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TECHNICAL PAPER

Effects of advanced traffic signal status warning systems on vehicle emission reductions at signalized intersections

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ABSTRACT

Signalized intersections have been identified as vehicle emission hotspots, where drivers decelerate, idle, and accelerate their vehicles in response to signal changes. Advanced traffic signal status warning systems (ATSSWSs) can be applied to reduce traffic emissions at intersections by mitigating unnecessary braking and acceleration. In this study, two types of ATSSWSs, variable message sign (VMS) based and vehicle-to-infrastructure (V2I) based, were designed, and their environmental effectiveness was evaluated through driving simulator-based experiments. Three scenarios were designed and tested: (1) baseline without an ATSSWS, (2) with the VMS-based ATSSWS, and (3) with the V2I-based ATSSWS. The Motor Vehicle Emission Simulator model was used to evaluate and compare the environmental effectiveness of these two types of ATSSWSs. The results indicate that the proposed ATSSWSs can reduce traffic emissions at signalized intersections. In particular, the V2I-based ATSSWS can substantially reduce CO_2, NOx, CO, and HC emissions. The results will help transportation practitioners with implementing advanced driver information systems and decision making on emission reduction policies.

Implications: Signalized intersection has been identified as one of hottest spots for vehicle emissions where signal control causes vehicles to frequently decelerate, idle, and accelerate. Advanced Traffic Signal Status Warning Systems (ATSSWS) can be applied to reduce traffic emission at intersections by decreasing vehicles' unnecessary brakes and accelerations. The results of this study will assist transportation practitioners in implementing advanced driver information systems and making decisions on emission reduction policies.

PAPER HISTORY
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Introduction

Automobiles are the major mode of surface transportation and are mainly powered by fuels. The gasoline consumption of car and light trucks accounted for 59% of U. S. transportation energy use (Davis, Williams, and Boundy 2016). This large consumption generates a large amount of emissions, which is the main contributor to climate change and air pollution. At signalized intersections, drivers often accelerate and decelerate their vehicles unnecessarily in response to signal changes, thus increasing fuel consumption and emissions. Therefore, traffic warning systems designed to limit hard braking and unnecessary acceleration, deceleration, and idling are potentially effective solutions for reducing vehicle emissions at signalized intersections.

Two types of traffic warning systems have been commonly used for warning or guiding drivers at signalized intersections. (1) Conventional static traffic signs warn drivers about the next signalized intersection and its speed limit. They cost relatively little with less expensive facilities but cannot provide real-time traffic information. (2) A variable message sign (VMS) warns and guides drivers by providing traffic-related information (Chatterjee and Mcdonald 2004), such as congestion and incident notices and suggestions on slowing down at intersections (Peeta and Ramos 2006). However, neither of these systems provides real-time signal status information in advance. In addition, the amount of information provided by the VMS is often too large to be understood by drivers within a short time. Vehicle-to-infrastructure (V2I)-based driver warning systems can provide customized warnings, such as recommended speed and incident information, to individual drivers through wireless communication (Qi, Chen, and Yang et al. 2009; Yang, Rakha, and Ala 2016). One disadvantage of such systems is the lack of traffic signal status information, which is one of the crucial factors influencing drivers' decision making at signalized

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intersections. To overcome this disadvantage by assisting drivers in proceeding through signalized intersections with less unnecessary acceleration, deceleration, and idling, two types of advanced traffic signal status warning systems (ATSSWSs) were designed and tested in this study: VMS-based and V2I-based. The effectiveness of the proposed ATSSWSs (which can provide real-time information such as traffic signal status and speed recommendations) in reducing vehicle emissions at signalized intersections was assessed through driving simulator-based experiments.

For the driving simulator experiments, three scenarios were designed: baseline without an ATSSWS, with the VMS-based ATSSWS, and with the V2I-based ATSSWS. The driving profile data obtained from the simulator experiments were input to the Motor Vehicle Emission Simulator (MOVES) model to estimate the vehicle emissions in the three test scenarios. Different measurements of effectiveness (MOEs) were designed to compare drivers' performance and vehicle emission levels. The results of this study will assist transportation practitioners in implementing advanced driver information systems and making decisions on emission reduction policies.

The main contributions of this paper include (1) drivers' reactions to two types of traffic warning systems are tested by being given the real-time signal status information under different traffic signal conditions; (2) the driving simulator-based experiments are designed and performed for the data collection in order to simulate the response of drivers to the provided information of traffic signal status in the real world; and (3) the characteristics of driving mode distributions, as well as the relationship between vehicle operations and emissions at intersections with ATSSWSs, are explored.

Literature review

A number of studies have investigated the effectiveness of different driver warning systems, especially for the V2I-based and VMS-based systems. Also, more investigations on the emission impacts of driver warning systems have been conducted.

Driver warning systems

Li et al. proposed a V2I-based onboard warning system that recommends speeds to drivers. This system efficiently reduced the average vehicle delay and average number of stops at intersections by 30% and 60%, respectively (Li, Yan, and Wu et al. 2012). They analyzed the operational effects of the V2I-based warning system but not its effects on vehicle emission reduction. Matsumoto and Tsurudome tested a traffic information provision system, which provides speed guidance and operational suggestions (e.g., to release the accelerator pedal), by using a three-dimensional driving simulator. The recommended speed was calculated according to the distance to the signal and the current vehicle speed, and the indication to release an accelerator pedal was provided (Matsumoto and Tsurudome 2014). In addition, several studies have investigated dynamic eco-driving systems, which recommend speeds for facilitating smooth driving (Kamal et al. 2010; Kamalanathsharma, Rakha, and Badillo 2014). However, most of these V2I-based warning systems do not convey traffic signal status information to drivers.

In terms of VMS-based driver warning systems, Chatterjee and McDonald investigated four types of information provided by VMSs: incident messages, route guidance, traffic status on major routes, and travel time information. Using VMS to apprise drivers of traffic conditions can shorten network travel times and reduce the environmental impacts of vehicles (Chatterjee and Mcdonald 2004). Li et al. proposed an advanced driving warning system to help drivers limit hard braking at intersections. In this system, if a vehicle cannot proceed through an intersection before the signal turns red, the driver is alerted to prepare for stopping (Li, Boriboonsomsin, and Wu et al. 2009).

Emission impacts of driver warning systems

Limanond et al. reported that the availability of signal status information for drivers approaching a signalized intersection can improve intersection safety and operation and reduce vehicle emissions (Limanond, Prabjabok, and Tippayawong 2010). Bhavsar et al. investigated the utility of plug-in hybrid electric vehicles with V2I-based onboard warning system in terms of energy consumption reduction. The real data proved that receiving signal timing and headway data can reduce energy consumption by 31% to 35% (Bhavsar et al. 2014). Englund et al. investigated the highly utilized intersection and proposed a cooperative V2I application based on cooperative speed harmonization, which has a wave-based control mechanism. Simulations showed that the introduction of the cooperative speed harmonization application contributes to the overall traffic efficiency, such as carbon dioxide and speed for both the cooperative and non-cooperative vehicles (Englund, Chen, and Voronov 2014). Wu et al. proposed both roadside and in-vehicle driving warning systems for conveying intersection traffic signal status. They assessed the benefits of their proposed driving warning systems in terms of energy consumption and vehicle emissions by using the microscopic traffic simulation model PARAMICS, and reported that both roadside and in-vehicle warning systems reduced CO_2 emissions by up to 40%. In particular, in-vehicle warning systems reduced CO_2 emissions to a higher extent in most cases (Wu et al. 2010). Jin et al. analyzed the driving trajectories of vehicle crossing the intersections in different conditions of traffic signal status. A scenario was established with designed eco-driving strategies and simulated using emission model based on the vehicle specific power, and the results showed that the proposed optimized algorithms of eco-driving trajectories are able to reduce CO_2, NO_2, CO, and hydrocarbons (HC) by 30.1%, 23.6%, 24.9%, and 21.5% (Jin et al. 2015). Recently, Almannaa et al. designed a speed recommendation algorithm used to compute in real time fuel-efficient speeds that are promptly communicated via an audio signal to the driver to follow. A controlled-field experiment was conducted to evaluate the efficiency of reduction of vehicle fuel consumption at signalized intersections (Almannaa et al. 2017). Chen et al. developed a dynamic eco-driving speed guidance strategy (DESGS) using real-time signal timing and vehicle positioning information in a connected vehicle (CV) environment. The experimental results showed that compared to vehicles without speed guidance, those with DESGS had a significantly reduced number of stops and approximately 25% lower fuel consumption and CO_2 emissions (Chen et al. 2018)

In summary, most of these studies are limited to the effects of such systems on facilitating efficient driving or reducing total vehicle emissions at intersections. Thus, it is necessary to perform an in-depth analysis on the characteristics of driving mode distributions at intersections with driver warning systems. Under such a circumstance, the relationship between vehicle operations and emissions also needs to be further studied. This paper mainly addresses the two topics and provides some research conclusions.

Methodology

Figure 1 presents the framework of the study procedure: (1) conduct driving simulator test, (2) collect and process data, and (3) analyze data.

First, a driving simulator test was designed and conducted to investigate the impacts of the proposed ATSSWSs on the driving behaviors. Based on the testing results, the MOVES model was used to identify and evaluate the effects of the proposed ATSSWSs on emissions at signalized intersections. The final step was data analysis, in which the emission and driving performance data were analyzed from various aspects.

Scenario design

Driving simulator-based experiments were conducted to assess the environmental impacts of the two traffic signal status warning systems. For this purpose, three scenarios were designed: (1) baseline scenario, (2) scenario with VMS-based ATSSWS, and (3) scenario with V2I-based ATSSWS.

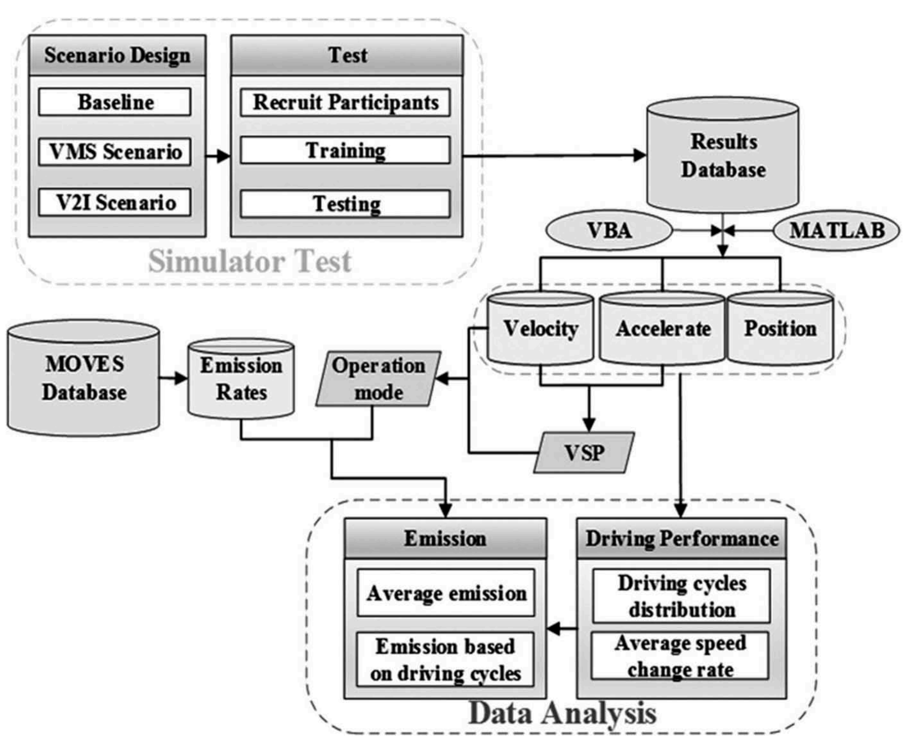

Figure 1. Framework of study procedure.

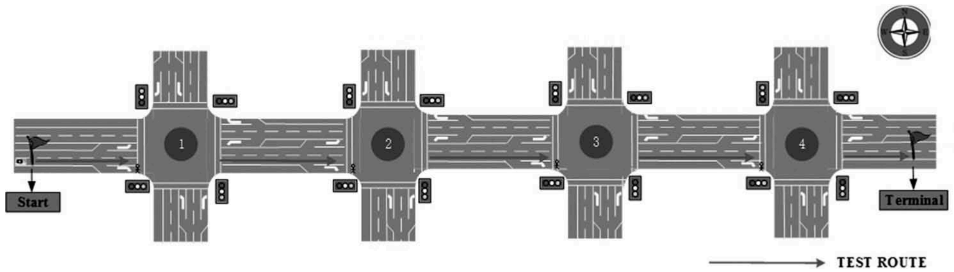

Figure 2. Design of driving experiments.

The same traffic conditions, roadway geometries, and traffic signal control characteristics were used in the three scenarios to ensure an accurate comparison. Figure 2 depicts the test route, a four-lane roadway in a suburban area with a 45-mph speed limit, and its start and terminal points. The intersections were about 800 m apart. Note that the road grade was assumed to be zero since it is too small to be considered, especially at intersections. All participants were asked to navigate through these four signalized intersections, and they arrived at these intersections with different status of traffic signal timing as follows:

- Intersection 1: at the beginning green signal interval (about 15 sec of green time left) when the vehicle arrived at a location 250 m in advance of the intersection.
- Intersection 2: at the end of red signal interval (about 3 sec of red time left) when the vehicle arrived at a location 250 m in advance of the intersection.
- Intersection 3: at the transition interval (about 3 sec of yellow time left) when the vehicle arrived at a location 250 m in advance of the intersection.
- Intersection 4: at the end of green signal interval (about 3 sec of green time left) when the vehicle arrived at a location 250 m in advance of the intersection.

These distinct traffic signal status designs enabled testing the drivers' reactions under different traffic signal conditions and made the driving experiments more realistic, because the traffic signal timing status is generally unrecognized to drivers in the real world. To compare the effectiveness of the two ATSSWSs under the same provided information of traffic signal status, the signal timing at intersections is fixed for each participant. The simulation experiments focused on the vehicle driven by the participant. To ensure that the vehicle was not disturbed by other vehicles, roadway traffic with low saturation was assumed in the simulation. Accordingly, there is enough space between the vehicles on the test road.

Baseline (scenario 1)

Figure 3a presents the baseline scenario. On the approach to the intersection, no traffic warnings are provided to the drivers, except for roadside static speed limit signs. Moreover, no onboard warning systems are used in the vehicles.

With VMS-based ATSSWS (scenario 2)

Figure 3b presents the scenario with the VMS-based ATSSWS. According to the guidelines for advance placement of VMS board provided by the MUTCD (Manual on Uniform Traffic Control Devices), as well as the speed limit in the test, the VMS board is set on the roadside 50 m away from the intersections (U.S. DOT 2012). The visible distance of the VMS board for the driver in the experiment is 200 m. Accordingly, the driver can see the VMS board clearly 250 m from the intersection. The VMS displays a number indicating the remaining time (in seconds) of the current signal status, which is counted down until 1 sec, and the color of the number (red, yellow, or green) denotes the current traffic signal status. In this study, a four-phase traffic signal timing plan was applied at all of the intersections. The signal phase sequence is the "lead–lead" sequence, which lets the two opposing left-turn phases start at the same time. The VMS countdown is only for the through direction. Thus, the green color countdown indication begins right after the left-turn phase, and it lasts until the end of the green through phase. It was followed by a 3-sec transition phase with yellow color countdown indication. After that, the red color countdown indication started. Note that each signal timing is fixed for each participant as long as he or she can see what the VMS indicates. To avoid the biases caused by the order effect in the driving experiment, VMS showed the remaining time and the status of the current signal lights as each vehicle reached 250 m upstream of the

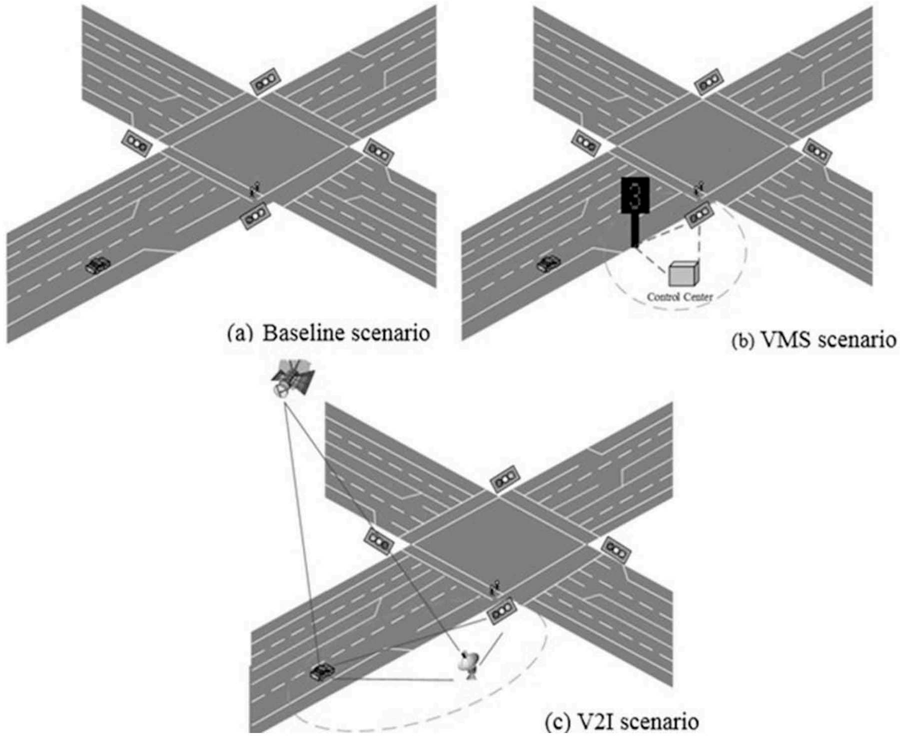

Figure 3. Schematics of experimental scenarios: (a) baseline scenario, (b) VMS scenario, and (c) V2I scenario.

intersections. Thus, drivers were able to make their stop-or-go decisions based on this information. For example, if a driver sees a red light when approaching an intersection and a red 3 on the VMS (indicating that the red light changes in 3 sec), the driver need not brake to stop the vehicle completely because the driver is aware that the signal will turn green shortly and that the vehicle can pass through the intersection without stopping.

With V2I-based ATSSWS (scenario 3)

Figure 3 (c) presents the scenario with the V2I-based ATSSWS. In this scenario, the vehicle is equipped with an onboard audio warning system that informs the driver of the time (in seconds) remaining before the current signal status changes, and provides acceleration recommendations (e.g., "slow down" and "keep a certain speed") to ensure that the vehicle can proceed through the intersection smoothly and safely. The audio warnings are provided when the vehicle is 250 m upstream of the intersection.

Different audio warnings are provided according to the vehicle's speed and location, traffic signal status, and presence of pedestrians on the intersection crosswalk. Shown next is the detailed algorithms for this V2I-based ATSSWS (Wu et al. 2010).

Estimate the travel time to the intersection

As discussed in a previous study (Wu et al. 2010), it is assumed that vehicles are traveling approximately at the current speed with uncertainty ω, which is caused by a mild acceleration or deceleration. The fit for the distribution of ω is a normal distribution with zero mean and standard deviation of σ. Hence, the travel time to intersection can be estimated in eq 1,

$$t(t) = \frac{d(t)}{v(t) + \omega} \tag{1}$$

where $t(t)$ is the travel time to the intersection in unit of seconds; $d(t)$ is the distance to the intersection in units of meters; $v(t)$ is the current speed (m/sec); and ω is the normally distributed uncertainty factor on speed.

Estimate the probability of passing through the intersection

The probability of a vehicle being able to pass through the intersection before the signal turns to red is given by eq 2 (Wu et al. 2010),

$$P(t) = P[0 \leq t(t) \leq TTR(t)] \tag{2}$$

where $P(t)$ is the probability of a vehicle being able to pass through the intersection before the signal turns to red, and $TTR(t)$ is the time to red of the same intersection.

Determine the audio warnings

A threshold value (α) is set to determine the audio warnings. When $P(t)$ is lower than the threshold α, "slow down" will be provided to the driver. When $P(t)$ is higher than the threshold α, V2I-based ATSSWS will advise the driver to keep a certain speed, which will be calculated according to the distance to the intersection and the time to red of the same intersection.

The threshold α is selected to be high enough to reduce the number of false warnings. Moreover, the threshold can be designed considering safety (Wu et al. 2010) (presence of pedestrians on the intersection crosswalk), which is assumed to be 0.5.

Experimental procedure

Participant recruitment

Fifty drivers were initially recruited according to the demographic information in Houston, TX (U.S. Census Bureau 2012). Female and male participants with different levels of driving experience attended the driving simulator test. Their professions include student, teacher, worker, and so on. Table 1 presents the detailed information for the participants.

Practice scenario

The practice session was primarily designed to acquaint the participants with driving in the simulator. Each participant had to attend this training session. They were instructed via a course, which took an hour in total. During the practice session, the participants were advised to obey the acceleration recommendation as far as possible. When the participants had become familiar with the driving environment, the meaning of information provided by VMS, and the onboard audio warning system, the test was conducted.

This study was conducted using the fully integrated, high-performance, high-fidelity driving simulator DriveSafety DS-600c at Texas Southern University. The simulator provides multichannel audio and visual systems; 180°, 240°, 300°, and 360° wrap-around display options; and a full-width automobile cab, which includes a windshield, driver and passenger seats, center console and dashboard, complete instrumentation, control-loaded steering, braking and acceleration pedals, mini-LCD rearview mirrors, and real-time motion simulation through its Q-Motion platform (Qi, Chen, and Yang et al. 2009). The driving simulator effectively approximates real-world driving, as shown in Figure 4. Similar to a real car, drivers can easily control the steering and acceleration and brake pedals of the simulator. The system collects second-by-second driving performance data for parameters such as speed, time, and acceleration.

Table 1. Driver information for the experiments.

Category	Level	Driver analysis	
		Number of drivers	Percent of total
Gender	Male	29	58%
	Female	21	42%
Age (years)	Under 25	15	30%
	25 to 35	23	46%
	36 to 55	7	14%
	Over 55	5	10%
Driving years	Less than1	10	20%
	1 to 3	15	30%
	More than 3	25	50%

Test scenario

After the practice scenarios, the participants should attend the test session. In order to reduce unnecessary influencing factors, the meteorological data in test session are fixed. During the test session, the test scenarios and two driving warning systems were introduced to enable the participants to respond appropriately to the warning messages received during the test. Subsequently, the participants drove through the three designed scenarios. All participants were asked to drive through all three scenarios and the sequence of the three scenarios is determined randomly to ensure unbiased testing results. In each scenario, all participants needed to navigate through the four illustrated signalized intersections. The duration of each scenario was about 3 or 4 min. When participates finished the three designed scenarios, the data collected would be saved in the specific files.

Data collection and process

Quantitative data were collected from the driving experiment, and were used to calculate the MOEs of the two ATSSWSs. Note that the countdown timer has also negative effect in driving behaviour, such as early start just before green phase and accelerating just before red phase, which happened as approximately 6% of the all behaviors during the test. The negative behavior easily leads to the additional acceleration and even unsafe maneuvers. In this case, the effect of the ATTSSWS on smoothing speed, reducing emissions, and ensuring safety may be weakened. Accordingly, the integration between the ATTSSWS and vehicle powertrain control systems need to be explored to prevent such negative behavior via the automatic control of equipped vehicles. To evaluate the driving performance and emissions under the different scenarios, the following MOEs of ATSSWS were obtained from the simulator data.

Figure 4. Practice session in a simulated suburban area.

Acceleration distribution

The acceleration distribution is calculated according to the second-by-second vehicle speed profiles obtained from the driving simulator experiments, as shown ineq 3. Drivers often make stop-or-go decisions when proceeding through a signalized intersection. Without traffic signal status warnings, unnecessary acceleration, deceleration, and idling may occur when responding to traffic signal changes. These problems can be avoided or mitigated by using the proposed ATSSWSs. Therefore, the acceleration distribution is an appropriate measure for assessing the effectiveness of the proposed ATSSWSs:

$$a = v_{t+1} - v_t \tag{3}$$

where a is the speed change rate (i.e., accelerate/decelerate; m/sec^2), and v_t and v_{t+1} are the velocities of the ith and $(i + 1)$th seconds (m/sec), respectively.

Driving mode distribution

There are four types of driving modes: acceleration (acceleration > 0), deceleration (acceleration < 0), cruise (velocity > 0 and acceleration = 0), and idling (velocity = 0) (Zhang et al. 2009). Using the second-by-second vehicle speed profiles obtained from the driving simulator experiments enables deriving the type of driving modes, which have different vehicle emission rates.

Total amount of vehicle emissions per test

The second-by-second vehicle speed profiles obtained from the simulator experiments were input to MOVES for estimating the total amount of vehicle emissions generated during each driving test. MOVES is a new-generation emission measure model, developed by the U.S. Environmental Protection Agency. It uses vehicle specific power (VSP) to calculate the emission factors of vehicles. VSP considers the change of the motor vehicle kinetic energy, potential energy, and the work of overcoming the air resistance. It is more relative to the fuel consumption and emissions, rather than velocity and acceleration. General speaking, MOVES calculates the emission factors in micro-level with higher accuracy than other models. The calculation procedure is as follows:

Step 1. Determine vehicle operation mode. In MOVES, the classification of the operation mode identification (OpMode ID, or OMID) is defined by using the binning standard of a vehicle specific power (VSP), acceleration rate (a), and speed (v). VSP can be calculated using eq 4 and is estimated using the second-by-second speed profile by using the parameters for a typical light-duty vehicle (U.S. EPA 2010; Wu, Song, and Yu 2014):

$$VSP_t = \frac{Av_t + Bv_t^2 + Cv_t^3}{m} + v_t(a_t + g\sin\theta) \tag{4}$$

where VSP is the vehicle specific power (m^2/s^3); v_t are the vehicle speeds at time t (m/sec); a_t is the acceleration (m/sec^2); g is the acceleration due to gravity, which is 9.8 m/sec^2; sinθ is the road grade, which is assumed to be 0; A, B, and C are road load coefficients, representing rolling resistance, rotational resistance, and aerodynamic drag, in units of kW sec/m, kW sec^2/m^2 and kW sec^3/m^3, respectively; and m is the vehicle weight (metric tons). For LDVs, the recommended values of A, B, C, and m are 0.156461, 0.0020002, 0.000493, and 1.4788, respectively.

Step 2. Obtain emission rates. Emission rates for every operation mode are defined such that they cover all unique combinations of the vehicle class, model year group, vehicle age, vehicle weight, engine size and technology, fuel type, temperature, humidity, and other factors (U.S. EPA 2007). The MOVES default average emission rates for a 5-year-old passenger car powered by gasoline with octane 87 were used in this study.

Step 3. Calculate the time in mode. The total amount of time spent in each operation mode—the time-in mode (TIM)—was calculated for each driving test.

Step 4. Estimate the total amount of vehicle emissions per test. The total amount of vehicle emissions during each driving test can be estimated as the product of the total TIM and the corresponding emission rates (Papson, Hartley, and Kuo 2012; Henry Christopher and Liu 2013; U.S. EPA 2009).

Results analysis

The data obtained from the driving simulator experiments were used to derive the MOEs for the different scenarios. The effectiveness of the proposed ATSSWS was assessed by comparing these MOEs.

Acceleration distribution

Figure 5 presents the acceleration distribution. Smaller acceleration/deceleration indicates smoother driving. As shown in Figure 5, the acceleration distribution ranges from −3 m/sec^2 to 3 m/sec^2. The frequency of zero acceleration in both ATSSWS scenarios, particularly the V2I-based ATSSWS scenario (52.0%), was significantly higher than that in the baseline scenario (43.3%). There are 84.6% of vehicles running at low-acceleration (absolute value less than 0.5) in the V2I-based scenario, and 81.7% of vehicles in the baseline scenario. These results imply that by using the ATSSWSs, drivers can proceed more smoothly through intersections with less unnecessary acceleration and deceleration. To verify the acceleration distribution in three different test scenarios, the driving trajectory is presented in Figure 6. The good linearity of the line indicates smooth driving of the vehicle. It is showed that vehicles in three scenarios can pass through Intersection 1 and Intersection 2 smoothly due to the status of traffic signal timing of the two intersections. In terms of Intersection 3 and Intersection 4, the vehicle needs to slow down for going through or stopping at intersections. As can be seen, the acceleration/deceleration of vehicles in the baseline scenario is the highest. Moreover, vehicles are provided the optimum speed limits to pass Intersection 3 without stops in the scenario with V2I and VMS. These analyses mean that the ATSSWSs can help to minimize the idling time and smooth acceleration/deceleration maneuvers of vehicles at intersections. To analyze the relationship between vehicle operations and emissions, the driving mode distribution is analyzed next.

Driving mode distributions

Figure 7 presents a plot of the percentages of time spent in each driving mode in the three scenarios. The ATSSWSs reduced the percentage of acceleration and idling. The acceleration in the VMS and V2I scenarios decreased by 2.38% and 13.03%, respectively. Studies have shown that emission rates during acceleration are considerably higher than those in other driving modes (Zhang et al. 2009), implying that the amount of vehicle emissions is reduced as the time spent accelerating decreases. Moreover, idling time of vehicles decreased by as much as 8.11% and 46.25% in the scenarios with VMS and V2I, respectively.

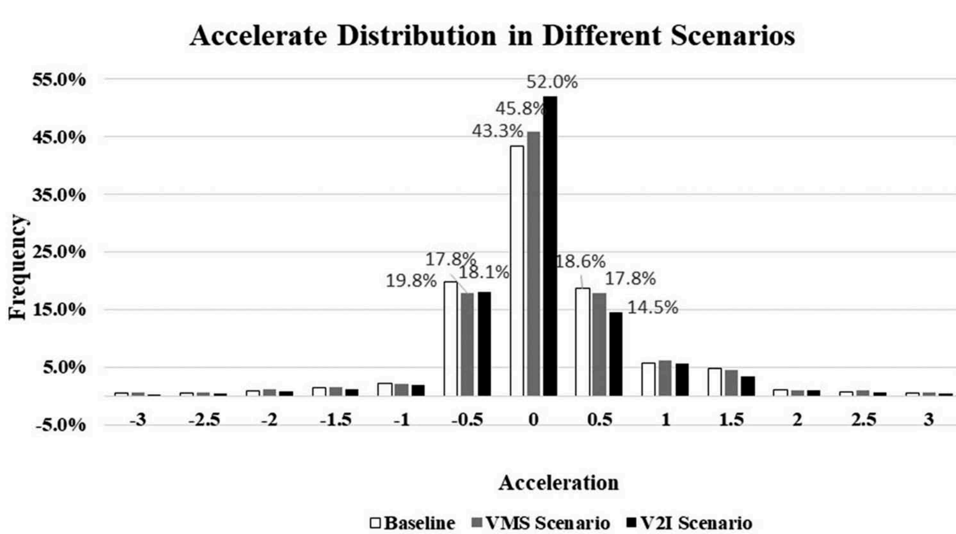

Figure 5. Acceleration distribution in different scenarios.

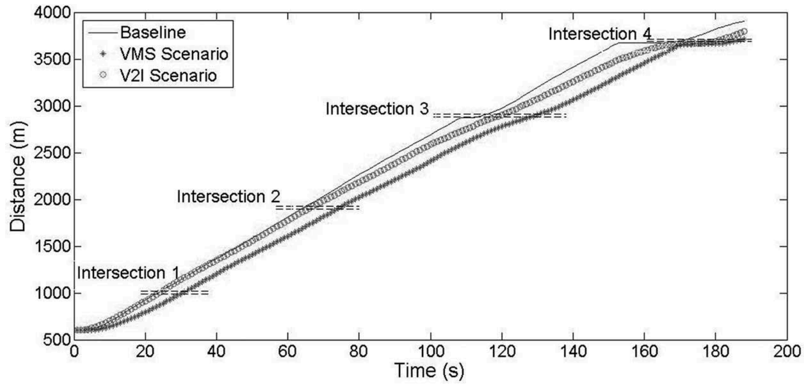

Figure 6. Driving trajectory of a vehicle crossing the four intersections in different scenarios.

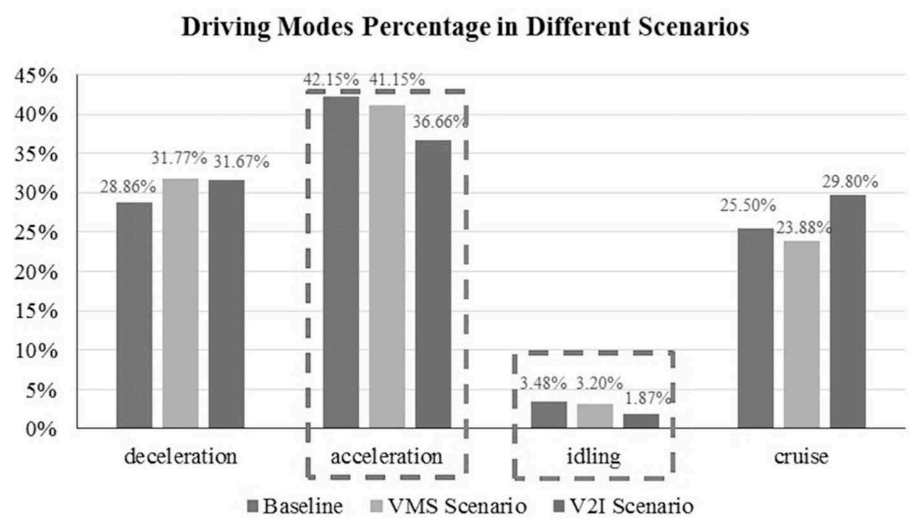

Figure 7. Time spent in driving mode in different scenarios.

Less idling time indicates that lower emissions per second at intersections can be achieved using ATSSWSs.

Total amount of vehicle emissions per test

Table 2 presents the average total amount of vehicle emissions per test for the three scenarios. Overall, the scenarios with the ATSSWSs produced less emission for all selected types of pollutants, including CO_2, NOx, CO, and HC. Specifically, CO_2 emissions decreased respectively by 0.48% and 4.27% when the VMS- and V2I-based ATSSWSs were applied, and HC emissions decreased by 22.78% (the largest decrease in this study) in the V2I-based scenario. Moreover, the emission reductions of all pollutants in the V2I-based scenario were significantly higher than those in the VMS-based scenario, indicating that the V2I-based ATSSWS is more efficient than the VMS-based ATSSWS in reducing emissions.

To further analyze the emission reductions caused by the use of the ATSSWSs, the frequencies (average results of the 50 participants) of the operating mode bins were plotted (Figure 8). Because the speed limit was 45 mph,

Table 2. Average emissions in three test scenarios.

Pollutants	Baseline (g)	VMS scenario (g)	Improved percentage of VMS scenario	V2I Scenario (g)	Improved percentage of V2I scenario
CO_2	709.3035	705.9167	0.48%	679.0490	4.27%
NOx	0.1833	0.1736	5.29%	0.1555	15.13%
CO	4.0064	3.5546	11.28%	3.2427	19.06%
HC	0.0305	0.0268	12.09%	0.0236	22.78%

OpModes 21–30 (25 mph speed < 50 mph) constituted a high proportion of all the OpModes. A considerably large difference was observed in OpModes 0 and 1, which represented braking and idling, respectively. The average frequencies decreased rapidly for the scenarios with the ATSSWSs, particularly for that with the V2I-based ATSSWS. These results imply that by using ATSSWSs, braking and idling decreased significantly and drivers could proceed through intersections more smoothly.

The aforementioned results prove that both ATSSWSs can assist drivers in driving passing through

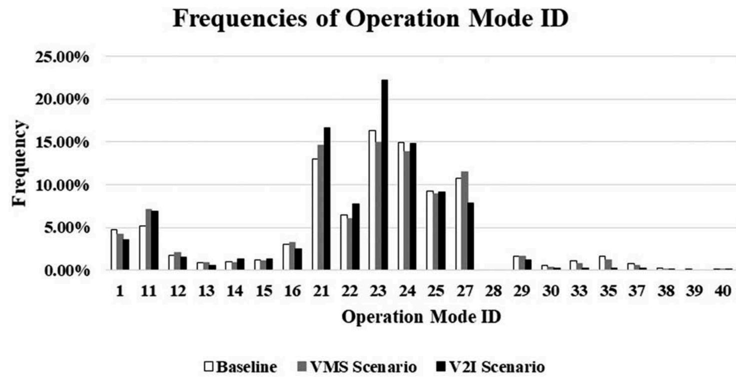

Figure 8. Frequencies of operation mode numbers (IDs) in three test scenarios.

signalized intersections more smoothly with less unnecessary acceleration and deceleration, thus significantly reducing the vehicle emission levels at signalized intersections. Moreover, the V2I-based ATSSWS proved to be more effective than the VMS-based ATSSWS in improving drivers' performance and reducing vehicle emissions at intersections.

Conclusion and future work

This study investigated the effects of two ATSSWSs, VMS-based and V2I-based ATSSWSs, on emission reductions at signalized intersections through driving simulator-based experiments. The major findings of this study are as follows:

First, both tested ATSSWSs could assist drivers in proceeding through signalized intersections more smoothly (i.e., with less unnecessary acceleration and deceleration). The ASCRs decreased by 5.07% and 21.50% when the VMS-based and V2I-based ATSSWSs were used, respectively.

Second, the ATSSWSs reduced the percentage of acceleration and idling. V2I-based ATSSWSs made more decrease of the percentage of acceleration and idling than VMS-based ATSSWSs.

Finally, vehicle emissions in the two ATSSWSs scenarios decreased by up to 28%, indicating that the ATSSWSs—particularly the V2I-based ATSSWS—were beneficial to the environment.

This study entailed conducting driving simulator experiments, and the results should therefore be further verified and improved. The experiments can be extended to a road network with more intersections, and the effects of traffic volumes at different congestion levels and vehicle types on the performance of ATSSWSs can be investigated. Furthermore, the arrival distribution of vehicles at 250 m upstream of the intersections may be affected by the distance between intersections when the traffic volume is relatively high. Accordingly, the impact of spacing between two consecutive intersections on the effectiveness of ATSSWSs can be considered based on the further experiments. In addition, some changes of demographic groups, meteorology, and inspection and maintenance (I/M), as well as confounding variables such as human errors, are not considered, and need to be further studied in the future. Considering that fuel consumption is also an important factor to evaluate the effectiveness of the ATSSWSs, the fuel savings can be further studied with more collected data.

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