U.S.Department of Transportation
Federal Highway Administration
Office of Operations
Research and Development

TECHBRIEF

ECO-DRIVE EXPERIMENT ON ROLLING TERRAIN FOR FUEL CONSUMPTION OPTIMIZATION

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INTRODUCTION

Eco-drive is one of many techniques that have been developed to increase vehicle fuel efficiency. Connected Vehicle (CV) data is now being leveraged to allow vehicles to cooperate better within current and future environments vis-a-vis traffic conditions, signal timing, and terrain information. This study investigates the use of vehicle automation and mobile communication technology to derive the maximum benefits from eco-drive. The concept of vehicle-to-infrastructure (V2I)-based eco-drive is illustrated in figure 1. Traffic management centers (TMCs) maintain databases of roadway profiles (i.e., location, horizontal and vertical curves, work zones, etc.). In this concept, TMCs predefine a list of roadway segments on which automated eco-drive is recommended or enforced. These segments are selected because of their potential for significant fuel savings according to segment characteristics. Once the eco-drive vehicle receives information from the TMC, an onboard computer equipped with a preloaded algorithm will design a recommended trajectory (e.g., speed profile) for the vehicle to follow through the entire rolling segment. This algorithm also accounts for other factors such as vehicle operating capability, driver comfort, safety, and speed limits.

OBJECTIVE

The objective of this study is to propose an efficient algorithm and test it on a vehicle platform such that the potential benefit of eco-drive can be quantified in a real-world environment. The experiment is being conducted on various vertical alignments using a Federal Highway Administration (FHWA) Saxton Transportation Operations Laboratory (STOL) research vehicle (2013 Cadillac SRX with a regular gasoline engine) and by controlling the speed only as estimated by the given algorithm. Hopefully, the algorithm and the experiment will support State departments of transportation

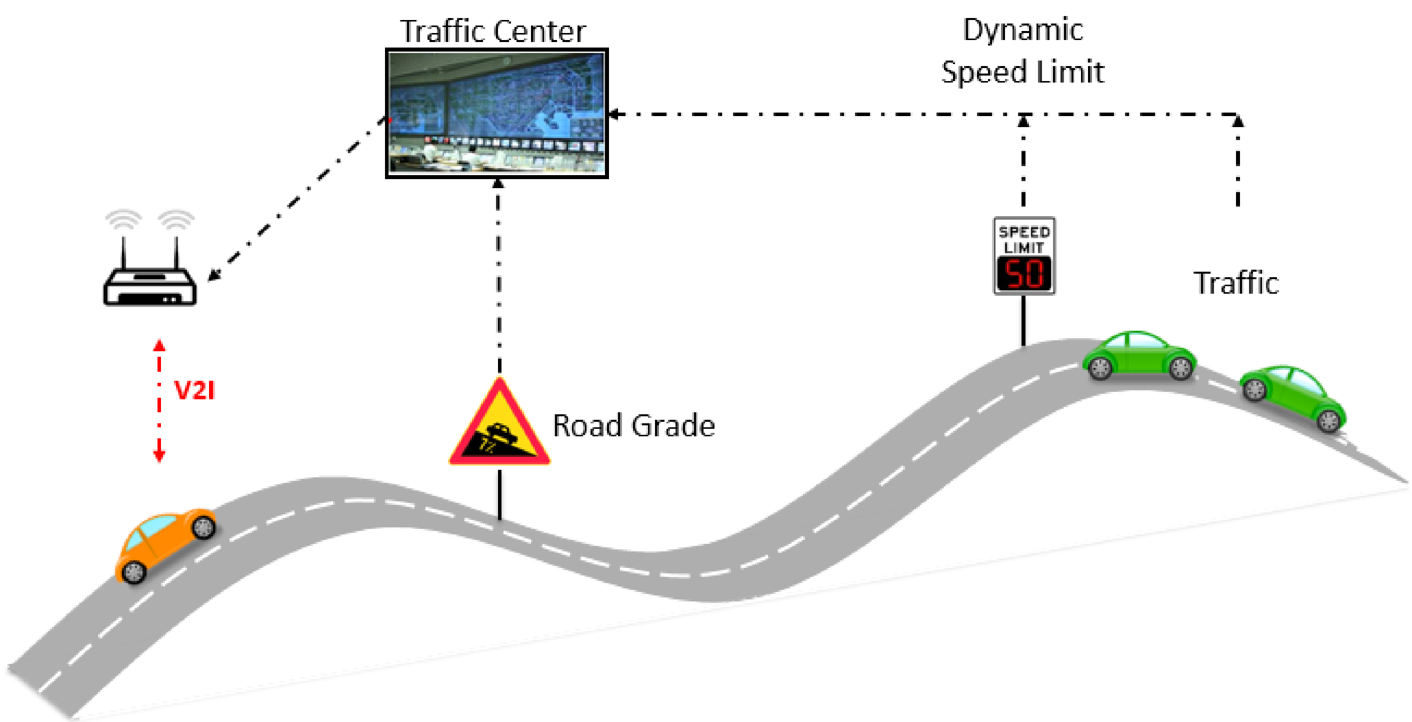


Figure 1. Concept of V2I-based eco-drive on rolling terrains (source: FHWA)

(DOTs) and original equipment manufacturers (OEMs) in developing and marketing this technology to reduce fuel consumption and emissions. The contributions made by this research include:

1. Developing an eco-drive algorithm, using the Relaxed Pontryagin's Minimum Principle (RPMP), that is computationally efficient and applicable in real time.

2. Executing field experiments using an innovative vehicle control platform with recent vehicular and communication technologies.

3. Quantifying eco-drive benefits in a real-world environment and providing decisionmakers with data and tools for better management strategies.

APPROACH

Vehicle Control System

The proposed speed controller consists of two components. The first component is an upper-level controller that is responsible for trajectory planning to generate optimal speed profiles. The other is a secondary controller that adjusts speed commands in real-time for enhanced performance, and contains a classic proportional-integral-derivative (PID) controller for vehicle speed following. The recommended speed profile generated from the upper-level controller is processed by the secondary controller and sent to the vehicle for execution.

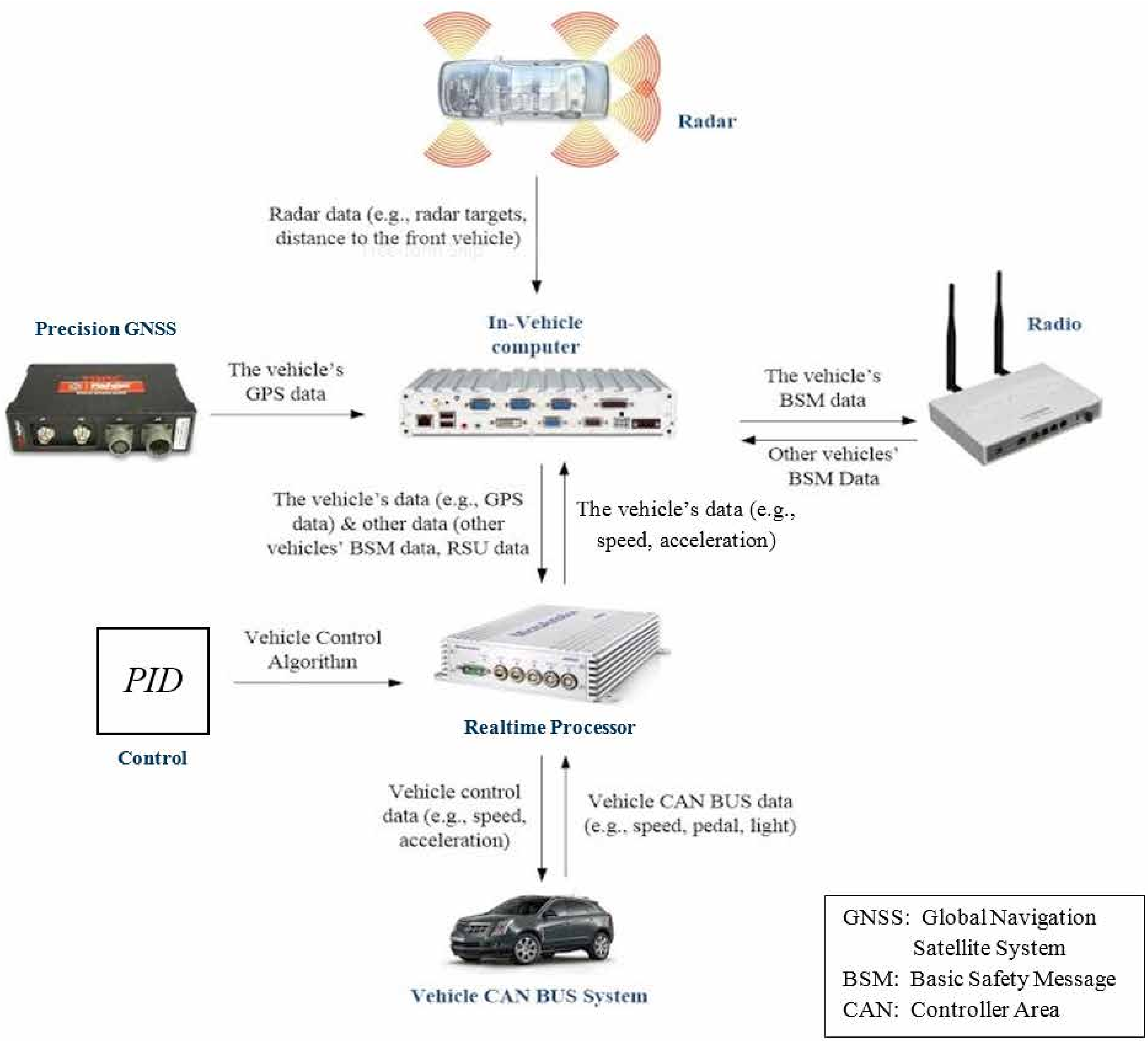


Figure 2. Data flow of the vehicle control system (source: FHWA)

The connected automated vehicle (CAV) used in the field experiment is a part of the FHWA's automated vehicle fleet. Each vehicle was designed to be a complete research platform. Each research platform is outfitted with the following components:

- Longitudinal Controller
- Real-time processor
- Dedicated Short Range Communications (DSRC) Onboard Unit (OBU)
- Industrial Computer
- Precision Localization Device

Figure 2 demonstrates the data flow between these different vehicle system components and data collection.[2]

Field Experimental Setup

In the experiment, two scenarios are tested:

Baseline: The benchmark is commercial cruise control with cruising speeds set to corresponding roadway speed limits.

Eco-Drive: For eco-drive scenarios, the proposed controller is used. Vehicles are given an optimal speed profile and are controlled by the secondary speed controller in real time to adhere to the recommended speeds.

A field experiment was conducted on seven rolling roadway segments in Virginia and Maryland, with a total experimental mileage of around 47 miles. These segments vary from mildly rolling to mountainous. Detailed roadway elevation profile data are not widely available for all roads. This study uses the PinPoint device and Precise Point Positioning (PPP) Global Positioning System (GPS) service to collect elevation data. This method is preferred in the future, especially when all vehicles can be equipped with such advanced sensors. Fuel consumption was recorded, and the set of parameters that yield the lowest fuel consumption were selected (speed commands are given 13 meters (45 feet) in advance, geofence size/radius = 2 meters, maximum acceleration = 1 meter/sec2, and speed command interval = 10 meters).

Table 1. Results of eco-drive benefits for each roadway segment and subsegment.

Segment	Scenario	Length (miles)	Max Fuel Flow (mL/min)	Min Fuel Flow (mL/min)	Average Fuel Flow (mL/min)	Total Fuel Used (L)	Travel Time (s)	Reduction in fuel usage
Georgetown Pike NB	Baseline	2.3	505.1	0.231	84.0	0.204	160.6	21.2%
	Eco-drive	2.3	200.7	14.09	59.8	0.160	163.0	
GW Parkway NB	Baseline	8.6	270.7	0	95.78	0.685	429.4	2.0%
	Eco-drive	8.6	224.1	0	92.02	0.674	439.4	
GW Parkway SB	Baseline	8.7	313.21	0	81.86	0.875	641.5	5.3%
	Eco-drive	8.7	216.58	0	76.9	0.831	648.7	
River Road NB	Baseline	4.9	366.9	0	112.96	0.688	365.6	8.0%
	Eco-drive	4.9	264.5	0	93.54	0.633	405.8	
River Road SB	Baseline	4.9	468.98	0	104.84	0.828	473.7	13.3%
	Eco-drive	4.9	262.81	0	95.74	0.71	444.9	
US Route 17 NB	Baseline	7.4	286.55	0	117.62	0.921	469.8	4.9%
	Eco-drive	7.4	200.34	50.397	101.45	0.863	510.5	
US Route 17 SB	Baseline	7.4	293.6	0	105.43	0.909	517	3.3%
	Eco-drive	7.4	303.6	47.5	94.66	0.873	553.4	

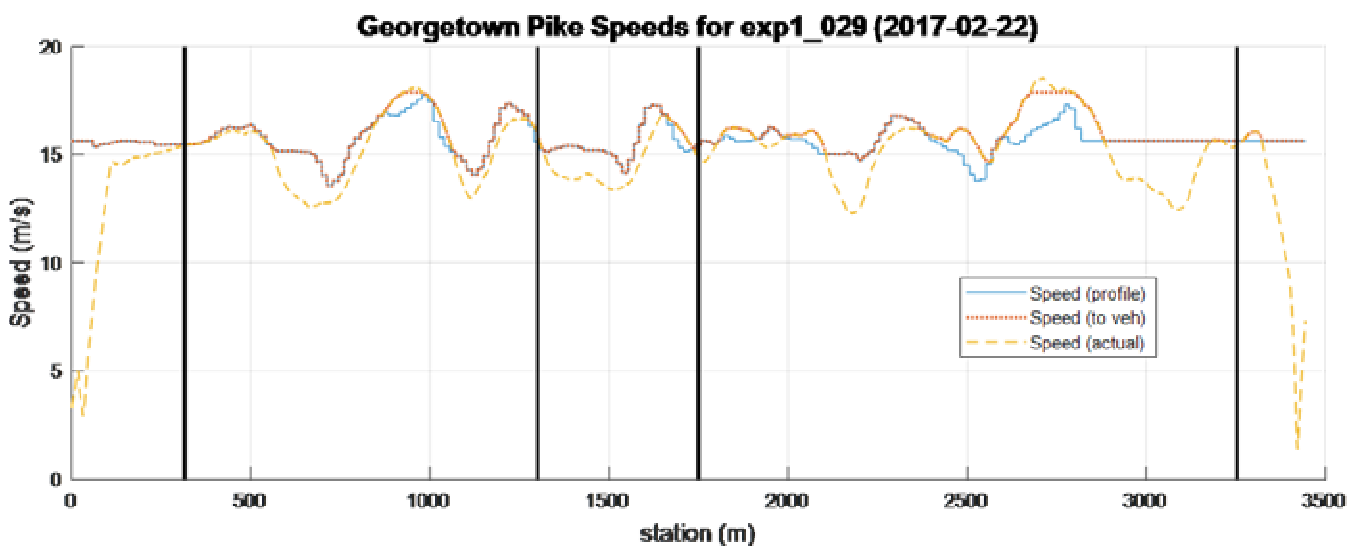
NB: northbound; SB: southbound. GW Parkway: George Washington Parkway

RESULTS

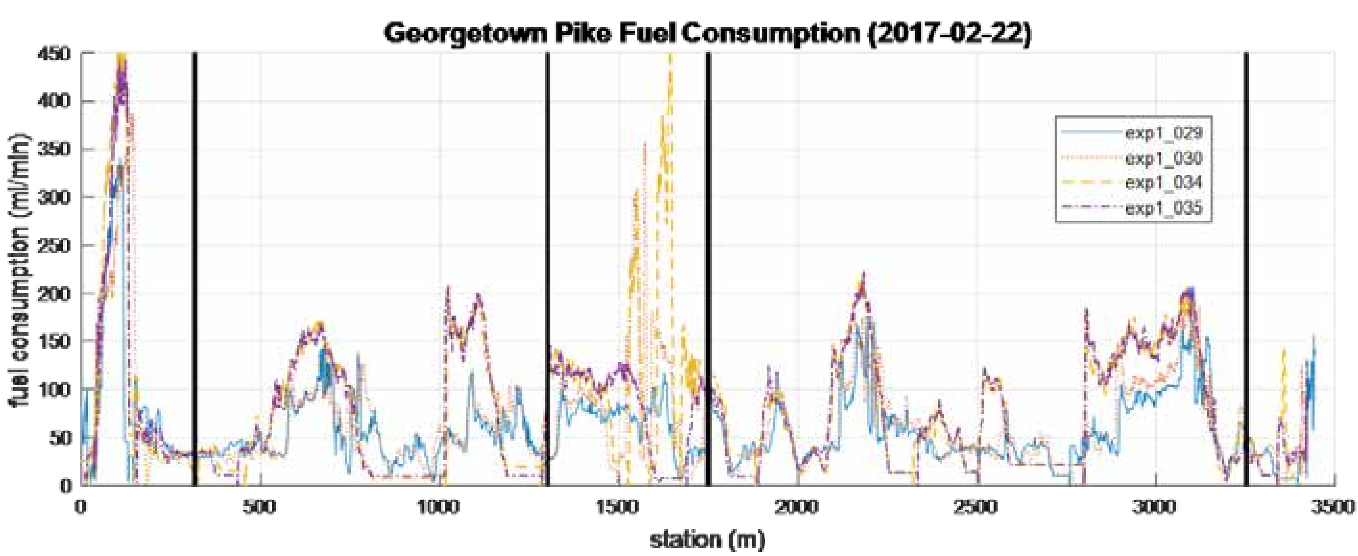
The proposed eco-drive controller significantly reduces fuel consumption. Table 1 details average results from each experimental site. Note that the travel times for the baseline and eco-drive are quite similar (mostly within a range of five percent) because the trajectory planning algorithm aims to maintain the same level of mobility while improving fuel consumption. The table also shows basic statistics of instantaneous fuel consumption throughout the experimental runs. Maximum instant fuel consumption (mL/min) of baseline runs are usually much larger than eco-drive runs.

The total fuel consumption savings vary significantly from 2 percent to over 20 percent. This result is expected because fuel use greatly depends on attributes of the terrain, such as hill length and slope. The roadway profile of Georgetown Pike northbound consists of constant, continuous uphill and downhill segments with steep grades (4 to 8 percent), and thus, there is greater room for improvement. For roadway segments like the George Washington Parkway northbound, the savings are relatively small because the roadway's vertical profile is mild and it includes a flat subsegment that generates very small fuel consumption differences between the baseline and eco-drive scenarios. This result indicates that eco-driving may not be necessary on all roads. Only the mountainous segments require installation of eco-drive roadside equipment and associated investment. In the end, the question of whether a road needs eco-drive investment becomes a cost-benefit analysis.

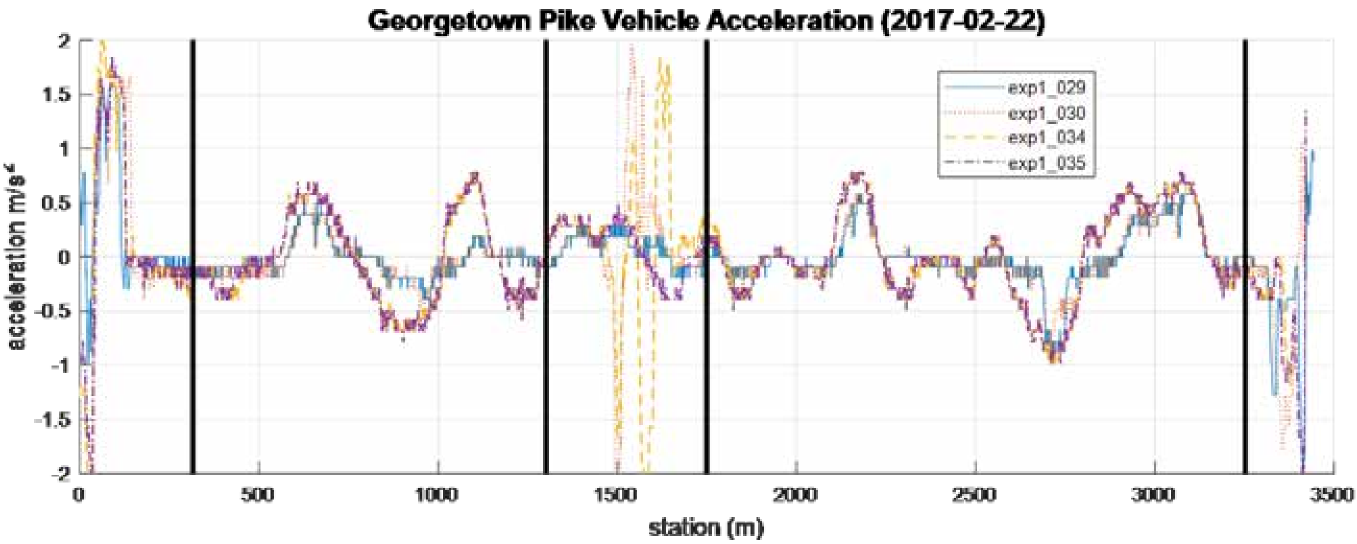
Figure 3(a) demonstrates actual speed data collected from one experimental run (eco-drive and baseline) on Georgetown Pike as compared to commanded speed. The blue line shows the speed profile generated by the upper-level controller; the orange line shows the speed commands from the secondary



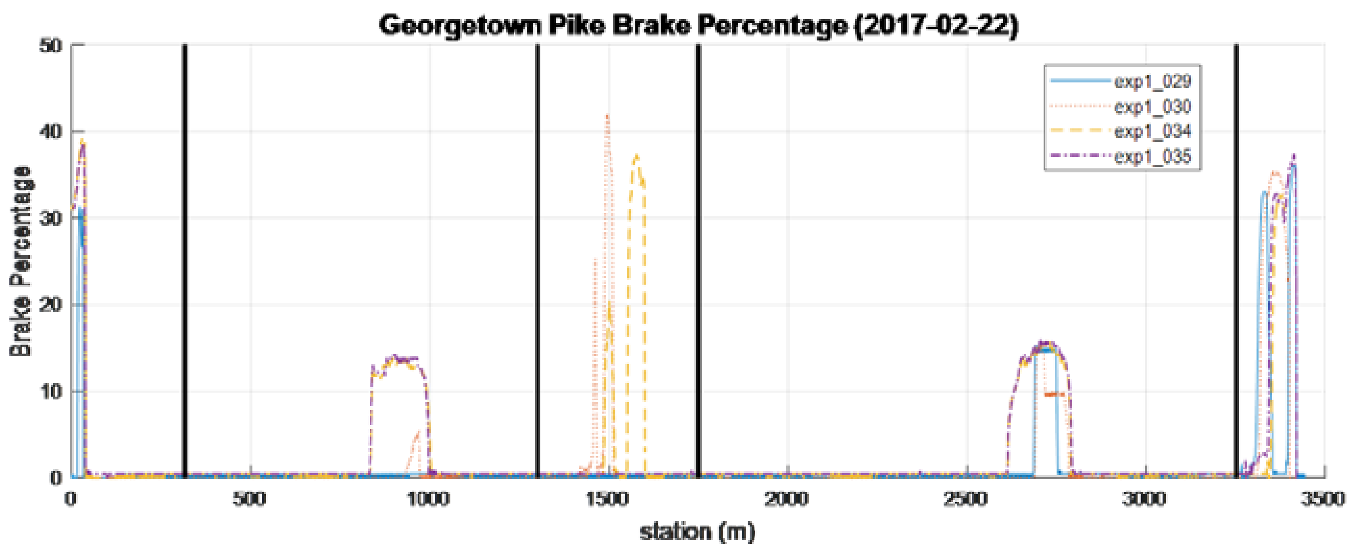
(a) Georgetown Pike example speed profile for eco-drive.



(b) Georgetown Pike fuel consumption for multiple runs



(c) Georgetown Pike acceleration for multiple runs



(d) Georgetown Pike brake percentage

Figure 3. Experimental results at segmental level for example runs (exp1_029 and exp1_030 are eco-drive runs, and exp1_034 and exp1_035 are baseline runs) (source: FHWA)

controller. The yellow line is the actual speed profile when the vehicle tried to follow the orange speed commands. Figure 3(a) shows that the vehicle can generally follow the speed commands closely even on this rolling terrain. At 1500 meters, the data between two black bars is removed because there is a traffic light, and the vehicle stops during some runs. The resulting fuel consumption benefits are reflected in figure 3(b). In many locations where acceleration was avoided, eco-drive runs consumed much less fuel. Less braking and smaller brake percentages translate to a more effective transformation between potential and kinetic energy, thus less fuel is needed to provide the extra kinetic energy. Figures 3(c) and 3(d) show acceleration and braking effort of the vehicle, respectively, which are less extreme during the eco-drive runs in comparison to the baseline runs.

SUMMARY

This study advances the development of eco-driving systems in three ways: i) proposed an eco-drive controller; ii) field evaluation of the proposed controller; iii) developed a tool to identify potential eco-driving hotspot. This study further tested the proposed controller in real-world scenarios using an innovative CAV platform to better understand the algorithm performance. The proposed eco-drive system is compared against conventional constant-speed cruise control on a total of 7 road segments over 47 miles. The number of replication for each test is confirmed by statistical methods. The results confirm the fuel saving benefits of eco-drive. Experimental data show that more than 20 percent of fuel consumption can be saved on certain terrains for a single vehicle without traffic interference. Nevertheless, further research is still needed to study the impact of this univariate finding on the surrounding traffic, including non-automated and automated vehicles.

From this study, there are many directions in which to build. First, field data on more experiment sites can be collected to examine eco-drive performance on a wide range of terrain conditions, and then more detailed subsegment analyses can be conducted. Second, this study considered only a single vehicle with an unobstructed path. Advanced algorithms may also consider the existence of a front vehicle (via vehicle-to-vehicle information) and downstream traffic congestion through addition of speed harmonization component to the algorithm. Third, the proposed algorithm used speed commands to control the vehicle and did not exert control over the vehicle transmission. A future version of this study may further improve the fuel consumption by controlling the transmission state. Last, the proposed algorithm relies on an approximate vehicle dynamics model, and thus actual vehicles may not follow the commanded speed profiles well. Incorporating machine learning and artificial intelligence components in future algorithms means that vehicles can plan the most suitable trajectories for themselves by using data from earlier operations.

REFERENCES

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2. Raboy, K., Ma, J., Stark, J., Zhou, F., Rush, K. and Leslie, E., 2017. Cooperative Control for Lane Change Maneuvers with Connected Automated Vehicles: A Field Experiment (No. 17-05142). Transportation Research Board Annual Meeting, Washington, D.C.

Researchers—This study was performed by Dr. Jiaqi Ma, Ed Leslie, and Fang Zhou of the Saxton Transportation Operations Laboratory, operated by Leidos, Inc., and Dr. Jia Hu, Federal Highway Administration Research Associate. Dr. Joe Bared and Dr. Peter Huang were the Government Task Managers. Sponsored by the FHWA Office of Operations Research and Development under contract number DTFH61-16-D00030 / Task Order 07.

Distribution—This TechBrief is being distributed according to a standard distribution. Direct distribution is being made to the FHWA divisions and Resource Center.

Availability—The publication associated with this TechBrief is titled “Eco-Drive Experiment on Rolling Terrain for Fuel Consumption Optimization Summary Report”. Publication number TBD.

Key Words—Ecodrive, fuel consumption, fuel economy, connected automated vehicle, fuel optimization, emissions, efficiency