acceleration and 2 for deceleration, γ_k is the acceleration/deceleration rate (mph/sec or kph/sec), v_f is the free-flow speed (mph or kph), and t_k is defined as

$$t_k = \frac{v_f}{\gamma_k}. \tag{4}$$

Since the average travel time, $\bar{t}_C$ is known for each signal cycle C, the following four equations provide the estimates for the time spent (in seconds) and the fraction of time spent per driving mode.

The time spent in acceleration (deceleration), $t_{acc}(t_{dec})$, mode in each cycle is equal to the average number of times a vehicle stopped multiplied by the time $t_1(t_2)$ needed to travel from speed zero to v_f (v_f to zero):

$$t_{acc} = N_{s,C} t_1 = \sum_i \left(\frac{n_{s,C}^i}{q_C^i} + b_C^i \right) t_1 \tag{5a}$$

$$t_{dec} = N_{s,C} t_2 = \sum_i \left(\frac{n_{s,C}^i}{q_C^i} + b_C^i \right) t_2 \tag{5b}$$

The cruising time, t_{cr}, is estimated as the distance traveled in free-flow speed, while the estimation of the remaining idling time is straightforward given the average travel time, $\bar{t}_C$:

$$t_{cr} = \frac{L - L_{acc} - L_{dec}}{v_f} = \frac{L}{v_f} - \sum_i \left(\frac{n_{s,C}^i}{q_C^i} + b_C^i \right) \left(\frac{t_1 + t_2}{2} \right) \tag{6}$$

$$t_{idle} = \bar{t}_C - t_{cr} - t_{dec} - t_{acc} \tag{7}$$

where $L = \sum L_i$, which is the total length of the corridor under consideration, L_{acc} is the corridor length traveled in acceleration, L_{dec} is the corridor length traveled in deceleration, and t_{idle} is the time spent idling.

TEST SITE

The selected test site is a 1.42-mile (2.3-km) stretch of a major urban arterial north of the Los Angeles International Airport, between Fiji Way and Venice Boulevard in the cities of Los Angeles and Santa Monica (Figure 1). The study section includes seven signalized intersections with link lengths varying from 450 ft (150 m) to 2,170 ft (660 m). There are three through lanes plus turning lanes at each intersection approach. The free-flow speed is 40 mph (64 kph). Traffic signals are all multiphase operating as coordinated under traffic responsive control as part of the Los Angeles Automated Traffic Surveillance and Control (ATSAC) signal system. System cycle lengths range from 100 sec early in the analysis period (6:00 to 6:30 a.m.) to a maximum of 150 sec during the periods of highest traffic volume (7:30 to 8:30 a.m.). System loop detectors are located on each lane approximately 300 ft (90 m) upstream of the intersection stopline on the arterial and on the major cross-street approaches. Detector data (flow and occupancy) are collected every 30 sec and stored in the ATSAC database.

A field study was undertaken to obtain a comprehensive database of operating conditions in the study area. First, basic data on intersection geometrics and spacing were obtained from field surveys. Free-flow speeds were obtained from the probe vehicle runs under light traffic conditions. Next, manual turning movement counts at each intersection and floating car studies were undertaken for the am peak period (6:00 to 10:00 a.m.). Floating car runs were performed at 7-min headways. The floating cars were instrumented with laptop computers and global positioning system (GPS) units that recorded vehicle location and speed on each second. Finally, the loop detector and signal timing data for the study period were obtained from the ATSAC database.

Traffic demands are high especially during the peak hour (7:30 to 8:30 a.m.). Traffic volumes are heavily directional with the higher through and turning volumes in the northbound direction. The average travel speeds on the test section are 25 mph (40 kph) during the off-peak times and drop to about 10 mph (16 kph) during the peak hour in the heavily traveled northbound direction. The average travel speeds are about 25 mph (40 kph) and remain fairly constant in the southbound direction throughout the analysis period.

SIMULATION EXPERIMENTS

We simulated the Lincoln Avenue test site with the CORSIM microscopic simulation model (FHWA, 2003) to obtain the time spent per driving mode and compare the results with the analytical model. The existing traffic conditions were simulated for 4 hours. Input data required for the simulation model as well as its calibration and validation with field data can be found in previous studies by the research team (Skabardonis & Geroliminis, 2005). The analysis of the results from the simulation experiments were focused on the northbound direction, which experiences the heaviest traffic during the 4-hour period of interest.

CORSIM has the option to store in a file the trajectories of each simulated vehicle as they travel through the network during the simulation run. The Vehicle Trajectory Analysis for Performance Evaluation (VTAPE) program (Courage, 2010) was used to read the trajectory file and calculate the time spent in each driving mode. The time spent is provided in vehicle-seconds and is tabulated by speed and acceleration categories; speeds vary from 0 to 55 mph (in 5 mph increments) and accelerations from –10 to 10 mph/sec (in 1-mph/sec increments).

Figure 2 shows two examples of the distribution of time spent at each speed–acceleration pair for uncongested and congested traffic conditions for the northbound direction of Lincoln Avenue. It is clear that when the arterial is congested, a high percentage of the travel time is spent at very low speeds and in idling. On the contrary, during uncongested conditions a higher percentage of travel time is spent in free-flow speeds. This indicates that the distribution of time spent can vary significantly for different traffic conditions, and so will the amount of pollutants emitted. Note that the results show percentage of time spent at each acceleration–speed state, but the overall total time spent is much bigger in the congested state and as a result higher emissions are expected for congested traffic states. Given that it is very tedious to estimate time spent in each acceleration–speed state, our analysis utilizes the analytical model of the previous section and average values for cruising speed, acceleration, and deceleration rates, to estimate time spent per driving mode. We will show that this simplification does not decrease the accuracy of our emissions estimation, given that emission factors exist for the total time spent in each mode (Frey, Rouphail, Unal, & Colyar, 2001).

Further simulation experiments were performed for different demand levels, which were defined as percentages of the peak hour vehicle demand (q_o) for the northbound direction of Lincoln Avenue. The results in Figure 3 show a significant increase in the proportion of time spent idling and decrease in the proportion of time spent cruising, but small changes in the percentages of travel time spent accelerating and decelerating as demand increases. However, since higher demand levels lead to longer travel times, the total time spent in acceleration and deceleration (in time units) is much higher for those levels of demand. The results presented in Figure 3 indicate that the level of demand affects the amount of time spent at each driving mode. This implies that time-dependent analysis is required to accurately estimate time spent in each of the driving modes and the consequent emissions. Furthermore, there is no one-to-one relationship between demand and travel times (or time spent per driving mode). This is because dynamics of traffic flow are not memoryless and history matters, especially in the case of

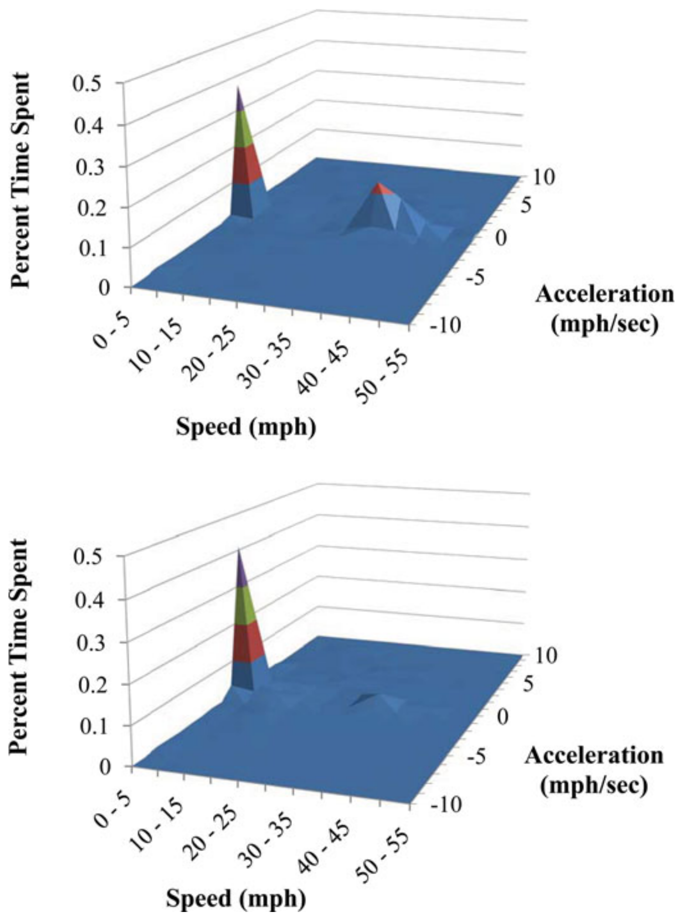

Figure 2 Sample output from the processing of CORSIM trajectory file for Lincoln Avenue (northbound, NB): (a) uncongested traffic conditions and (b) congested traffic conditions (color figure available online).

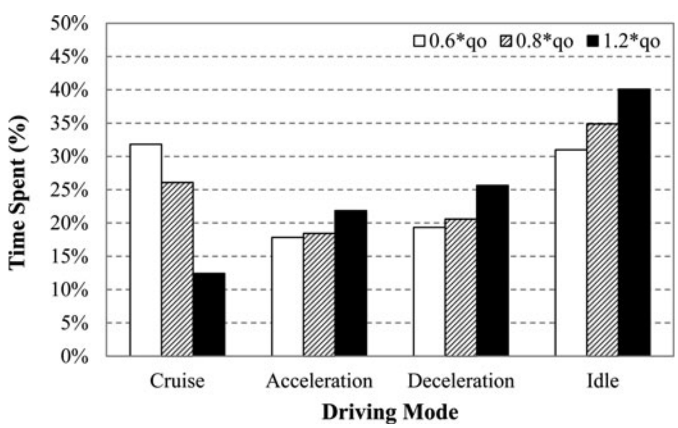

Figure 3 Predicted vehicle activity for different demand—Lincoln Avenue (NB).

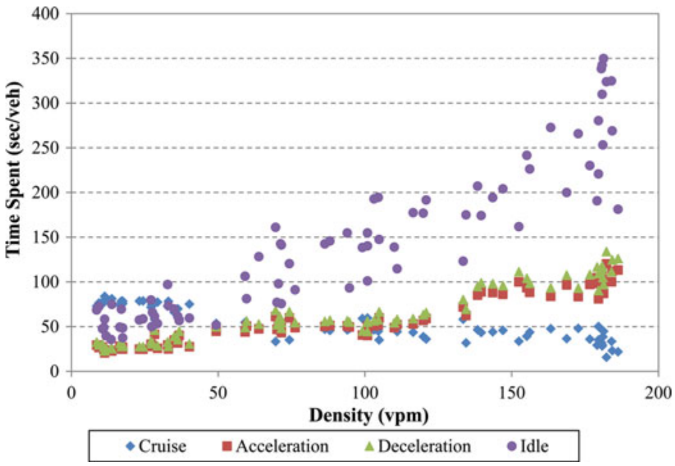

Figure 4 Predicted vehicle activity vs. density—Lincoln Avenue (NB) (color figure available online).

oversaturated conditions where residual queues form. In other words, traffic systems are dynamic and to estimate the state of the system at time t, the knowledge of the input flow (demand) is not sufficient, but boundary conditions are also needed, that is, the state of the system at a prior time $t - 1$. Thus, a traffic model that estimates the average travel time based on a specific demand–cost curve not only ignores variations in the demand, but more importantly this travel time will be different if the initial state of the system is uncongested, at near maximum flow conditions, or in the congested regime.

The time spent in each driving mode against the average density (vehicles/mile or vehicles/km) on the arterial is shown in Figure 4. The average density is the weighted average of the densities for all northbound arterial links throughout the simulation period. It can be seen that there is an increase in the average travel time as density increases, which is mainly due to the additional time spent in the idle mode. Also, the cruising time decreases with density as vehicles spend more time accelerating and decelerating, given the increase in the number of stops.

Figure 4 also shows that there is a well-defined relationship with low scatter between all four driving modes and the average density. The results from additional simulation runs with different demand profiles and graphs of "time spent per mode versus density" exhibit the same shape with low scatter. This means that by calculating the average density and a travel time in a corridor per time of day (e.g., using loop detector or mobile sensor data), one can estimate the distribution of time spent in the different modes and obtain accurate estimates of vehicle emissions. The robustness of this curve is in agreement with recent empirical observations that showed the existence of a well-defined (low-scatter) macroscopic fundamental diagram (MFD) between network average density and space-mean flow (or speed) for regions of a city with (roughly) homogeneous distribution of congestion (Geroliminis & Daganzo, 2008; Geroliminis & Skabardonis, 2011; Geroliminis & Sun, 2011).

ANALYTICAL MODEL APPLICATION

The proposed analytical model was applied to the northbound direction of Lincoln Avenue test site (which is the most congested) in order to estimate the time spent in each driving mode and the results were compared with the output from the simulation. Values for the variables $n^i_{s,t}$, t_c, and b^i_t for each cycle have been estimated with the methodologies developed in Skabardonis and Geroliminis (2005, 2008) and Geroliminis and Skabardonis (2011).

Figure 5 shows the ratio of queue over link length for every signal cycle (an average signal cycle of 150 sec was used for the output) for all links in the northbound direction of the Lincoln Avenue test site (link 1–2 is the most upstream one). It is noticeable that spillbacks propagate upstream from link 4–5 to link 1–2. Queues fill all four links between times 6,600 sec and 9,400 sec, from downstream to upstream. This causes a significant increase in the number of stops, total delays, and emissions. In order to use the analytical model, we have assumed a free flow speed of 40 mph, acceleration rate equal to 4 mph/sec, and deceleration rate equal to 10 mph/sec. Microsimulation considers heterogeneous drivers and different accelerations for different speeds. The average values of the simulation are close to the ones used in the model.

Figure 6 compares the estimated time spent per driving mode from the analytical model versus the simulated average time spent per driving mode. It is clear that the proposed model accurately estimates the time spent per driving mode for different levels of congestion, from uncongested states to highly congested ones with long queues and spillbacks. This is promising in the sense that the proposed analytical model can predict time spent on different driving modes at least as accurately as the simulation results do. The main advantage is that the application model is simple to implement and it only requires readily

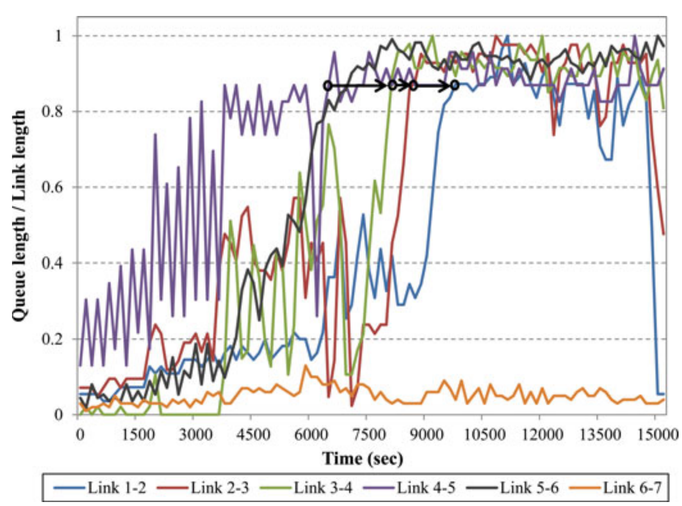

Figure 5 Queue over link length ratio—Lincoln Avenue (NB) (color figure available online).

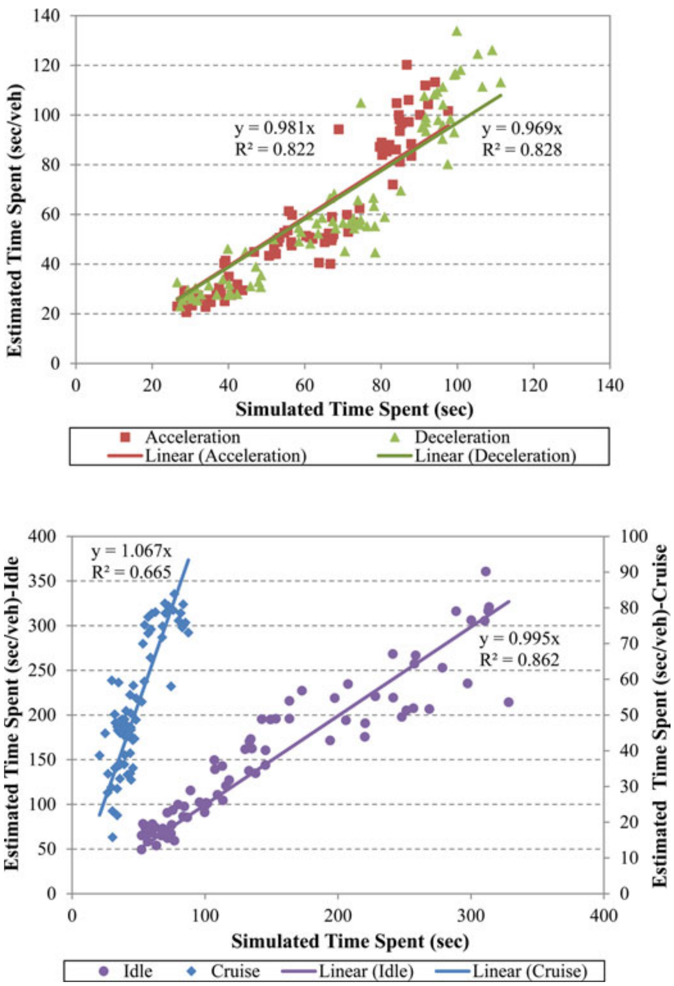

Figure 6 Estimated vs. simulated time spent per cycle per driving mode (sec/veh): (a) acceleration and deceleration modes and (b) cruise (right *y*-axis) and idle (left *y*-axis) modes (color figure available online).

Table 1 Emission rates per driving mode (Frey et al., 2001).

	Cruise	Acceleration	Deceleration	Idle
CO (mg/sec)	10.00	22.50	7.50	1.50
HC (mg/sec)	0.60	1.10	0.40	0.25
NO (mg/sec)	1.25	1.50	0.60	0.10

available information from loop detectors as input. In addition, using this model we are able to obtain more accurate emission estimates and evaluate the performance of control strategies without the need for data-intensive simulations.

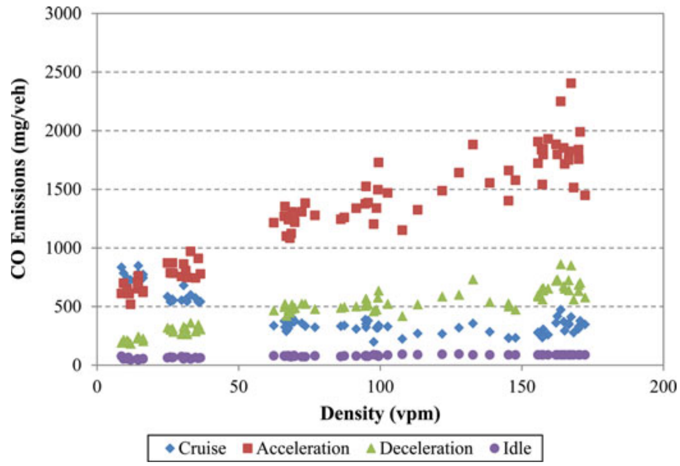

Figure 7 CO emissions vs. density for Lincoln Avenue (NB)—initial signal settings (color figure available online).

EMISSIONS ESTIMATION

Using the travel times from the analytical model, and a modal emissions model, the emissions for CO, HC, and NO can be estimated. The emissions estimation model used in this study has been developed by Frey et al. (2001), who derived emission rates for CO, HC, and NO per driving mode (cruise, acceleration, deceleration, and idle) through repeated on-board measurements for a gasoline-powered vehicle (shown in Table 1).

Table 2 shows the estimated emissions and corresponding percentage of the total emissions by driving mode for all vehicles traveling through the northbound direction of Lincoln Avenue, based on the estimated time spent in each mode from the analytical model. The results indicate that CO emissions are much higher than the other two pollutant emissions. Also, accelerations are causing the highest emissions, especially CO. Estimation of the emissions using the CORSIM simulated travel times spent at each mode reveals similar results.

Figure 7 represents the estimated average CO emissions (mg/vehicle) per driving mode for vehicles traveling through the northbound direction of Lincoln Avenue as a function of the network average density. It is clearly shown that acceleration is responsible for emitting higher quantities of CO compared to the other modes for a wide range of densities. The latter implies that smoothing traffic operations at signalized arterials, for example, by improving progression through signal coordination and signal timing optimization, can significantly reduce emission levels. This is illustrated in the next section.

Table 2 Emission estimates (percentages) for Lincoln Avenue (NB).

	Cruise	Acceleration	Deceleration	Idle	Total
CO (g)	4,430 (26.48%)	8,115 (48.51%)	3,057 (18.28%)	1,125 (6.73%)	16,727
HC (g)	264 (14.52%)	804 (44.22%)	320 (17.60%)	430 (23.65%)	1,818
NO (g)	550 (23.93%)	1,096 (47.69%)	480 (20.89%)	172 (7.48%)	2,298

OPTIMIZATION OF SIGNAL SETTINGS

A number of studies have shown improvements on emissions because of signal control improvements. In order to investigate the potential benefits of improved signal control at the selected site, we optimized the signal settings (cycle length, splits, and offsets). Signal timing optimization is a highly cost-effective operational strategy. We used TRANSYT-7F (McTrans Center, 2008), which is the most widely used software package, and its latest version can model queue spillbacks and multiple time periods. TRANSYT-7F optimizes the cycle length, splits, and offsets by minimizing delay and stops:

$$J = \sum_{i=1}^{n} \left\{ \left(w_{d_i} d_i + K\, w_{S_i} S_i \right) + QP \right\} \tag{8}$$

where J is the objective function, d_i the delay on link i (of n links), K the stop penalty factor (the importance of stops relative to delay), S_i the stops on link i per second, w_{d_i} and w_{S_i} the weighting factors for delay and stops for link i, and QP the queue penalty.

We optimized the signal settings for nine 15-min time periods, a total of 2 hours and 15 min in the peak morning period. The following optimization strategies were tested:

1. Minimize system delay: This strategy optimizes the signal settings by minimizing the system delay, without any consideration to the number of stops. This strategy seems appropriate for congested conditions on most network links and its goal is equal treatment for through arterial traffic and cross streets.
2. Minimize system delay and stops with weighting factors for northbound direction: This strategy optimizes the signal settings by minimizing system delay and stops while assigning a weight to the delays and stops for the northbound through traffic arterial links. The value of 500 was used for both delay (w_{d_i}) and stops (w_{S_i}) weighting factors, which means that the delays and stops for the northbound direction are five times more "important" than the delays and stops for the rest of the system.
3. Minimize system delay and stops with queue penalty: This strategy optimizes the signal settings by minimizing system delay and stops while assigning a penalty, QP, for excessive queues as shown in Eq. 8.

The outputs from the optimization strategies just described are compared to the baseline signal settings scenario for the 2.25 hours tested that includes the peak traffic of the 4.25 hours available. The baseline scenario represents the initial signal settings of the test site. We compared the results for the northbound arterial traffic and the total system.

A comparison of the time spent per driving mode for the different optimization strategies reveals that minimization of delays and stops with either weighting the northbound direction or with queue penalty (strategies 2 and 3) are the most beneficial for the northbound direction. As Figure 8 shows, these two strategies reduce substantially the time spent idling and in acceleration/deceleration while increasing the time spent cruising. Looking at the overall system performance, however, we observe that optimization strategies 2 and 3 might not be as beneficial for the whole system. As shown in Figure 9, the total system delay is higher for strategies 2 and 3 compared to just minimizing delay (strategy 1). This is expected if we consider that strategies 2 and 3 favor the northbound direction, which is the heaviest traffic direction. However, the increase in the total system delay is about 6%, while the benefit to the northbound heavily traveled direction is about 34% in total time spent.

A comparison of the time spent per driving mode for the baseline signal settings with the optimized signal settings under strategy 3 (delay and stop minimization with queue penalty) indicates that there is a significant reduction in the time spent idling as well as accelerating and decelerating (Figure 10). If one takes into account that the optimized signal settings also result in an average reduction in total travel time of 34% for the northbound direction, the benefit from minimizing

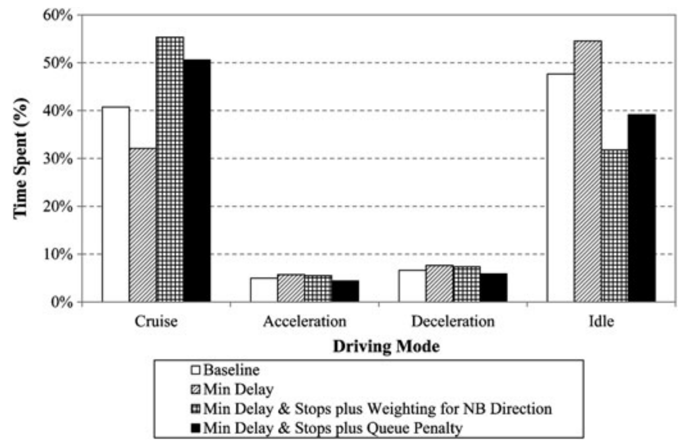

Figure 8 Time spent per driving mode for Lincoln Avenue (NB).

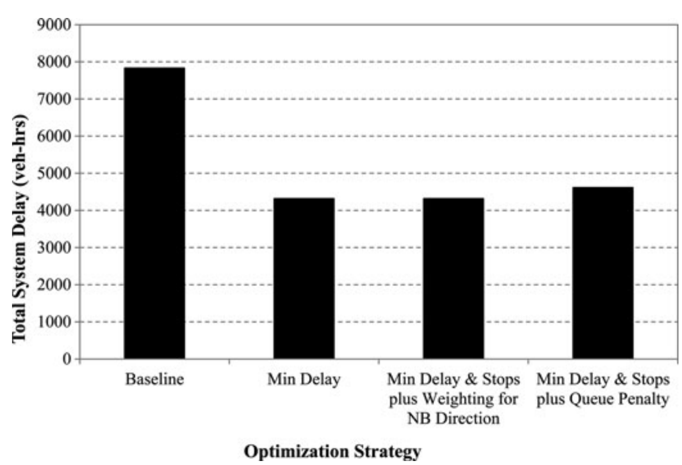

Figure 9 Total system delay.

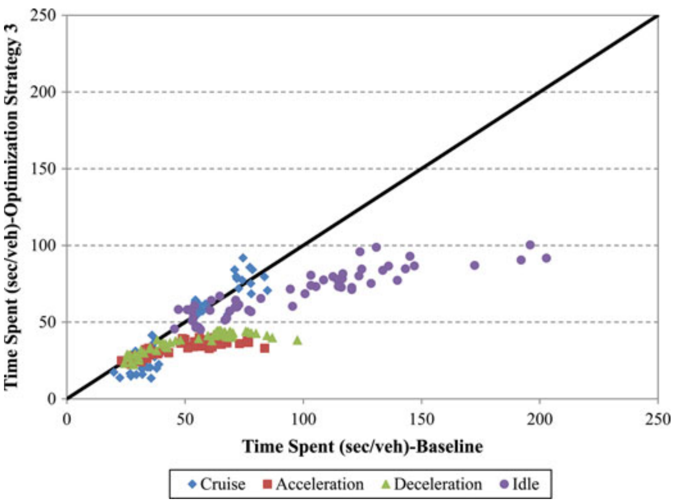

Figure 10 Time spent per driving mode—baseline vs. minimum delay and stops with queue penalty signal settings (color figure available online).

delay and stops with queue penalty becomes substantial. Note that almost all points in Figure 10 are below the 45-degree line and no vehicles experience idle time more than 100 sec (many states in the 100–200 sec range in the baseline scenario). This also results in reductions of CO emissions per vehicle, as shown in Figure 11 for the northbound direction of Lincoln Avenue.

Minimization of delays and stops while incorporating favorable treatment for the heaviest direction, either through weighting factors or through queue spillover penalties, substantially reduces CO emissions as well as other air pollutants compared to more common optimization strategies of minimizing delays for the entire system. The reason for this is that both signal optimization strategies favor the heaviest direction, which results in fewer stops and leads to smoother traffic operations and less time spent accelerating, decelerating, or idling.

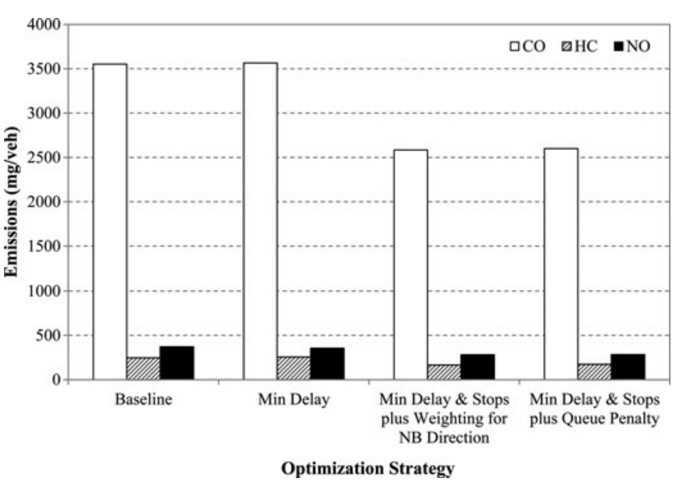

Figure 11 Emissions for Lincoln Avenue (NB).

CONCLUSIONS

In this article, an analytical model was developed to estimate the time spent in each driving mode at signalized arterials. The model is based on data commonly provided by system loop detectors (flow and occupancy) and the signal settings at each intersection (cycle length, splits, and offsets). The results from the model application and comparisons with simulated data show that it accurately estimates the time spent per driving mode for a wide range of traffic operating conditions. Such estimates can be used along with modal emission factors to obtain accurate vehicle emission estimates.

The proposed model can be applied in the real world to estimate emissions and evaluate the performance of emission reduction strategies without the need for time-consuming simulations. Ongoing and future research involves further testing and refinement of the proposed analytical model, including relaxing the assumption of constant acceleration (deceleration) rates, as well as sensitivity analysis for different driving behaviors. In addition, future research will incorporate intervehicle variability in emission rates and include development of improved and robust signal control strategies for emissions reduction.

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