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An Energy and Emissions Impact Evaluation
of Intelligent Speed Adaptation

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Abstract— Excessive vehicle speed on today's roadways often results in accidents, high fuel consumption rates, and excessive pollutant emissions. Traditional methods of limiting speed have only been moderately effective. Using the latest intelligent transportation technology, speed enforcement can be enhanced through vehicle speed management programs, often referred to as *Intelligent Speed Adaptation* (ISA). An ISA system monitors the location and speed of the vehicle, compares it to a defined set speed, and takes corrective action such as advising the driver and/or governing the top speed of the vehicle. ISA is an active research field in Europe where it is currently being evaluated. In addition to safety improvements, ISA has the potential to mitigate congestion by smoothing traffic flow during congested conditions, which may also lead to lower fuel consumption and pollutant emissions. In this paper, the energy and emissions impacts of ISA are investigated in detail using both simulation tools and real-world experimentation. This research makes use of state-of-the-art transportation/emissions modeling tools. The simulation analysis is focused on examining different speed management strategies under varying freeway congestion conditions. A set of limited real-world experiments have also been performed using real-time traffic information provided to an ISA-equipped vehicle driving in traffic. Results are compared to another non-equipped-ISA vehicle acting as a control, representing the general traffic flow. Preliminary results indicate that significant reductions are possible for both fuel consumption and emissions without drastically affecting travel time.

Index Terms — speed control, probe vehicles, telematics, GPS.

I.   INTRODUCTION

It is well known that excessive vehicle speed on our roadways is a major cause of traffic accidents, injuries, and deaths [1]. This has been documented in many accident reports and safety studies. In addition to these safety issues, excessive vehicle speed has a significant impact of fuel consumption and can also cause vehicles to emit higher levels of pollutants (e.g., carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOx)). Traditional methods of limiting speed such as police enforcement and speed bumps have proven to be only moderately effective [2]. As a result, alternative techniques for speed enforcement are being investigated, particularly those that take advantage of today's intelligent transportation system (ITS) technology.

One such method is termed *Intelligent Speed Adaptation* or ISA, which uses time and/or location information to manage vehicle speed. More specifically, ISA comprises a process that monitors the current speed of a vehicle, compares it to an externally defined set speed, and takes corrective action (e.g., advising the driver and/or governing the top speed). There are many forms of ISA, most of them relying on modern technology such as Global Position System (GPS) receivers, on-board roadway databases, and/or wireless communication. There are several ISA implementation methods, based on how the set speed is determined [3]:

1) ***fixed:*** in this case, the maximum permissible speed is set by the user and the on-board control system never exceeds that value; for this, ISA can be implemented as an independent on-board control system.
2) ***variable:*** in this case, the set speed is determined by vehicle location, where different speed limits are set spatially. This is the most common implementation of ISA, where the maximum vehicle speed never exceeds the speed limit for a given area. This can be implemented based solely on position information or based on broadcasted values.
3) ***dynamic:*** in this case, speed is determined by time and location. The temporal aspect can vary based on road network conditions or weather. This information can be provided from a transportation management center via vehicle-infrastructure communication.

Another dimension to ISA systems is how it intervenes with driver behavior. Categories include:
1) ***advisory***, where limits are displayed on a messaging device and the driver changes vehicle speed accordingly;
2) ***active support***, where the control system can change vehicle speed but driver can override; and
3) ***mandatory***, where ISA controls maximum speed and driver cannot override.

ISA has been tested over the last several years in a few European countries (e.g., Netherlands, Sweden, UK) and is thought to be an effective transportation measure for safety improvements and improving traffic flow in certain corridors [4, 5, 6]. Initial results are beginning to accumulate, showing safety improvements anywhere from 10% to 36% in terms of injury accident reductions [7]. Other results have shown accident rate reductions as high as 48.5% and approximate fuel savings up to 8%, while not increasing travel time more than 2.5% [8]. These initial results look promising, however further research has yet to be performed with ISA systems, focusing on user acceptance, quantitative safety, traffic, fuel economy, emissions benefits, and technical solutions [9].

In addition, several researchers have proposed using speed control to mitigate freeway traffic congestion (see, e.g. [10] and [11]). In these studies, the focus has been to examine the changes in overall freeway traffic characteristics (e.g., speed, density, and flow) due to the implementation of speed management. These studies have utilized macroscopic traffic flow models to examine a number of scenarios and control mechanisms. These studies have provided some initial insight on overall traffic effects, however to date, the microscopic effects (e.g., individual vehicle trajectories) associated with implementing this type of speed control have not been well understood. If the microscopic effects can be determined, then it will also be possible to accurately estimate vehicle emissions and energy consumption impacts of a variety of speed control techniques for a variety of roadway conditions.

This paper describes preliminary research carried out to better understand the energy consumption and vehicle emission impacts of the implementation of speed management on freeway traffic. This is accomplished through the use of a microscopic traffic simulation tool (i.e., PARAMICS) that has been tightly integrated with a modal emission/energy consumption model. In addition, a limited set of real-world experiments have been carried out using a set of instrumented vehicles where ISA can be implemented. The experiments were performed under different levels of freeway congestion and the vehicle's emissions/fuel consumption was carefully monitored. The goal of the ISA implementation was to minimize fuel consumption and pollutant emissions without adversely affecting overall travel time.

In Section 2, brief background material is provided on the simulation modeling tools, followed by a description of the overall methodology in Section 3. Section 4 describes the simulation setup and results, followed by a short description of the real-world experimentation and results in Section 5.

II. SIMULATION MODELING TOOLS BACKGROUND

Over the last several years, the authors have been developing and maintaining a unique Comprehensive Modal Emissions Model (CMEM, see [12]) under sponsorship of the U.S. National Cooperative Highway Research Program (NCHRP) and the U.S. Environmental Protection Agency (EPA). CMEM can predict second-by-second vehicle emissions and fuel consumption given any vehicle trajectory (i.e., velocity, acceleration, road grade). It is comprehensive in the sense that it covers essentially all types of vehicles found on the road today. It consists of nearly 30 vehicle/technology categories from the smallest light-duty vehicles to Class-8 heavy-duty diesel trucks. With CMEM, it is possible to predict fuel consumption and emissions from individual vehicles or from an entire fleet of vehicles, operating under a variety of conditions. The need for this type of microscale model that can predict second-by-second fuel consumption and emissions based on different traffic operations was and remains critical for developing and evaluating transportation policies, particularly those related to ITS. In the past, large regional emissions inventory models were applied to these types of microscale evaluations with little success.

One of the most important features of CMEM (and other related models) is that it uses a physical, power-demand approach based on a parameterized analytical representation of fuel consumption and emissions production. In this type of model, the entire fuel consumption and emissions process is broken down into components that correspond to physical phenomena associated with vehicle operation and emissions production. Each component is modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, emission technology, and level of deterioration. One distinct advantage of this physical approach is that it is possible to adjust many of these physical parameters to predict energy consumption and emissions of future vehicle models and applications of new technology (e.g., aftertreatment devices). For further information on the CMEM effort, please refer to [12, 13, 14, 15].

CMEM was designed so that it can interface with a wide variety of transportation models and/or transportation data sets in order to perform detailed fuel consumption analyses and to produce a localized emissions inventory. CMEM has been developed primarily for microscale transportation models that typically produce second-by-second vehicle trajectories (location, velocity, acceleration). These vehicle trajectories can be applied directly to the model, resulting in both individual and aggregate energy/emissions estimates. CMEM has been successfully integrated with the state-of-the-art traffic simulation model PARAMICS [16]. PARAMICS consists of a suite of high performance software tools for microscopic traffic simulation. Individual vehicles are modeled in fine detail for the duration of their entire trip, providing very accurate traffic flow, travel time, and congestion information, as well as enabling the modeling of the interface between drivers and ITS. One of the key features of PARAMICS is that it allows users to easily integrate additional modules through the use of an Application Programming Interface (API). A separate CMEM API was developed for PARAMICS that can predict emissions and fuel consumption in real time [17].

III. METHODOLOGY

In this study, the focus is placed on applying speed management techniques on the freeway to smooth traffic flow, thereby reducing fuel consumption and vehicle emissions. Under congested conditions, it is well known that traffic instability (i.e., stop-and-go conditions) can often develop. This instability generally takes place when traffic is flowing at or near the roadway capacity, and some type of perturbation occurs (e.g., sudden slowing, lane drop, accident, etc.). Traffic flow instability is characterized by significant speed variations in the individual vehicles due to the random and non-homogenous nature of individual driver behavior.

This roadway congestion has been categorized into different "levels-of-service" or LOS (see [18]). For freeways (i.e., non-interrupted flow), LOS can be represented as a ratio of the traffic flow divided by the roadway capacity.

There are several different LOS values that range from the letters "A – F". For these different levels of service, a typical vehicle velocity trajectory will have different characteristics. Examples of these velocity trajectories are shown in Fig. 1. Under LOS A, vehicles will typically travel near the highway's free flow speed, with little acceleration/deceleration perturbations. As LOS conditions get progressively worse (i.e., LOS B, C, D, E, and F), vehicles will encounter lower average speeds with a greater number of acceleration/deceleration events.
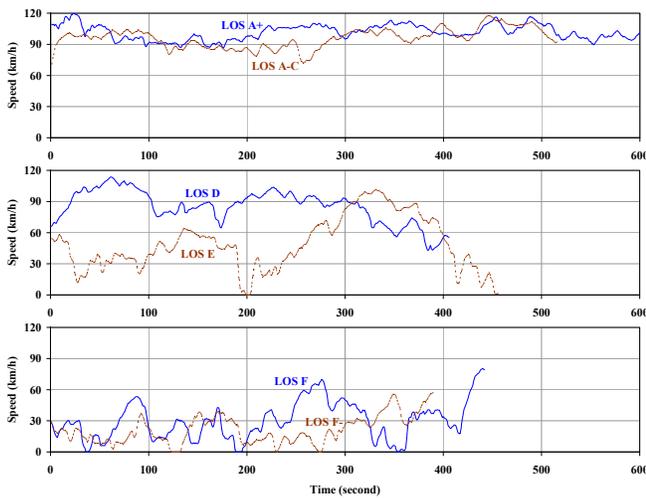
Fig. 1. Example vehicle velocity trajectories for different congestion levels-of-service on a freeway.

The acceleration/deceleration events that occur under high congestion result in higher fuel consumption and vehicle emissions. In order to smooth the traffic flow, it is desired to employ intelligent speed adaptation where the vehicle is limited to a maximum speed under specific conditions. For example, if the average traffic speed is 48 km/h under LOS E conditions, the maximum speed of the vehicle can be limited in such a way that sharp accelerations above this limit can be eliminated. This will not adversely affect the overall travel times, but it will provide a smoother vehicle velocity profile.

In this research project, we have developed speed control strategies that can dynamically change based on current traffic conditions. The overall system setup is shown in Fig. 2. In this figure, several different components interact together. This architecture takes advantage of the existing California Freeway Performance Measurement System (PeMS), developed by UC Berkeley and Caltrans (see [19]). The PeMS system consists of numerous embedded loop detectors on the major freeways in California, each which reports flow and occupancy from which speed can be computed. These data are collected through local Traffic Management Centers, and then filtered, processed, and made accessible at 30-second intervals on the Internet via the PeMS server. Depending on the speed control strategy, the PeMS data (e.g., average traffic speed on a link-by-link basis) will be used and communicated to ISA-equipped vehicles via a wireless communications provider. The

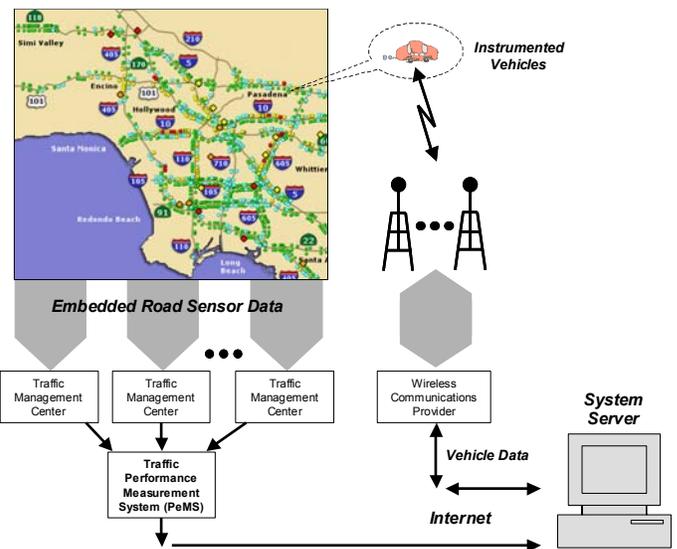vehicles will also provide velocity trajectory data back to the system server for analysis.

Fig. 2. Overall system architecture for real-world experimentation.

For the real-world experiments, on-board "telematics" hardware is used to allow for communications between the system server and the vehicles. This hardware was originally developed for managing carsharing applications, but has also been used for lane-level automatic vehicle location systems, vehicle activity analysis, and remote vehicle sensing. The on-board electronics (shown in Fig. 3) are capable of hybrid communications, using both dedicated short-range communication (DSRC) and a wide-area cellular data network. The on-board electronics also include a GPS receiver that allows for vehicle localization and a message display unit (MDU) that allows for messaging between the system and the users. The on-board electronics can record a number of vehicle parameters and system events that are then sent to the system database. The overall database accumulates all trip information which can then be analyzed in detail. The system can also send data from the system management directly to the vehicles.
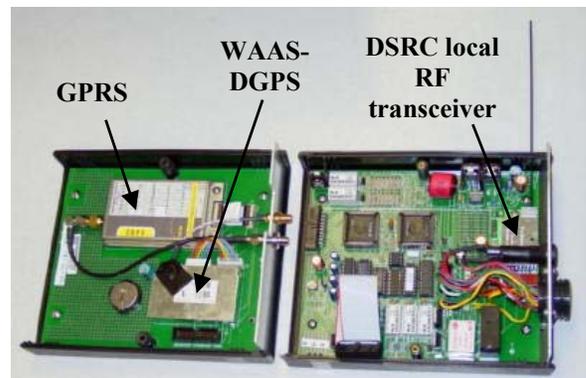

Fig. 3. On-Board Electronics: GPRS - General Packet Radio Service cellular modem; WAAS-DGPS – Wide Area Augmentation System enabled Differential Global Position System receiver; DSRC – Dedicated Short Range Communications.

IV. SIMULATION SETUP AND RESULTS

Using the PARAMICS/CMEM modeling tools described in Section 2, a variety of freeway traffic scenarios have been analyzed. As a starting point, a straightforward roadway section is considered, as shown in Figure 4a. For this roadway section, different levels of congestion are induced by varying the travel demand and capacity of the segment. In this initial analysis, we will focus on "steady-state" congestion levels, i.e., where the congestion levels are consistent both spatially and temporally, after any shock waves have passed through the traffic stream. For different congestion levels (specified by different volume-to-capacity ratios), total traffic emissions and fuel consumption are compared between a non-ISA implementation and different levels of ISA-equipped vehicle penetration.

An example of this is shown in Figure 4b. Steady-state congestion has been induced where the average traffic speed is approximately 48 km/h. A sample vehicle velocity trajectory is shown as a (blue) dashed line for normal, non-ISA conditions. In contrast, a simple speed control strategy is used that limits the top speed of a vehicle to the average speed of traffic. An example velocity trajectory of this is shown in Figure 4b as a (red) solid line. The two trajectories have approximately the same travel time, however the ISA-equipped vehicle has a much smoother velocity trajectory, resulting in lower fuel consumption and pollutant emissions.
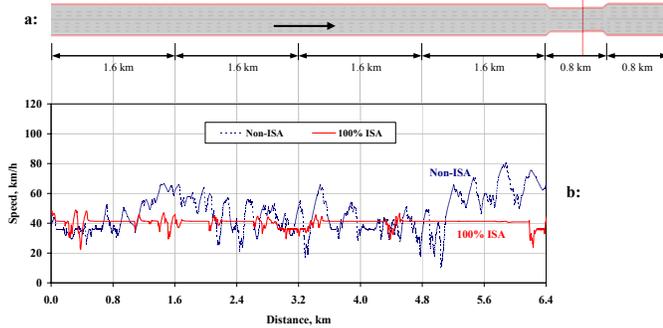
Fig. 4. a: Simulated simple freeway network; b: Resulting velocity trajectories for non-ISA-equipped vehicle (blue dash) and ISA-equipped vehicle (red solid) under steady-state congestion.

The statistics of these example vehicle trajectories are given in Table 1. Further, the fuel consumption and emissions for a typical passenger vehicle operating with these velocity trajectories are given in Table 2. From this example, it can be seen that significant fuel savings (37%) and emissions (CO: 85%; HC: 69%; NOx: 74% reduction) are possible with very little difference in the overall travel time.

The overall traffic flow is expected to be smoother if all vehicles are equipped with this intelligent speed adaptation. However, it is likely that not all vehicles will have these devices. As such, additional simulation runs were carried out using different ISA-equipped vehicle penetration rates. For these simulation runs, the resulting emissions, fuel consumption, and travel times were calculated and compared to the controlled simulation, where 100% of the

vehicles are non-ISA equipped. It was observed during the simulation runs that in the traffic stream containing both ISA and non-ISA vehicles, ISA vehicles have influence on a non-ISA vehicles' maneuverability. A non-ISA vehicle's velocity is often indirectly limited to that of an ISA-equipped vehicle in front. This phenomenon occurs for a certain period of time until the non-ISA vehicle finds a sufficiently large gap in the adjacent lanes to overtake the ISA vehicle. The effects of these different penetration rates are shown in Fig. 5 for the traffic conditions at LOS E. It can be seen that the energy/emissions benefits are significant even with the ISA penetration rate as low as 20%. The preliminary results presented in Fig. 5 consist of single simulation runs at each penetration rate.

Table 1. Statistics of example vehicle trajectories.

Velocity Trajectory	Non-ISA	100% ISA	Difference
Max (km/h)	80.5	48.9	-31.7
Min (km/h)	10.3	22.7	+12.4
Average (km/h)	43.3	40.2	-3.05
Std. dev. (km/h)	12.7	3.2	-9.5
Skewness (km/h)	.64	-2.9	-3.5

Table 2. Fuel consumption, emissions, and travel times for the example vehicle trajectories for a typical passenger vehicle.

Energy/Emissions/TT	Non-ISA	100% ISA	Difference
CO2 (g)	1605.13	1044.81	-34.9%
CO (g)	47.83	6.97	-85.4%
HC (g)	1.46	0.45	-69.3%
NOx (g)	2.36	0.62	-73.6%
Fuel consumption (g)	531.23	333.29	-37.3%
Travel time (minute)	8.9	9.6	+7.7%
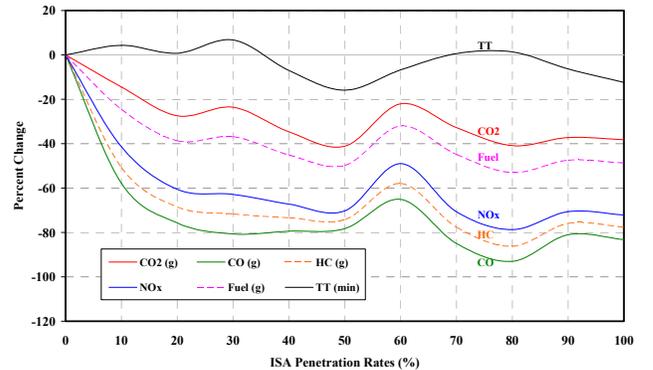
Fig. 5. Energy/emissions reduction at different penetration rates, at LOS E.

To determine the effectiveness of the speed management strategies across different congestion levels, a number of other simulation runs were carried out. It is expected that the speed management techniques will have little effect at LOS A when the traffic density is low. The greatest gains should occur during the more congested conditions. Using the simulation modeling tools, LOS A – F conditions were simulated using the speed control strategy that has the lowest impact on overall travel time. The resulting fuel savings and emissions reductions of an ISA-equipped vehicle as compared to a non-ISA vehicle are illustrated in Fig. 6. These savings/reductions are calculated for a 100% ISA penetration rate. The corresponding travel time differences between the two scenarios are also plotted.
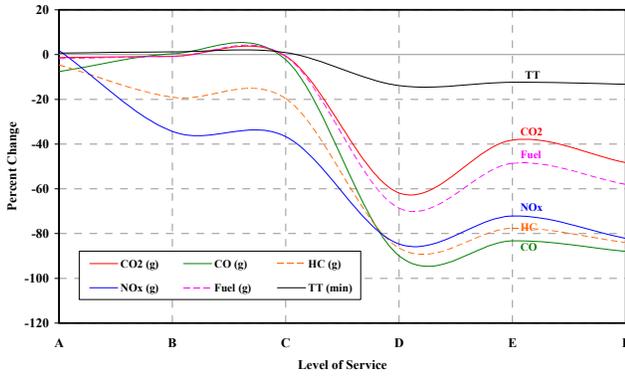
Fig. 6. Effects of ISA implementation at different LOS

As expected, little benefit was seen at LOS A–C since very little congestion occurs during these conditions. On the other hand, the energy/emissions benefits of ISA are much more significant for congested freeways, i.e., at LOS conditions D-F. Implementing ISA to limit the vehicles speed at LOS D, where traffic approaches unstable flow, has the greatest impact on emissions (CO: 93%, HC: 90%, NOx: 86% reduction) and fuel savings (70%). This is because the normal acceleration/deceleration events associated with stop-and-go maneuvers of the vehicle velocity trajectory is damped out considerably. Interestingly, it was found that ISA also helps decrease travel time by up to 15% during congested freeway conditions (LOS D-F).

V. REAL-WORLD EXPERIMENTATION

In addition to the simulation analysis described in the previous section, some initial real-world experimentation has been carried out. For this experimentation, the overall system architecture illustrated in Fig. 2 was used. Real-time freeway congestion data (speed, density, flow) were acquired from the California traffic PeMS system and were used to compute a maximum recommended speed for an ISA-equipped vehicle in traffic. Using the telematic hardware shown in Fig. 3, a vehicle can receive the data from the system server. This experimental system operated in an advisory mode where the driver attempted to limit the vehicle speed to the speed recommended from the system server based on the current average speed of traffic. The recommended speed was updated dynamically depending on the overall traffic data.
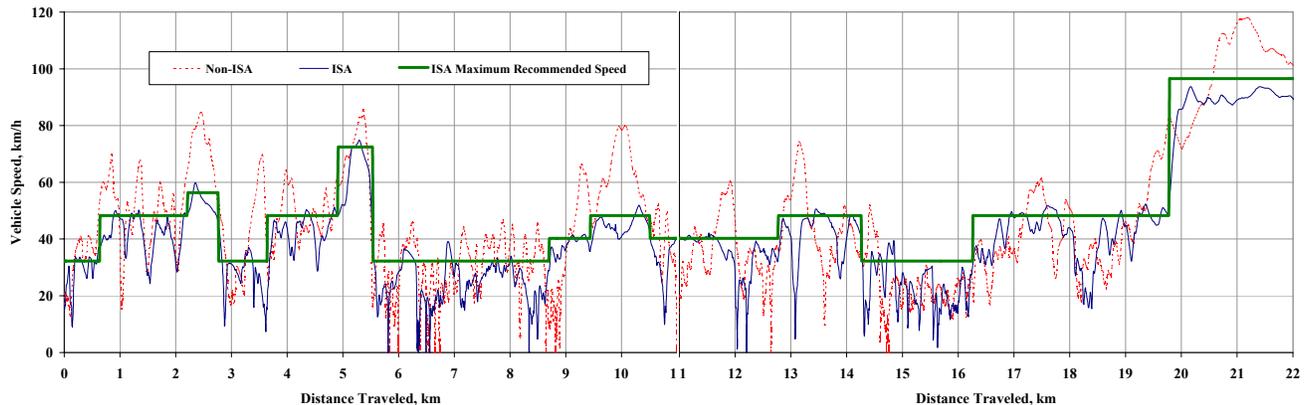
To serve as a "control" in the experimentation, a second vehicle operated along the same route in the same traffic, however without any ISA information. The overall goal was to compare the recorded vehicle trajectories of both the ISA-equipped vehicle and the non-ISA vehicle. The vehicles were sent off into traffic, seeking significant congestion conditions. A variety of experimental runs were accomplished. As an example, high levels of congestion were present on the California SR-91 freeway during the PM peak period. For this example, the velocity profiles for both vehicles are shown in Fig. 7. In this figure, the solid (green) thick line indicates the recommended speed from the system server, the (blue) thin line represents the velocity trajectory of the ISA-equipped vehicle, and the (red) dashed line shows the velocity trajectory of the non-ISA vehicle. It can be seen in this figure that the recommended maximum speed was rarely exceeded during the experimentation.

Fig. 8 shows the speed-acceleration histograms of the two vehicles for this example run. It is apparent that the velocity of the ISA-equipped vehicle was often limited below 56.3 km/h with very few acceleration/deceleration events when compared to the histogram of the non-ISA vehicle.
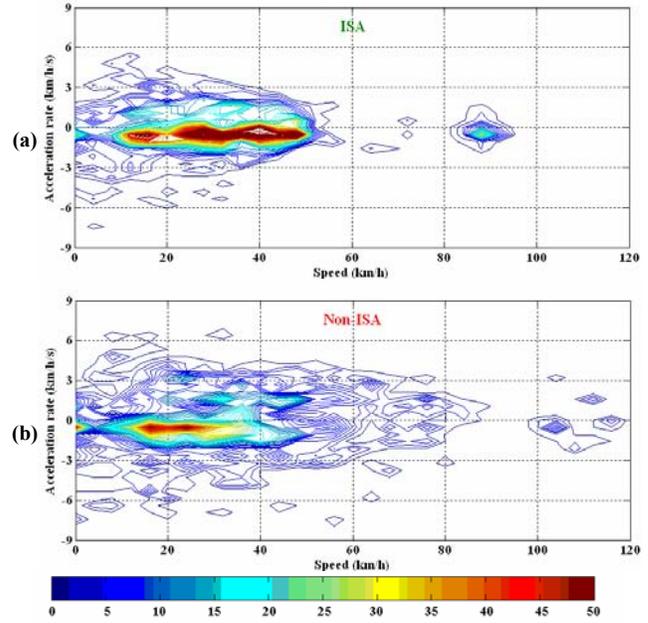

Fig. 8. Speed-acceleration histograms for both **(a)** ISA-equipped and **(b)** non-ISA vehicles.

Fig. 7. Velocity versus distance for both the ISA-equipped vehicle, non-equipped vehicle, and recommended speed profile.

Statistics from these experimental runs are provided in Table 3. It is clear that significant energy and emissions reductions do occur without much penalty to travel time, even for this simple experimental run where two vehicles are compared. It is also important to point out that greater traffic-related energy/emission impacts are likely if greater penetration rates are used. As described in the simulation analysis section, with higher penetration rates, traffic overall tends to flow more smoothly due to the influence of vehicles following ISA-equipped vehicles.

Table 3. Trajectory and energy/emission statistics of experimental runs.

Velocity Trajectory	Non-ISA	ISA	Difference
Max (km/h)	117.9	93.6	-24.3
Min (km/h)	0.0	0.0	0.0
Average (km/h)	33.9	32.1	-1.9
Std. dev. (km/h)	21.2	17.5	-4.0
Skewness (km/h)	1.7	1.6	-.16

Energy/Emissions	Non-ISA	ISA	Difference
CO2 (g)	5439	4781	-12%
CO (g)	97.01	50.47	-48%
HC (g)	3.20	1.90	-41%
NOx (g)	6.28	3.97	-37%
Fuel (g)	1766	1534	-13%
Travel time (min)	38.9	41.2	+6%

V. CONCLUSIONS AND FUTURE WORK

To date, intelligent speed adaptation techniques have primarily been implemented with a focus on increasing safety. However, ISA has the potential to mitigate congestion by smoothing traffic flow during congested conditions, which also leads to lower fuel consumption and pollutant emissions. In this paper, the microscopic effects in terms of individual vehicle trajectories under speed management have been examined in detail, both using simulation modeling tools and through limited real-world vehicle experimentation. In nearly all cases, it has been shown that fuel consumption and pollutant emissions can be reduced without affecting overall travel times. A variety of speed management strategies were implemented and examined under different steady-state congestion conditions.

In terms of future work, the simplistic speed management strategies will be further developed and applied to non-steady-state congestion conditions and evaluated using the simulation modeling tools. Further, additional real-world experimentation is planned, examining the ISA effects for different freeway traffic conditions.

ACKNOWLEDGMENTS

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