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Evaluating the Effectiveness of “Smart Pedal” Systems for Vehicle Fleets

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Evaluating the Effectiveness of “Smart Pedal” Systems for Vehicle Fleets

May 2023

A Research Report from the National Center for Sustainable Transportation

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16. Abstract

In recent years, a number of "Smart Pedal" systems have emerged, both as automotive OEM equipment and as third-party hardware. These "Smart Pedal" systems can be installed in vehicles with the potential to reduce fuel consumption and GHG emissions by smoothing a driver's acceleration patterns, with little effect on travel time or safety. This research evaluates the potential effectiveness of a select "Smart Pedal" system for improving fuel economy and reducing GHG emissions in the Caltrans vehicle fleet. Following a literature review, the SmartPedal™ throttle controller, currently a $299 device that effortlessly attaches to the accelerator pedal, was selected for evaluation. The SmartPedal™ device corrects the accelerator pedal signal for micro accelerations caused by the influence of artifacts in the roadway on the driver's foot and the accelerator pedal. The SmartPedal™ technology was evaluated using six Caltrans vehicles instrumented with Global Positioning Systems (GPS) enabled Engine Control Unit (ECU) data loggers. ECU and GPS data was collected for a baseline period of vehicle operation without the SmartPedal™ device installed, followed by a period of operation with the SmartPedal™ device installed. For each test vehicle, the two datasets provided comparison data to evaluate the "Smart Pedal" technology. The amount of data in each collection period, in terms of distance, ranged from 548 miles to roughly 2,800 miles. An average fuel economy increase of up to 6.29% was observed for a vehicle with the "Smart Pedal" technology installed. The payback period for that scenario was evaluated based on the vehicle's average monthly mileage during the study period and was about 15.76 months. Two of the six vehicles showed a small fuel economy decrease (-0.52% and -1.72%), which suggests that the effect of uncontrolled parameters is significant. This study consisted of real-world operation and the contribution of factors such as changes in payload, number of passengers, driver, accessory usage, etc., is unknown. Despite the limitations of this study, results were largely in-line with larger case studies based on fleet fuel consumption data that showed fuel economy savings in the range of 1.5% to 16.8%.

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Disclaimer

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NCST

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Acronyms and Abbreviations

Acronym	Definition
CARB	California Air Resources Board
CE-CERT	College of Engineering – Center for Environmental Research and Technology
CSV	comma-separated values
ECM	engine control module
ECU	engine control unit
EPA	United States Environmental Protection Agency
GPS	global positioning system
MPG	miles per gallon
OEM	Original Equipment Manufacturer
RPM	revolutions per minute
UCR	University of California at Riverside

Evaluating the Effectiveness of “Smart Pedal” Systems for Vehicle Fleets

EXECUTIVE SUMMARY

The objective of this research was to evaluate the potential effectiveness of a “Smart Pedal” technology for improving fuel economy in the Caltrans vehicle fleet. Following a literature review, the SmartPedal™ throttle controller, currently a $299 device that effortlessly attaches to the accelerator pedal, was selected for evaluation. Unlike common throttle controllers that simply scale down the accelerator signal, the SmartPedal™ device corrects the accelerator pedal signal for micro accelerations caused by the effect of bumps in the road or vibration on the accelerator pedal. The SmartPedal™ technology was evaluated using six Caltrans vehicles instrumented with Global Positioning Systems (GPS) enabled Engine Control Unit (ECU) data loggers. ECU and GPS data was collected for a period of vehicle operation without the SmartPedal™ device installed, followed by a period of operation with the SmartPedal™ device installed. These two datasets provided comparison data to evaluate the “Smart Pedal” technology. The data collection periods ranged from 34 to 77 days, with most collection periods closer to the 60-day data collection target.

The average fuel economy for the baseline and the “Smart Pedal” technology data collection periods was determined from the ECU reported fuel rate for non-idle data with zero or positive road grade. An overall fuel economy of 6.29% was observed between the vehicles with the "Smart Pedal" technology and those without. Two of the six vehicles, however, showed a small fuel economy decrease (-0.52% and -1.72%), which suggests that the effect of uncontrolled parameters is significant. This study consisted of real-world operation and the contribution of factors such as changes in payload, number of passengers, driver, accessory usage, etc., is unknown. The amount of data in each collection period, in terms of distance, ranged from 548 miles to roughly 2,800 miles. The effect of uncontrolled parameters would be expected to decrease as the sample size increases. In case studies based on 255 thousand to 1.99 million miles of data, fuel economy savings from SmartPedal™ ranged from 1.5% to 16.8%, and despite the limitations of this study, results were largely in-line with larger case studies. The payback period was evaluated for the vehicle with the highest fuel economy increase (6.29%) and was estimated to be about 15.76 months. Fuel economy was also calculated for speed binned data, but here the sample sizes in each bin were smaller and results were mixed across the speed bins.

To limit the effect of uncontrolled parameters and increase confidence in the effectiveness of the SmartPedal™ device, further testing is recommended. Two options for additional testing are a study with a much larger sample size performed under real-world conditions or a study performed under more controlled conditions in which specific routes are driven repeatedly, alternating between the baseline and the SmartPedal™ technology, and ensuring that the driver, the number of passengers, vehicle payload, traffic conditions, road conditions, accessory

usage, and other parameters that could potentially affect fuel economy remain as constant as possible

1. Introduction

California has major initiatives for reducing greenhouse gas (GHG) emissions by 40% below 1990 levels by 2030, and 80% reduction below 1990 levels by 2050. In recent years, there have been a number of "Smart Pedal" systems that have emerged, both as automotive OEM equipment and as third-party hardware. These "Smart Pedal" systems can be installed in vehicles with the potential to reduce fuel consumption and GHG emissions by smoothing a driver's acceleration patterns, with little effect on travel time or safety. This research evaluates the effectiveness of a select "Smart Pedal" system in reducing fuel consumption and GHG emissions.

In this study, a technology search was performed to identify existing "Smart Pedal" systems, followed by the selection of a promising "Smart Pedal" technology for evaluation. The selected technology was tested under real-world conditions to evaluate the usability, effectiveness, and potential savings of the system. Based on observations and testing, a cost benefit analysis was conducted to determine the economic benefit of deployment in the Caltrans fleet vehicles.

Six vehicles from the Caltrans fleet were identified for testing and Global Positioning System (GPS) enabled Engine Control Unit (ECU) data logging devices were installed on those vehicles. Baseline data was collected during the first phase of data collection prior to the "Smart Pedal" technology being installed, followed by the second phase of data collection after "Smart Pedal" installation. The target period for data collection for each phase was 2 months, after which the researchers evaluated the data to determine the relationship between vehicle activity, fuel economy, and GHG emissions. The observed fuel economy savings from test results was applied to Caltrans vehicle activity to determine the potential cost effectiveness of the system and payback period. Future phases may include a much larger pilot program, covering a larger number of vehicles in the fleet over longer periods of time.

1.1 Project Objectives and Report Organization

The objective of this research was to select a "Smart Pedal" technology and evaluate its effectiveness in reducing fuel consumption and GHG emissions from vehicles in the Caltrans fleet. To achieve the project objectives, the research team at the University of California Riverside (UCR) performed the following research tasks: 1) review of "Smart Pedal" technologies, 2) collection of vehicle ECU and activity data under real-world operating conditions for periods with and without the installation of the "Smart Pedal" technology, 3) analysis of baseline and "Smart Pedal" activity to determine technology benefits, and 4) evaluation of Caltrans' fleet activity data with respect to the technology benefit to determine the cost benefit of implementing the selected "Smart Pedal" technology. The research activities and results are presented in this report and are organized as follows:

- Chapter 2: Literature review of existing "Smart Pedal" technologies and selection of "Smart Pedal" technology for evaluation.
- Chapter 3: Field operational tests including data collection and equipment installation.
- Chapter 4: Provides analysis, results, and discussion.

- Chapter 5: Presents research conclusions and recommendations.

2. Literature Review and Technology Selection

The following section is a review of existing "Smart Pedal" technologies. These technologies can be grouped into two basic categories: haptic feedback pedals and throttle controllers. Haptic feedback pedals are discussed in Section 2.1 and throttle controllers in Section 2.2. In Section 2.2.1, the SmartPedal^{TM} system is discussed and presented as the selected "Smart Pedal" technology for evaluation in this project.

2.1 Haptic Feedback Pedals

Haptic pedals have long been considered to promote eco-driving behavior. They function by providing the driver with an increased force at the pedal or other haptic effect such as vibration, bumping, or pulsing. An increased pedal force can be used to discourage vehicle acceleration by the driver beyond a certain threshold and haptic effects can be used to alert or signal the driver for various purposes such as speed control, collision avoidance, car-following, or shifting. Haptic feedback can be found in vehicles from several car manufactures, some of which are presented in this section.

2.1.1 Nissan ECO Pedal

The Nissan ECO Pedal is a technology that was commercialized in 2009 and helps drivers become more fuel efficient. When the ECO Pedal system is engaged, each time the driver exerts excessive pressure on the accelerator pedal, the system counteracts with a pedal push-back control mechanism (tactile indicator) to prevent excessive revving up of the engine. At the same time, the current fuel efficiency is indicated through the color and flashing of the ECO-P lamp (visible indicator). According to Nissan marketing and internal research data, studies show that effective eco-driving behavior with ECO Pedal drive assist contributes to improved fuel efficiency by 5-10% under most driving conditions.

The ECO Pedal system monitors the rate of fuel consumption and transmission efficiency during acceleration and cruising, and then calculates the optimum acceleration rate. When the driver exerts excess pressure on the accelerator, the system counteracts with the pedal push-back control mechanism. At the same time, the eco-driving indicator incorporated on the instrument panel indicates the optimal level for fuel-efficient driving. Driving within the optimal fuel consumption range, the indicator is green. It begins to flash when it detects increased acceleration before reaching the fuel consumption threshold and finally turns amber to advise the driver of their driving behavior. ECO Pedal and ECO-P lamp operation is depicted in Figure 2-1.

Nissan uses a "triple-layer" approach to reducing CO_2 emissions that focuses on three elements: the vehicle, the driver, and traffic conditions. The ECO Pedal supports the second-layer, addressing driving behavior, and is among a range of eco-friendly technologies being pursued under the Nissan Green Program 2010 [1]

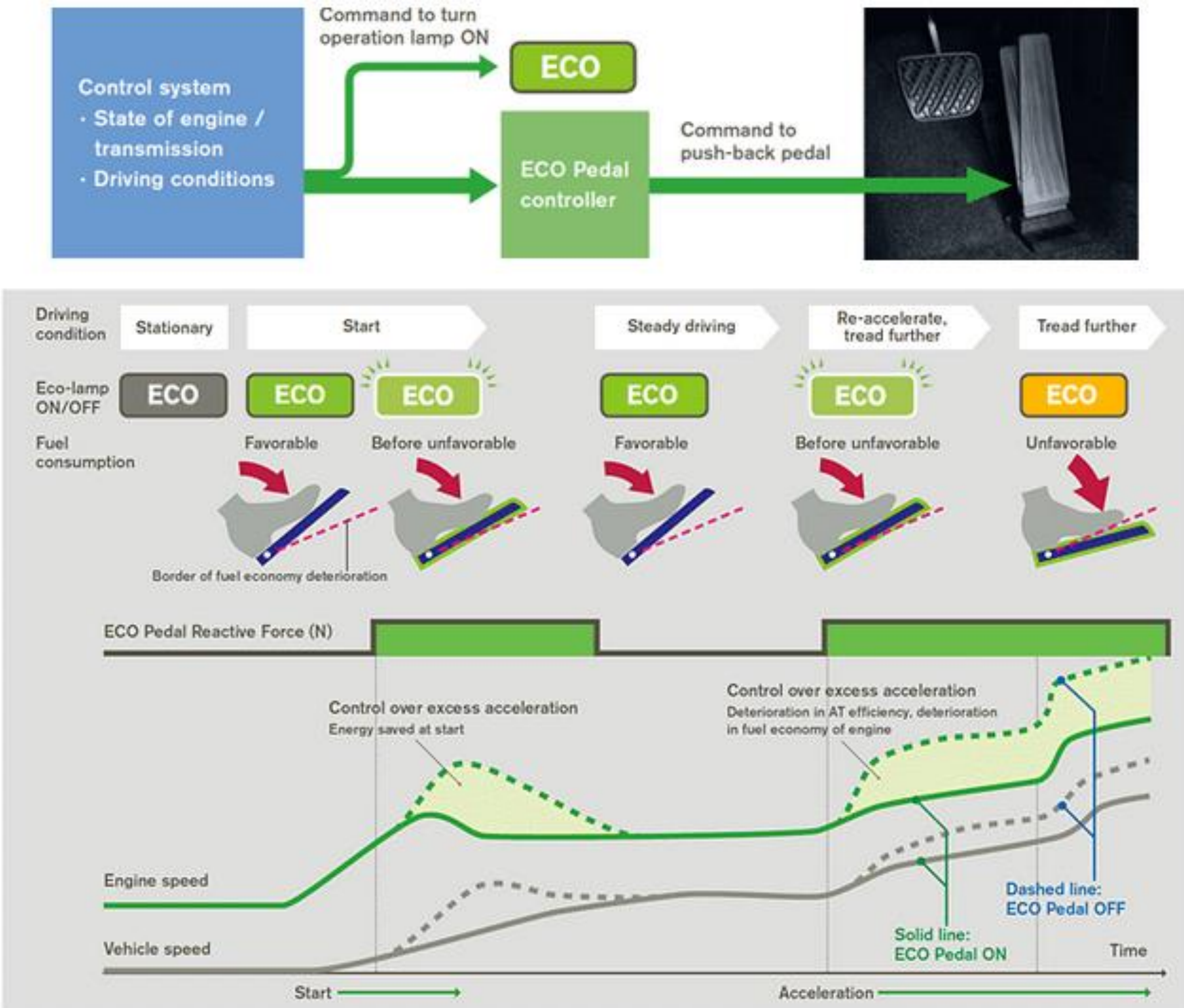

Figure 2-1. Nissan ECO Pedal Operation [1]

2.1.2 Bosch Active Gas Pedal

In 2016, Bosch introduced its Active Gas Pedal which is a "smart" gas pedal that uses haptic feedback such as pedal vibration, knocking, or applied counter pressure when the driver is applying the throttle too aggressively to teach the drivers efficient driving habits and alert drivers of safety concerns. Bosch claims up to a 7% savings in fuel consumption due to more efficient driving. [2]

2.2 Throttle Response Controllers

Throttle response controllers or throttle controllers operate by changing the way the vehicle's ECU interprets input from an electronic accelerator pedal and the rate at which the throttle input is applied to the engine. This is done by remapping the throttle response to the pedal position. Throttle controllers are often used to improve vehicle performance by reducing accelerator pedal lag and increasing acceleration. A throttle controller can also be used to manage fuel consumption and improve fuel economy by dampening the throttle response relative to the pedal position. Figure 2-2 shows the operation of a popular throttle response controller, Pedal Commander, and how the throttle response to the accelerator pedal position is remapped. In this figure, the throttle response in relation to the accelerator pedal position is increased for increased acceleration performance in sport modes and decreased for fuel management in the ECO mode. Pedal Commander claims that the device can achieve up to 20% fuel savings.

One of the features of throttle response controllers is ease of installation. Typically, the throttle response device is connected at the accelerator pedal connection to the wiring harness as seen in Figure 2-3. In order to install the device, the user simply disconnects the connector from the wiring harness into the accelerator pedal, plugs one end of the throttle controller into the wiring harness connector and the other end into the accelerator pedal. Some throttle controllers, such as the Pedal Commander, have control panels that allow the user to easily change the operating mode of the throttle controller.

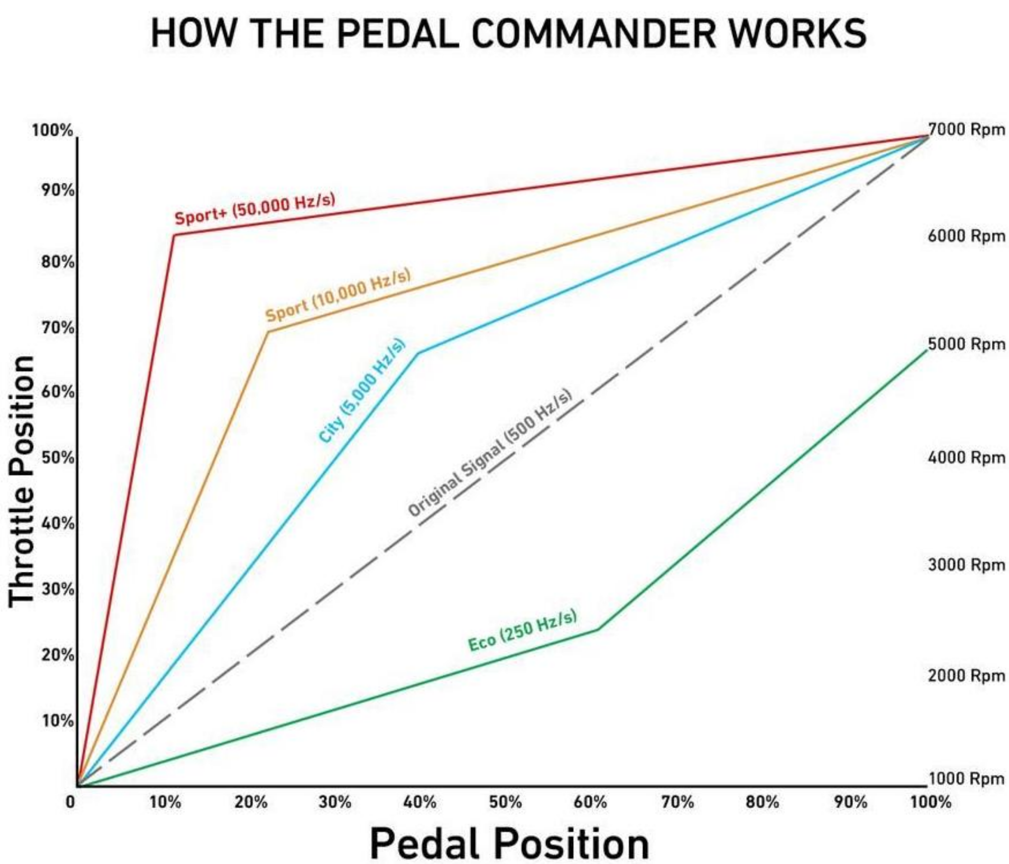

Figure 2-2. Example of throttle response controller signal modification [3]

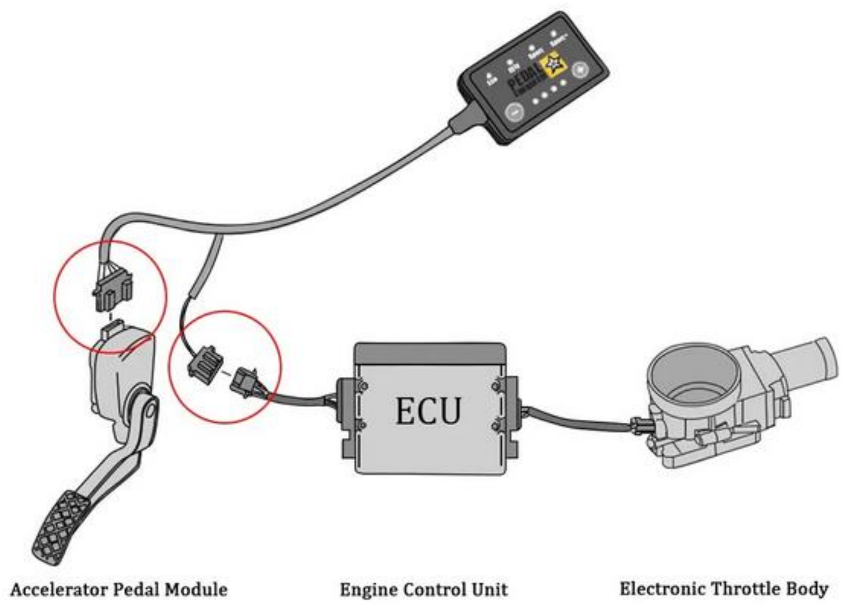

Figure 2-3. Typical throttle controller installation [3]

2.2.1 Smart Pedal

SmartPedal^{TM} is a throttle response controller designed to improve vehicle fuel economy and range using a multi-patented technology to correct the signal from the electronic accelerator pedal found on most electric, hybrid, and gas-powered cars and trucks. Built-in sensors on the SmartPedal^{TM} monitor vehicle motion and a second set of sensors tracks driver and pedal interaction by electronically monitoring the position of the accelerator pedal. SmartPedal^{TM} analyzes the sensor data dozens of times a second using a powerful 32-bit processor to determine the influence of the roadway on the driver's use of the pedal. Micro-accelerations related to artifacts in the roadway (bumps, potholes, etc.) are identified by the SmartPedal^{TM} device which then electronically corrects the pedal signal to eliminate unwanted changes in power. Figure 2-4 shows an example of a SmartPedal^{TM} accelerator pedal signal correction. The SmartPedal^{TM} device is also programmed with a pedal-to-metal override feature which temporarily suspends corrections to the pedal signal when the user presses the accelerator pedal 90% or more of the way to the floor.

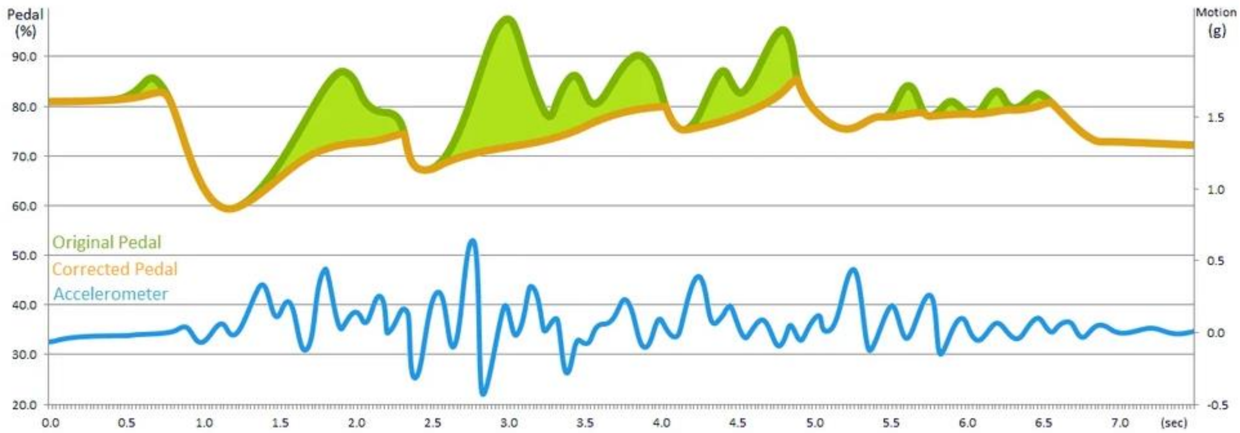

Figure 2-4. Depiction of SmartPedal™ accelerator pedal signal correction

The SmartPedal™ controller is a small device, Figure 2-5, that can be installed in a few minutes as depicted in Figure 2-6. The device is installed inline between the accelerator pedal and the accelerator pedal connector to the wiring harness leading to the ECU. The cost of the SmartPedal™ device at the time of this work is $299 per unit.

Figure 2-5. SmartPedal™ device

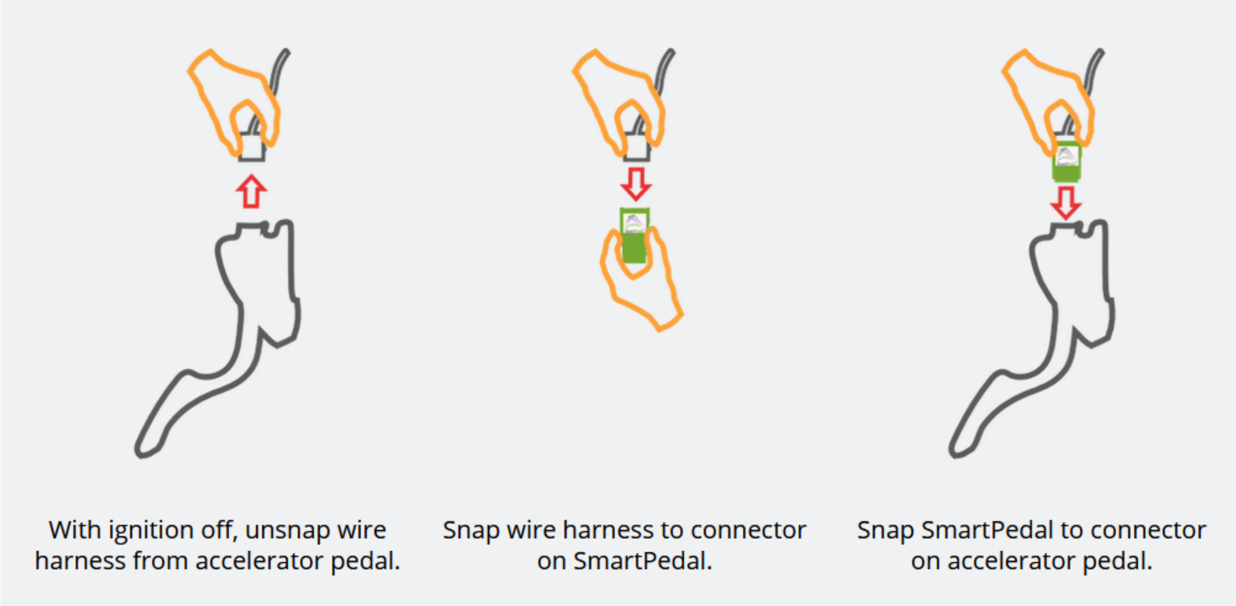

Figure 2-6. SmartPedal™ installation steps

2.2.2 Case Studies

The SmartPedal™ device was evaluated in three case studies that are documented on the SmartPedal™ website. The studies were performed on vehicles from three different vehicle fleets and included a variety of vehicle types. The studies and their results are summarized in Table 2-1.

In one study, the City of Oakland California installed SmartPedal™ devices on the city's electric and hybrid vehicle parking enforcement fleet in an effort to improve the fleet fuel economy and range. The test vehicles included Prius C's and a quarter of the all-electric Leafs in the day-use fleet. Within a 7-month period, the City of Oakland observed a 5.6% to 10.3% increase in hybrid and EV mileage.

In the County of Nevada in California, SmartPedal™ devices were deployed on 200 county vehicles including Ford C-Maxes, Escapes, Tauruses, Explorers, F-150s, and Transit Connect vehicles as well as Toyota Rav4s. The results showed a 1.5 to 16.8% increase in fuel economy over a two-year period. This equated to a 2.3 year payback for full investment at a cost of $299 per vehicle.

In a metropolitan public transportation system study in St. Louis Missouri, SmartPedal™ was installed on vehicles in the Call-A-Ride system. These were primarily Aero Elite vehicles built on the Chevrolet C4500 chassis. Each vehicle's regular usage is approximately 4,000 miles of monthly driving and 6,000 gallons of diesel consumption annually. In an eight-month period with over 1.2 million miles of driving, a 6.17% increase in fuel economy was observed. The payback period in this study was found to be 18 months.

Table 2-1. SmartPedal™ case study summary

Location	Fleet Size	Study Date	Duration	Study Miles	Fuel Savings	Emission Savings
Oakland, CA	Installation # Unknown Total Fleet 1,800	5/24/2018 – 12/31/2018	7 months	255k	Mileage gains: Prius C 5.6%, Leaf 10.3%	Estimated savings of 300,000 lbs of CO2 per year for this fleet with mileage increase of 5%
Nevada County, CA	Installation # Unknown Fleet 300	6/16/2018 – 6/15/2019	24 months	1.99 million	MPG Gain: C-Max 9.0%, Escape 6.7%, Explorer 1.5%, F-150 16.8%, Trans Conn 6.7%, RAV4 2.7%, Taurus 5.9%, Combined 7.0%	Estimated savings of 225,000 lbs of CO2 per year for this fleet of 300 vehicles
St. Louis, MO	Installed on 37 Vans, Installed on 13 Vans as Control Group Fleet 120 Vans	7/1/2016	8 months, late summer through early winter	Roughly 1.3 million	MPG Gain: Primarily Chevrolet C4500 6.17%	Estimated savings of 370 gallons of diesel per vehicle per year. This equates to roughly 8,280 lbs of CO2 per vehicle per year

2.3 Technology Selection

One of the objectives of this research work was to identify a suitable "Smart Pedal" technology for evaluation. Following review of the available technologies and discussions with Caltrans staff, the UCR research team selected the SmartPedal™ throttle controller from SmartPedal Labs for evaluation. The SmartPedal™ device was selected for the following reasons:

- The manner in which the SmartPedal™ device modified the throttle control signal seemed to have less of an impact on driving performance than the typical throttle controller in ECO mode which dampens the entire throttle response curve. The SmartPedal device has motion sensor which it uses to measure motion from bumps in the road and identify related unwanted micro-accelerations.
- The SmartPedal™ device is dedicated to improving fuel economy and does not have performance modes which users can easily access via an external control unit. The

SmartPedal^{TM} device is invisible to the user without having to hide an external control unit that is common to many throttle controllers.

- The SmartPedal^{TM} device has several case studies that demonstrated substantial fuel savings in several large service fleets similar to the Caltrans vehicle fleet.

3. Field Testing

Field testing was performed on six vehicles from the Caltrans fleet. The data collection period was split into two phases, the baseline phase and the technology phase. In the baseline phase, test vehicles were equipped with data loggers and monitored for a target period of two months. During the technology phase, the test vehicles were equipped with the selected "Smart Pedal" technology and monitored for a target period of two months. The following section provides details on the test vehicles, test vehicle selection, technology installation, and data collection.

3.1 Test Vehicles

Six vehicles were selected for testing for this project to evaluate the SmartPedal™ technology. Test vehicles were selected based on their prevalence in the Caltrans fleet, their compatibility with the SmartPedal™ device, and how easily ECU data could be accessed. The first step in the selection process was to identify and quantify the Caltrans light duty and medium duty car and truck fleet and identify vehicle types for which the SmartPedal™ technology was available. The basic fleet composition, in declining order based on vehicle count, is presented in Figure 3-1. The vehicle fleet consisted of a high number of pickup trucks, so these became the main focus of the project. Initially, the Chevy Bolt, an all-electric vehicle, was also included since the SmartPedal™ device was available for that vehicle and an all-electric Leaf showed 10% energy savings in the Oakland study. The Chevy Bolt was eventually dropped as a test vehicle following issues with data collection related to the proprietary nature of the desired OBD PIDs.

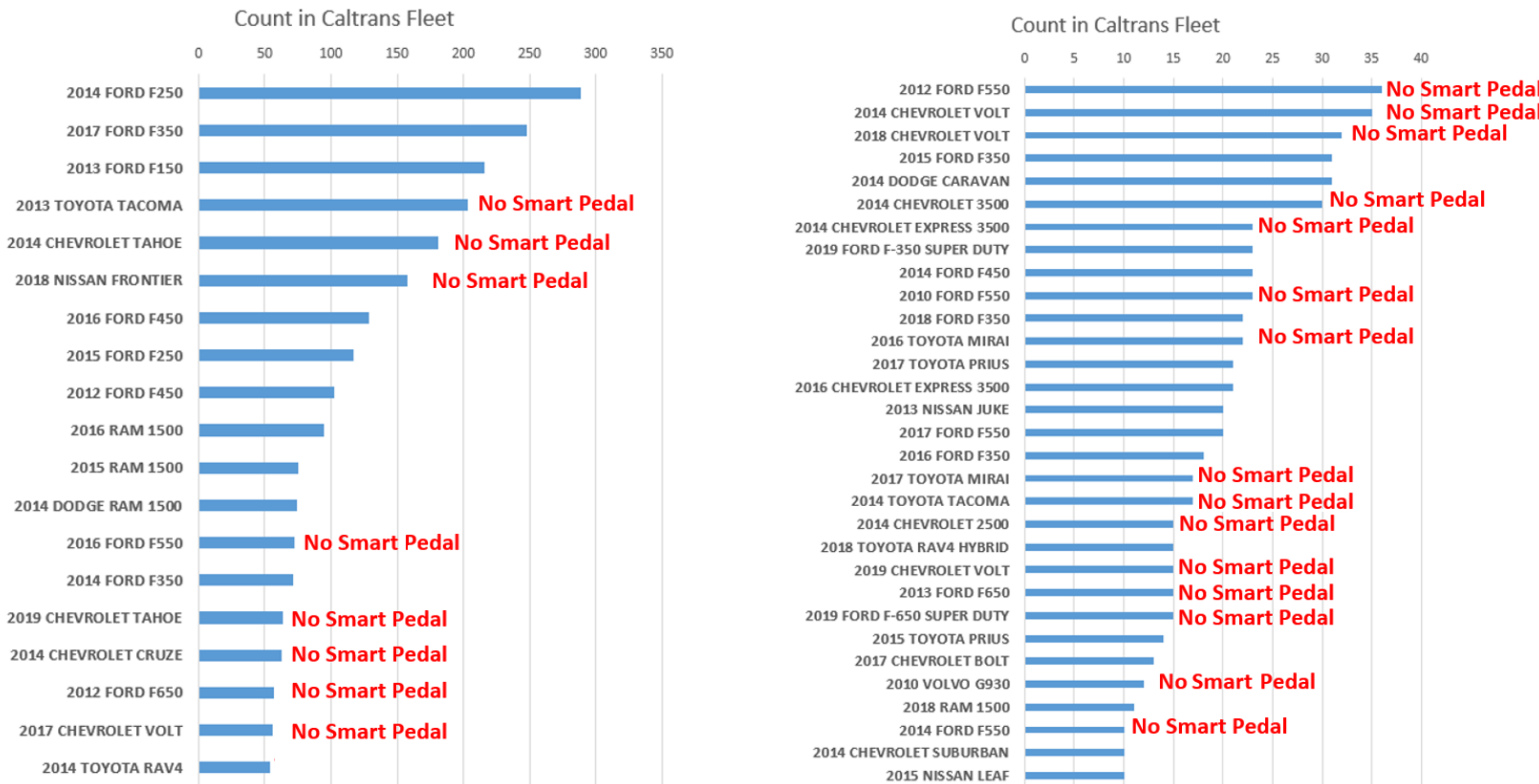

Figure 3-1. Caltrans fleet composition and availability of SmartPedal™

Additional considerations for vehicle selection were the vehicle's frequency of use and proximity to the research team. The final vehicle test matrix is presented in Table 3-1.

Table 3-1. Vehicle Test Matrix

Model Year	Make	Model	GVWR lbs
2013	Ford	F-150	6700
2013	Ford	F-150	6700
2015	Ford	F-250	10000
2019	Ford	F-350	11500
2016	Dodge	Ram 1500	6800
2015	Dodge	Ram 2500	9000

3.2 Data Collection

Data was collected in two phases for each test vehicle. The first phase was the baseline phase during which each vehicle was monitored under regular operating conditions without any "Smart Pedal" technology installed. This data serves as the base case for comparison. During the second phase, each vehicle was instrumented with the SmartPedal™ device and monitored under regular operating conditions. General test information is provided in Table 3-2, including data logger installation date, SmartPedal™ installation date, and number of installation days, hours of operation, and miles driven by each vehicle during each testing phase. The target test period was two months for each phase, however the exact date varied depending on technical and scheduling issues.

Table 3-2. Activity Data Collection Test Matrix

Vehicle	Logger Number	HEM Logger Install Date	SmartPedal Install Date	Data Collection End Date	Baseline				SmartPedal			
					Number of Days Installed	Number of Days Operating	Hours of Data	Miles Driven	Number of Days Installed	Number of Days Operating	Hours of Data	Miles Driven
2019 Ford F-350	3001	8/10/2022	10/12/2022	12/18/2022	63	25	75.63	994.8	67	47	123.96	2,068.9
2013 Ford F-150	3002	8/10/2022	10/12/2022	12/18/2022	63	40	45.53	1,298.2	67	39	40.81	1,204.7
2016 Dodge Ram 1500	1200[a]	8/10/2022	10/26/2022	12/12/2022	77	29	32.01	1,145.0	47	21	22.86	754.4
2015 Ford F-250	3003	8/12/2022	10/12/2022	12/18/2022	61	10	17.75	548.0	67	32	108.23	2,793.4
2015 Dodge Ram 2500	3004	8/12/2022	10/12/2022	12/18/2022	61	27	142.4	2,373.5	67	26	128.52	2,221.9
2013 Ford F-150	3005	9/30/2022	11/14/2022	12/18/2022	45	28	31.65	1,116.0	34	23	35.78	1,269.8

[a] This is a 3G logger that does not broadcast and data needs to be downloaded

3.2.1 Data Logger

Data from each vehicle's engine control unit (ECU) was collected using the GPS enabled J1939 Mini Logger™ from the HEM data corporation. The data loggers are configured to collect upwards of 200 ECM parameters at a frequency of 1 Hz. A subset of the type of data collected is provided in Table 3-3. The data loggers communicate with the engine's ECM/OBD through industry standard communication protocols. The data loggers are also equipped to collect GPS data on a second-by-second basis. The GPS is capable of measuring the vehicle's location (latitude and longitude) and altitude, from which speed can also be derived. The HEM data loggers are a small unit that can be attached quickly to a vehicle's 16 pin J1962 OBD II port under the driver's side dashboard. Figure 3-2 shows the OBD II port under the dashboard and Figure 3-3 shows the HEM Mini Logger. The HEM data loggers remained installed for the duration of both data collection periods and are set up to record from engine on to engine off. The data loggers accept SIM cards which allow the units to broadcast data via cellular transmission. One of the loggers used was an older model that only supported 3G networks, while the five other loggers were new and supported 4G networks. The 3G logger was no longer supported since 3G networks were in the process of being phased out. For this logger, the vehicle was brought in periodically and the data was downloaded manually. For the 4G loggers, the data was broadcasted automatically by the HEM to the CE-CERT data server.

Table 3-3. Key ECU/GPS Parameters

ECU Data	GPS Data
Wheel based Vehicle Speed	Velocity
Engine Load Percentage	Latitude
Engine Actual Torque Percentage	Longitude
Engine Frictional Torque Percentage	Altitude
Engine Reference Torque	Date and Time
Engine RPM	Number of Satellites Fixed
Fuel Rate	Fix Quality
Exhaust Temperature	Position Dilution of Precision
Equipment Speed	

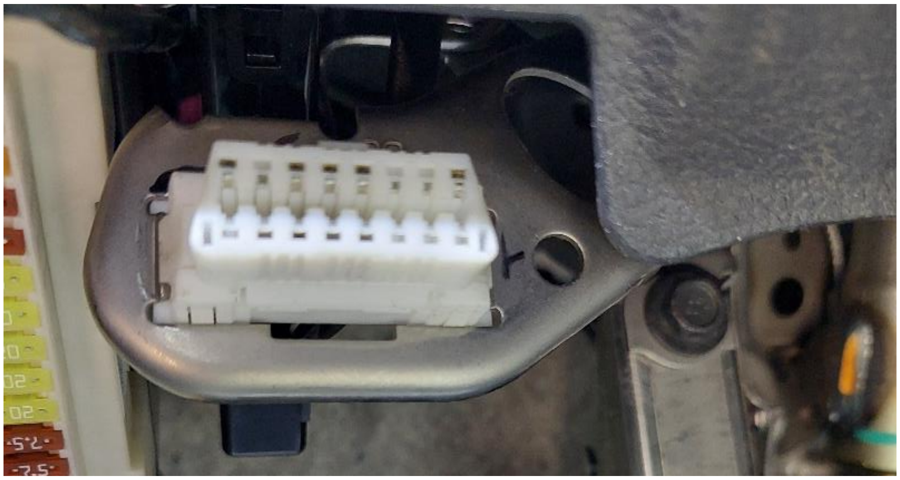

Figure 3-2. 16-pin J1962 OBD II port

Figure 3-3. HEM Mini Logger and installation

Early on in the project, there was a concern that the HEM data loggers might not work alongside the Geotab Fleet Management system that Caltrans uses. The Geotab system consists of a data broadcasting device (Geotab GO), see Figure 3-4, that is connected to the OBD II port, similar to the HEM data logger. In order for the Geotab device to share the OBD II port, it was attached to the OBD II port via a splitter cable with two ports as shown in Figure 3-5. This allowed both the Geotab and HEM data logging devices to be installed at the same time. Early testing of the HEM logger functionality indicated that there was no apparent conflict between the two devices.

Figure 3-4. Geotab GO monitoring device

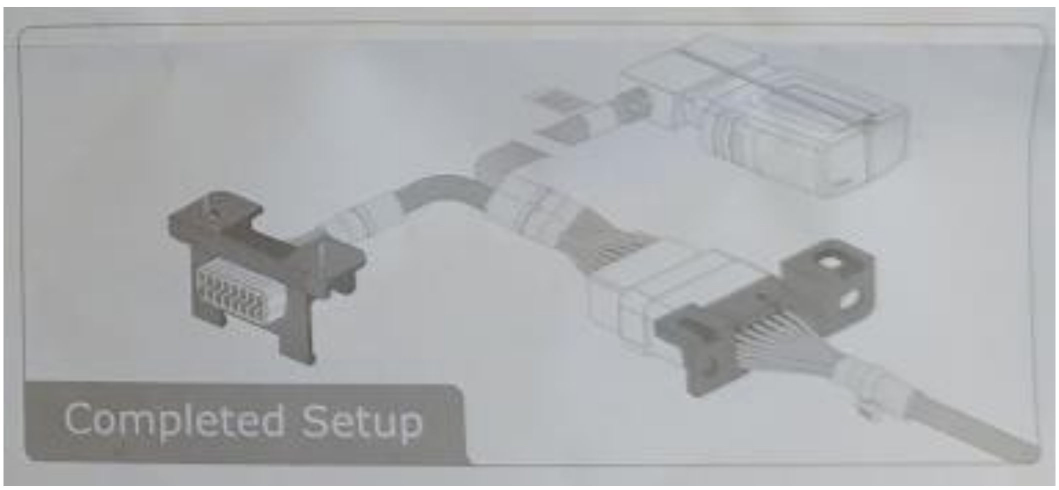

Figure 3-5. Geotab GO system installed with splitter cable from OBD II port

3.2.2 SmartPedal™ Installation

Following data collection for the baseline period, each vehicle was instrumented with the SmartPedal™ device, and data was collected for the SmartPedal™ technology phase. The SmartPedal™ device has more than four driving modes. Modes 1 and 2 are more conservative and are designed to make adjustments invisible to the driver. Mode 3 is the default mode which is designed to be unnoticeable for most drivers, yet deliver strong mileage performance. This is the mode that SmartPedal™ recommends as the best compromise between mileage and preserving performance. Mode 4 and higher are increasingly more aggressive and designed to generate better mileage. The more aggressive the pedal signal correction, the more likely the driver will notice an impact on performance. For this research work, the SmartPedal™ devices were left in mode 3, the default recommended driving mode, and left to self-calibrate through the use of the vehicle.

The actual installation of the SmartPedal™ device is a simple process that only takes a few minutes. The SmartPedal™ device is installed at the electrical connection between the electronic accelerator pedal and its connector from the ECU wiring harness as shown in Figure 3-6. Figure 3-6a shows the electronic accelerator pedal connected to the ECU wiring harness connector in its standard configuration. In the first installation step, the accelerator pedal ECU wiring harness connector is disconnected from the accelerator pedal and connected to the SmartPedal™ device as shown in Figure 3-6b. The SmartPedal™ device is then connected to the accelerator pedal electronic connection as shown in Figure 3-6c.

Figure 3-6. A) Electronic accelerator pedal without SmartPedal™ installed, B) SmartPedal™ connected to accelerator pedal wire harness connection, C) SmartPedal™ installed inline between accelerator pedal and accelerator pedal wire harness connection.

The SmartPedal™ devices are specific for particular vehicle models and range of model years. Figure 3-7 shows several of the SmartPedal™ units from the project and the range of vehicles for which each unit is compatible.

Figure 3-7. Vehicle specific SmartPedal™ units

3.2.3 Data Processing

There were several data processing steps that were performed in order to analyze the data collected from the HEM loggers. The main data processing steps are described here.

1. ***Data Conversion***: The J1939 Mini Logger™ creates two files for each trip: a .GPS file that logs the GPS data and a binary .IOS file that logs the ECM data. The DawnEdit™ software from the HEM Data Corporation, with the appropriate conversion database, was used to convert and align a binary .IOS data file with its accompanying .GPS file into a single comma-separated value (CSV) data file.
2. ***Data Aggregation***: HEM data loggers generate test data pairs for each engine on event. In some cases, during an engine on event, an interruption occurs and the engine on event is split into two or more sections. During the processing step, all of the separate data files are concatenated in chronological order into a single data file for each vehicle.
3. ***Data Cleaning***: The CSV data files produced by the DawnEdit software went through several data cleaning procedures. For this work, data points outside of the realistic range of operation for each parameter were replaced with not-a-number (NaN) values. This effectively removes the data point from the research analysis. In some cases, a smoothing algorithm was used to compensate for the lack of resolution in a parameter (e.g., vehicle speed).

4. ***Vehicle Speed:*** Vehicle speed information was taken from the wheel-based vehicle speed parameter from the ECU (OBD II decimal PID 13). The speed data reported by the ECM is based on the rotational speed of the wheels and can be affected by general tire wear, changing wheel size, and manufacturer's settings. ECM based speed is also subject to errors in signal transmission and may show maxed out default values, data drops, or other anomalies. The units of wheel-based speed from the ECU are in km/hr and the maximum resolution is one km/hr. To compensate for this lack of resolution in the speed parameter, a slight smoothing algorithm using a 3-second moving average window (MAW), was applied to the velocity profile as shown in Figure 3-8.

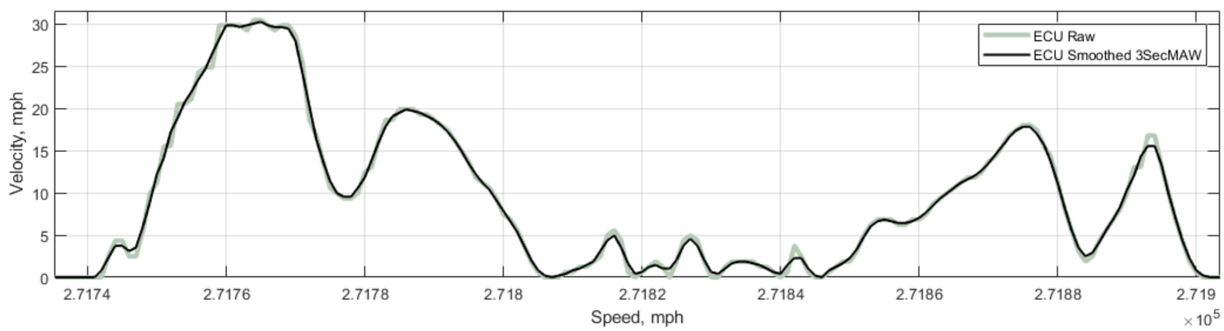

Figure 3-8. ECU velocity with 3-second moving average window smoothing

5. ***ECM Fuel Rate:*** The ECM fuel rate is important to analyze improvements in energy savings from the addition of a fuel saving technology. The real-time fuel rate information was based on the ECU data from the mass air flow (MAF) and the lambda sensor. For this research, all vehicles had mass air flow (MAF) sensors and the mass-air fuel rate information was provided by the ECU. The fuel calculation along with the fuel economy calculation were performed during the conversion process by the DawnEdit software and provided in the processed HEM data files.
6. ***Map Matching:*** Vehicle activity data was map matched based on the latitude, longitude, and heading information from the GPS data. The map matching results provided information on the road type and road grade for each second where map-matching data was sufficient. Road-type and road-grade were used to isolate similar data for comparison.

3.2.4 ECM Fuel Rate Issues

The data processing step described in Section 3.2.3 provides an instantaneous fuel economy value in MPG and an instantaneous fuel consumption value in mL of fuel. Figure 3-9 through Figure 3-14 provide histograms of the second-by-second fuel economy values for the combined baseline and SmartPedal^{TM} data for each test vehicle for positive grade values greater than zero. A review of the continuous MPG values shows that the reported MPG values for the Ford F-350 and the Dodge Ram 2500 are both centered around the mid 20's, an unrealistic fuel economy range for these heavier vehicles.

For this work, fuel economy was calculated using the distance traveled and the fuel consumed within a range as opposed to averaging the instantaneous fuel economy values within that range. Analysis presented in Section 4 shows that this fuel economy issue persists for these two vehicles for both the baseline and SmartPedal^{TM} data collection periods. The assumption is made that something in the ECU's calibration for fuel consumption and fuel economy is somehow off for these two vehicles, but that the problem is consistent throughout the dataset and therefore the data can still be used to calculate relative differences.

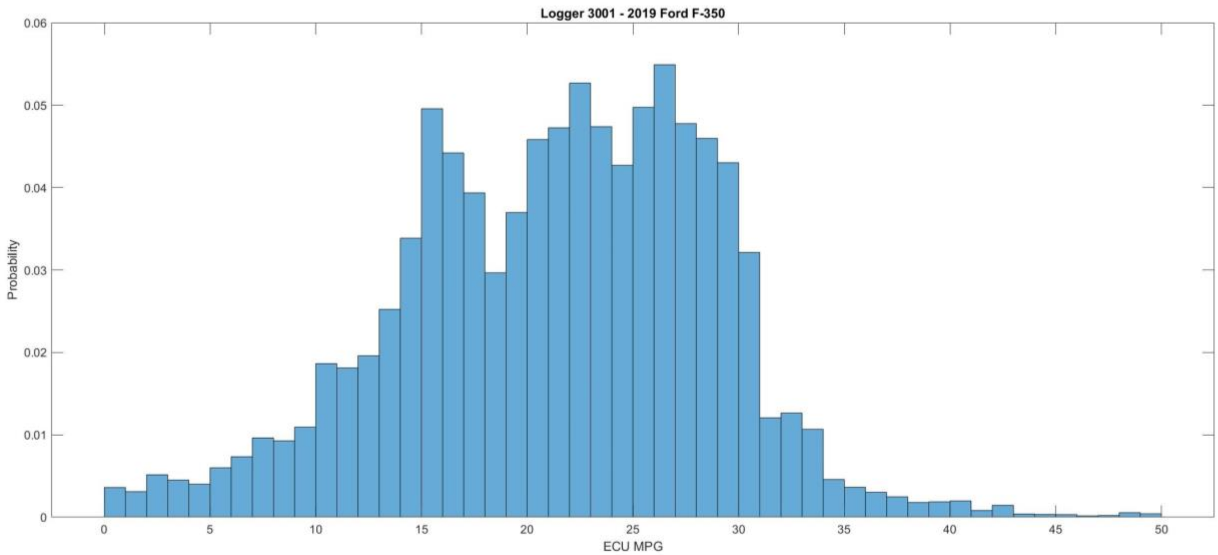

Figure 3-9. ECU MPG distribution for 2019 Ford F-350

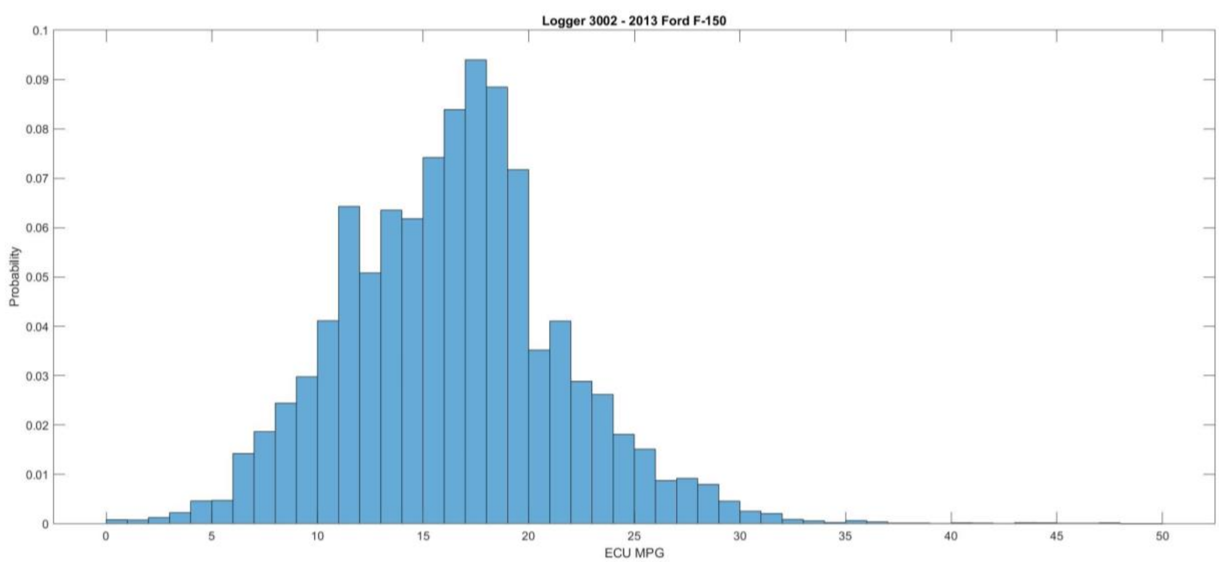

Figure 3-10. ECU MPG distribution for 2013 Ford F-150 (Logger 3002)

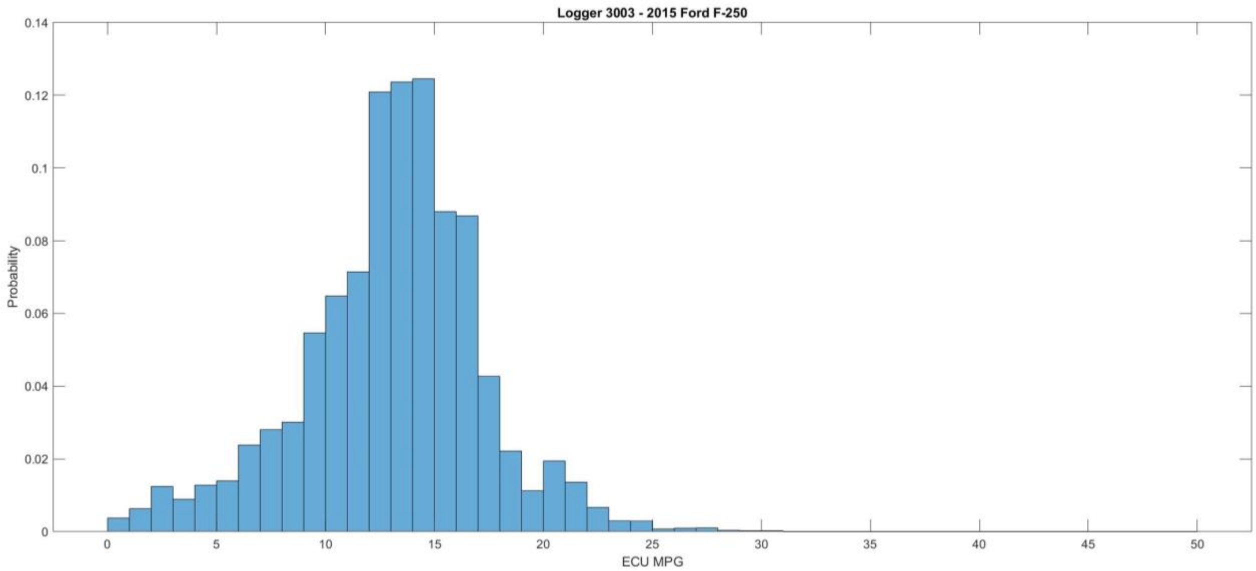

Figure 3-11. ECU MPG distribution for 2013 Ford F-250

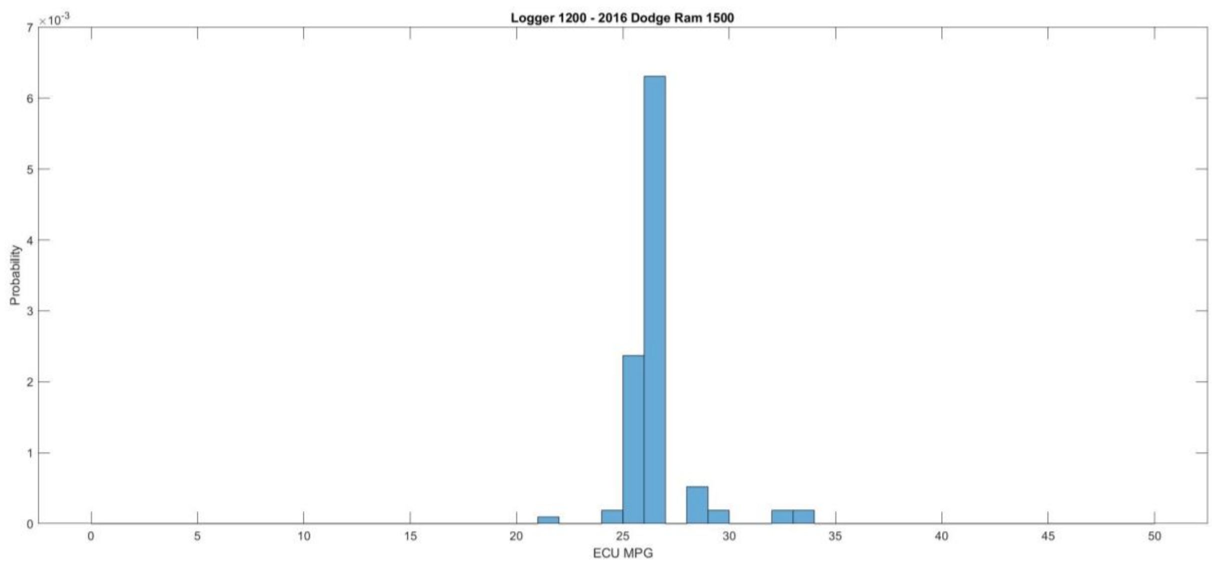

Figure 3-12. ECU MPG distribution for 2016 Dodge Ram 1500

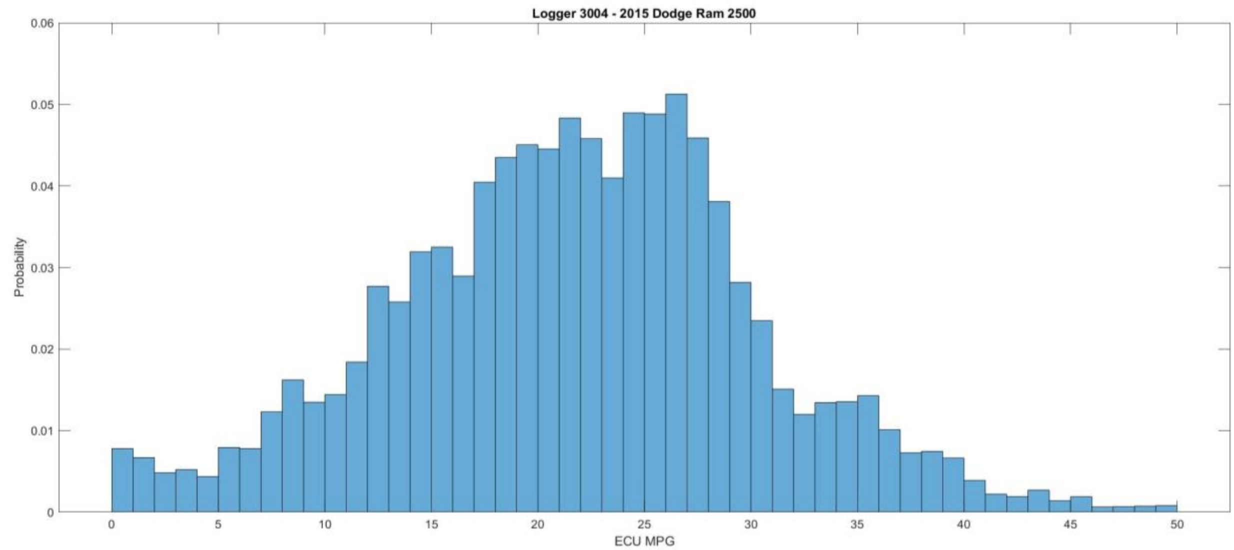

Figure 3-13. ECU MPG distribution for 2015 Dodge Ram 2500

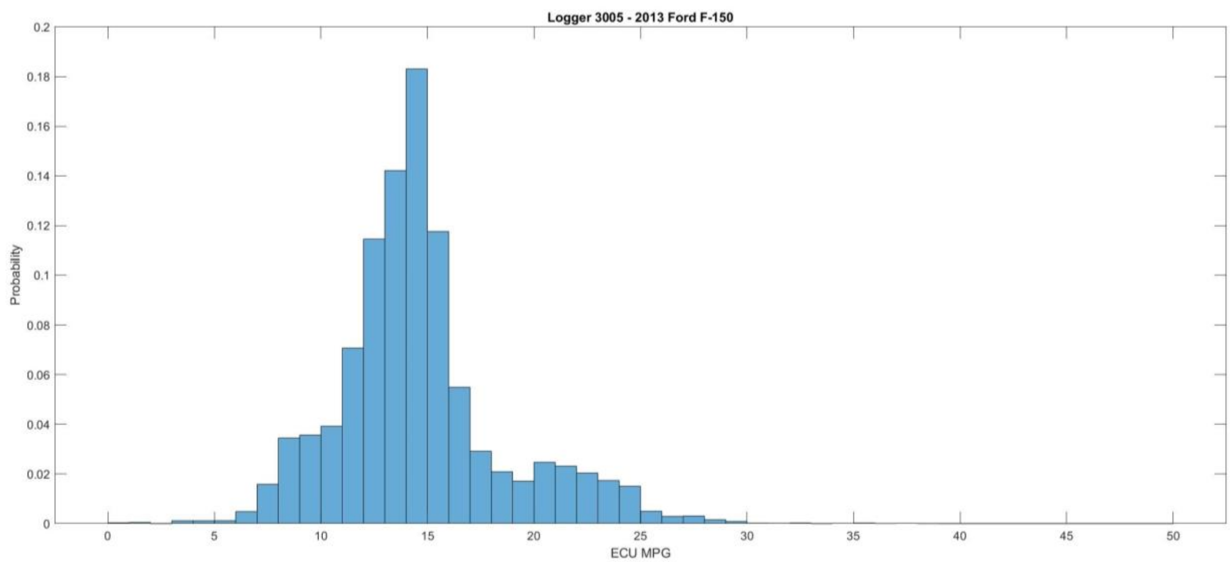

Figure 3-14. ECU MPG distribution for 2013 Ford F-150 (Logger 3005)

4. Analysis and Discussion

Data that was collected during the baseline and technology portion of this project were analyzed to determine the potential effectiveness of the SmartPedal^{TM} technology. This section describes analysis that was performed and provides results and discussion.

4.1 Factors Impacting Real World Fuel Economy

During field testing, there were a number of factors that could affect the vehicles' real-world fuel economy. If these factors differed significantly during the baseline and the technology data collection periods, then the real-world fuel economy numbers could be biased. Some of these potentially confounding factors are discussed below:

- **Vehicle factors** – A vehicle carrying more weight requires more energy to run, thus directly affecting its fuel economy. Tire pressure also has a significant effect on fuel economy. If an extra weight was put on the vehicle or the tire pressure was low for some parts of the field testing, then the fuel economy during those portions of the test period would be negatively impacted.
- **Road factors** – Climbing a steep road grade requires higher power from the engine to overcome the added gravitational force. This can put the engine in a power enrichment mode, which reduces the vehicle fuel economy. Driving on rough road surface also results in lower fuel economy.
- **Weather factors** – Weather affects vehicle fuel economy, both directly and indirectly. For instance, headwind reduces vehicle fuel economy as the vehicle needs additional power from the engine to combat the wind drag. Hot weather induces the use of air conditioning, which places accessory load requirement on the engine.
- **Traffic factors** – Traffic conditions heavily influence vehicle speed and driving patterns which can impact fuel economy significantly. Fuel economy varies by vehicle speed, with speeds on the low and high ends associated with decreases in fuel economy. Aerodynamic drag, for instance, increases rapidly with increasing vehicle speed. Another traffic related factor is the flow of traffic which is related to congestion level, road type (freeway vs. arterial), and driver aggressiveness. Stop-and-go driving, which is characteristic of congested traffic, has a negative impact on fuel consumption and fuel economy degrades significantly under this type of driving.
- **Driving patterns** – Similar to traffic factors, driving patterns have the potential to significantly influence fuel economy. Aggressive acceleration decreases fuel economy and in this study, there is no control for driving style or even that the driver of the vehicle is constant. Different drivers may have different driving patterns and the driver or drivers during one portion of testing may be different than during another. The impact of the SmartPedal^{TM} device is also expected to be somewhat less in situations where the vehicle is driven in a wide open throttle manner, as may be the case with heavy vehicles. Since these vehicles are not as sensitive to the accelerator pedal, they are often driven in a binary manner, either stop or go with the pedal to the floor.

Differences in travel patterns between the two data collection periods can cause bias associated with one or more of the factors described above. For instance, if a vehicle operated more on highways with constant flowing traffic during the baseline period and more in stop-and-go traffic on city streets during the SmartPedal™ period, then the change in fuel economy for this vehicle during the technology period might not be due to the effect of added technology alone since fuel economy is typically better in the case of constant speed driving relative to stop-and-go driving. Differences in routes could result in a vehicle experiencing a different amount of steep road grade, head wind, traffic congestion, etc. between the two data collection periods.

It is not practical to control for these factors for each test vehicle over months of data collection and under real-world operating conditions. For example, all the vehicles tested are trucks and the amount of payload that they were transporting or the number of passengers at any time is unknown. The extra weight of passengers or payload would certainly increase fuel usage and lower fuel economy.

In the absence of a large vehicle test pool and/or a large number of driven miles, where the impact of uncontrolled factors is more likely to wash-out, it is important to remove biases from the real-world fuel economy numbers as much as possible. This can help isolate the effect of the "SmartPedal™" technology on the fuel economy when comparing the baseline and "Smart Pedal" technology data collection periods.

4.2 Map Matching

Map-matching was performed on the collected data to help characterize vehicle activity, namely by identifying road type and road grade in the dataset. Map-matching was based on latitude, longitude, and vehicle heading information provided by the GPS. The map-matching process matched each data-point with valid GPS information to a link ID in a NAVTEQ network database. Information from the matched link ID, such as road type and road grade, were then assigned to the corresponding data point. This data was considered in the analysis.

4.2.1 Road Type

The map matching results provided information on the road type and road grade for each second where map-matching data was sufficient. Road type and road-grade were evaluated to determine if they impacted the comparison. Road type for each data set is presented in Figure 4-1 through Figure 4-6. Each of these figures depicts the arterial and freeway combined activity for the baseline and SmartPedal™ test periods.

Figure 4-1. Activity data for 2013 Ford F-150 (Logger 3005)

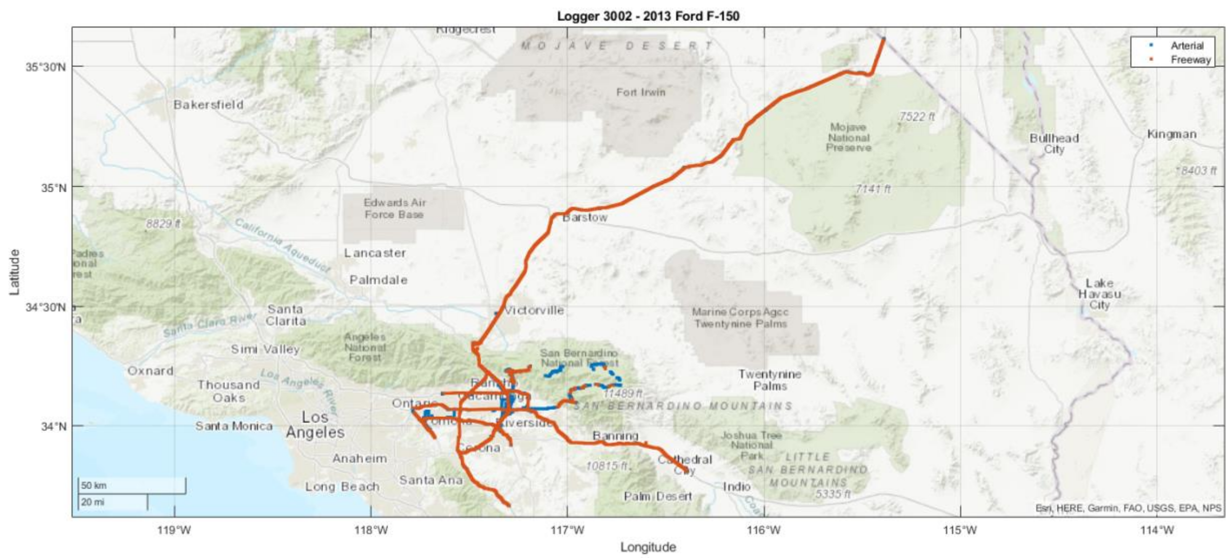

Figure 4-2. Activity data for 2013 Ford F-150 (Logger 3002)

Figure 4-3. Activity data for 2015 Dodge Ram 2500

Figure 4-4. Activity data for 2013 Ford F-250

Figure 4-5. Activity data for 2016 Dodge Ram 1500

Figure 4-6. Activity data for 2019 Ford F-350

4.2.2 Road Grade

The percent road grade was determined for each data point with valid GPS data based on map matching. Road grade is presented in Figure 4-7 through Figure 4-12, where vehicle freeway activity is colored by road-grade and separated by test phase. Some of the vehicle activity occurred on roadways with significant grade, as seen in Figure 4-13. This figure includes vehicle activity that occurred on the Cajon Pass on the I-15 and consisted of significant positive road grade heading up the pass (yellow) and negative road grade heading down the pass (blue). Vehicle speeds for the uphill and downhill portions are also likely not comparable, which means that the impact of excessive uphill grade on fuel economy would occur at lower speeds and the impact of excessive downhill grade on fuel economy would occur at higher speeds. The impact of downhill grade would increase fuel economy during both phases and uphill grade would decrease fuel economy. In an effort to limit the impact of road grade on the analysis, road grades were limited to positive road grades for both the baseline and SmartPedal^{TM} data sets.

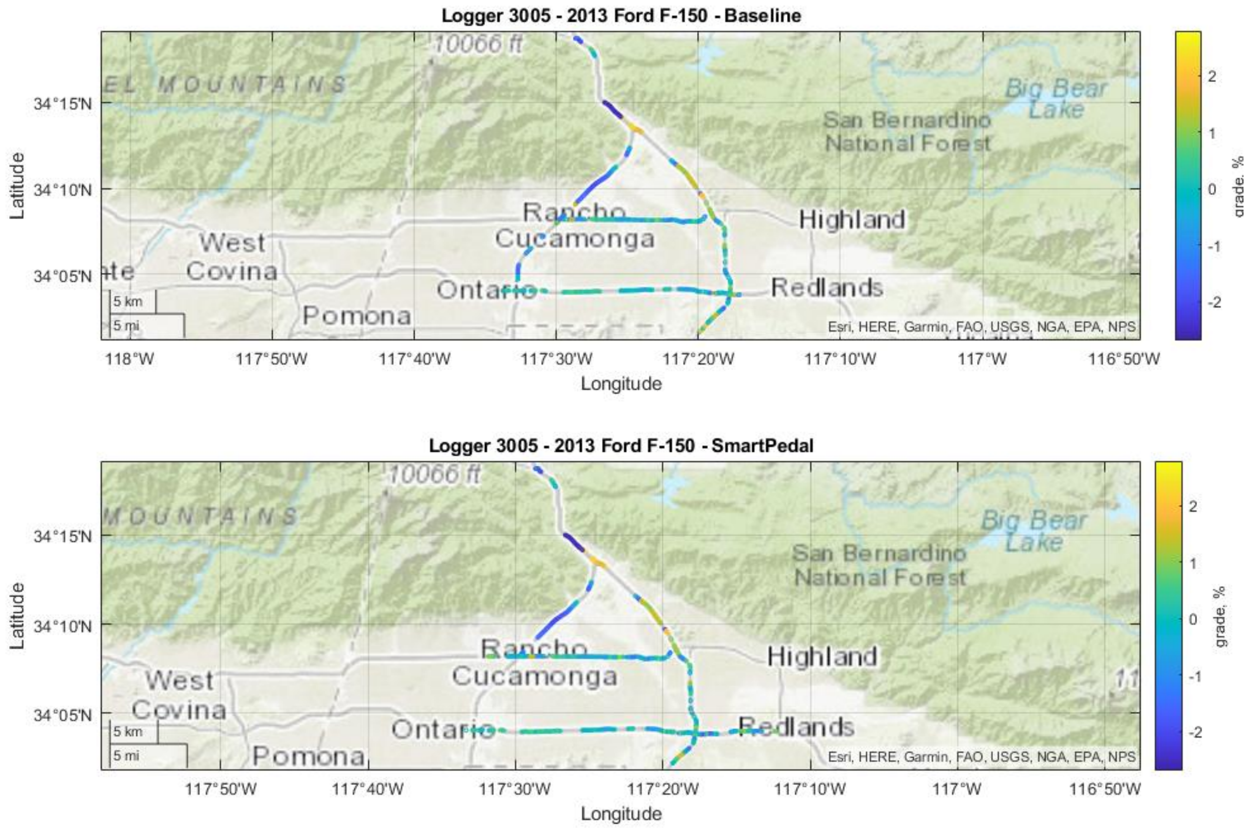

Figure 4-7. Activity for 2013 Ford F-150 (Logger 3005)

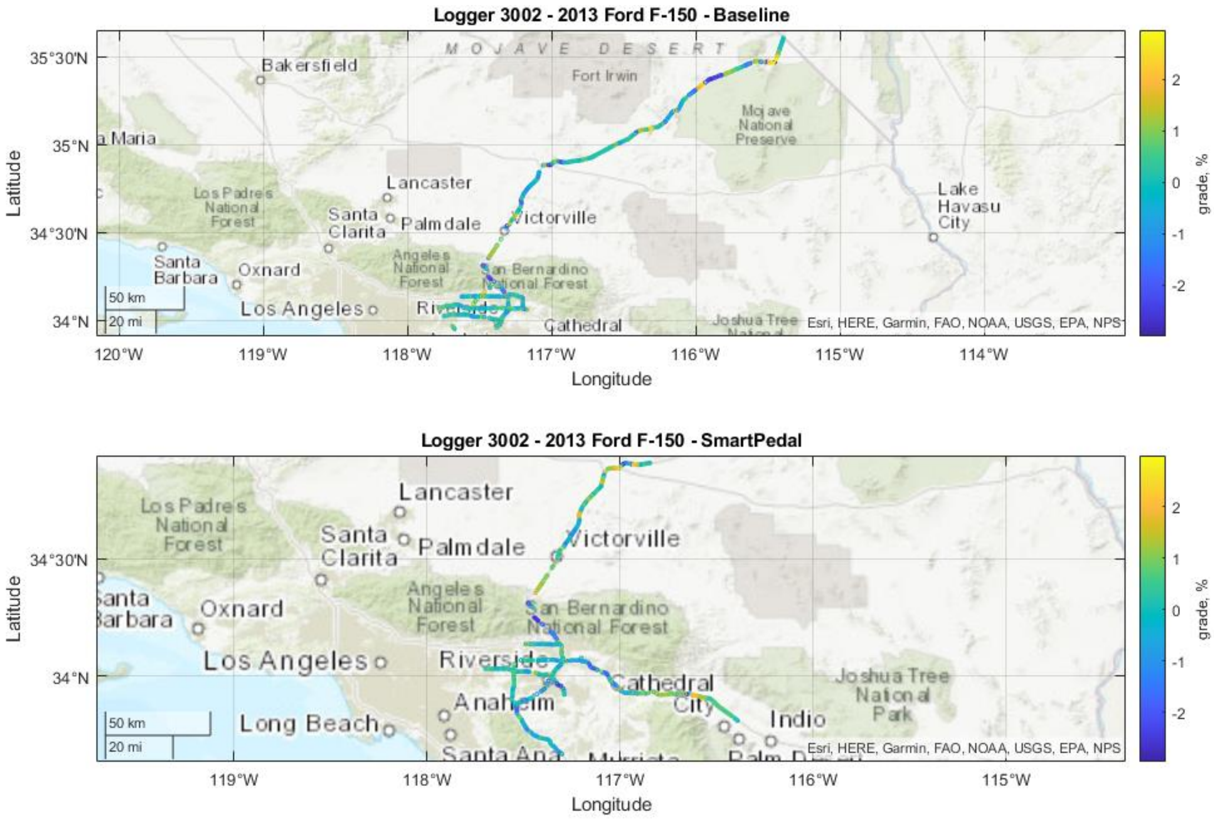

Figure 4-8. Activity for 2013 Ford F-150 (Logger 3002)

Figure 4-9. Activity for 2015 Dodge Ram 2500

Figure 4-10. Activity for 2013 Ford F-250

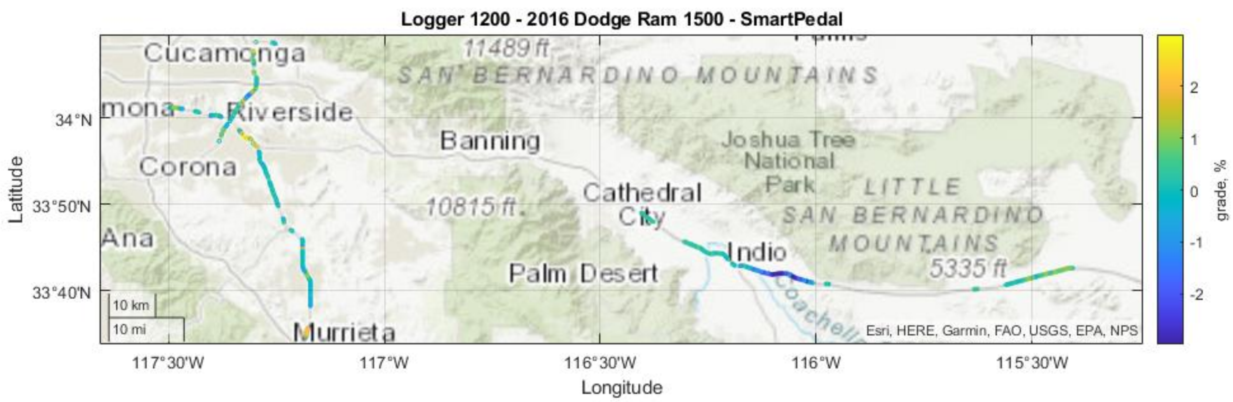

Figure 4-11. Activity for 2016 Dodge Ram 1500

Figure 4-12. Activity for 2019 Ford F-350

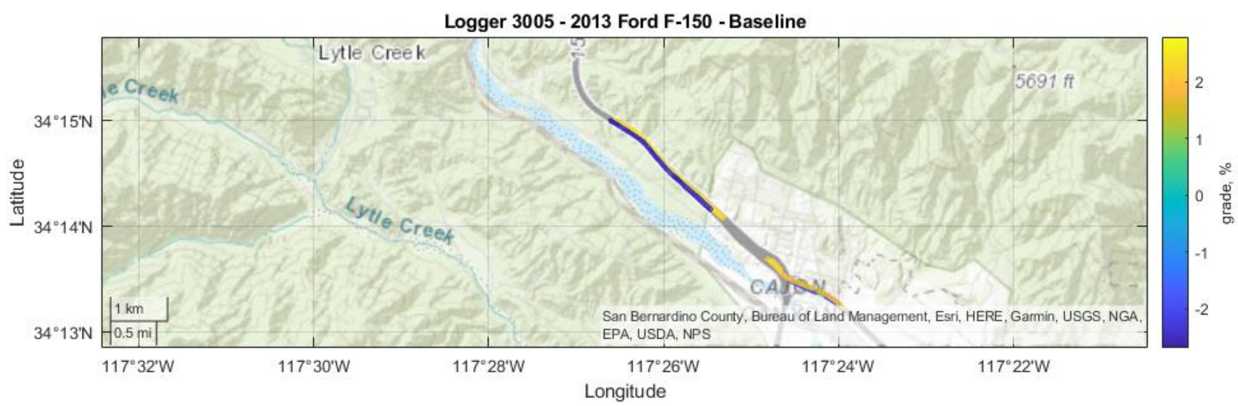

Figure 4-13. Example activity of the I-15 showing significant positive and negative road grade

4.3 Vehicle Activity Frequency by Speed

For each test vehicle, the frequency distribution of speed data was between the baseline and SmartPedal^{TM} data collection phase were compared. Figure 4-14 through Figure 4-19 show the frequency distribution of non-zero vehicle speed in 10mph speed bins for the baseline and SmartPedal^{TM} data collection periods. This provides a measure of how comparable the activity is between the baseline and SmartPedal^{TM} data collection period for each vehicle and also provides information on how the vehicle speed distribution varies between the test vehicles during the data collection period. The plots show that for most vehicles, the peak activity occurs in the 60-70 mph speed bin and in the case of 2019 F-350 and 2015 Dodge Ram 2500, in the 50-60 mph speed bin. The F-350 and Ram 2500 are among the three heaviest test vehicles. The F-350 and Ram 2500 also show more low speed bin activity than the other test vehicles, which all have a similar speed distribution profile.

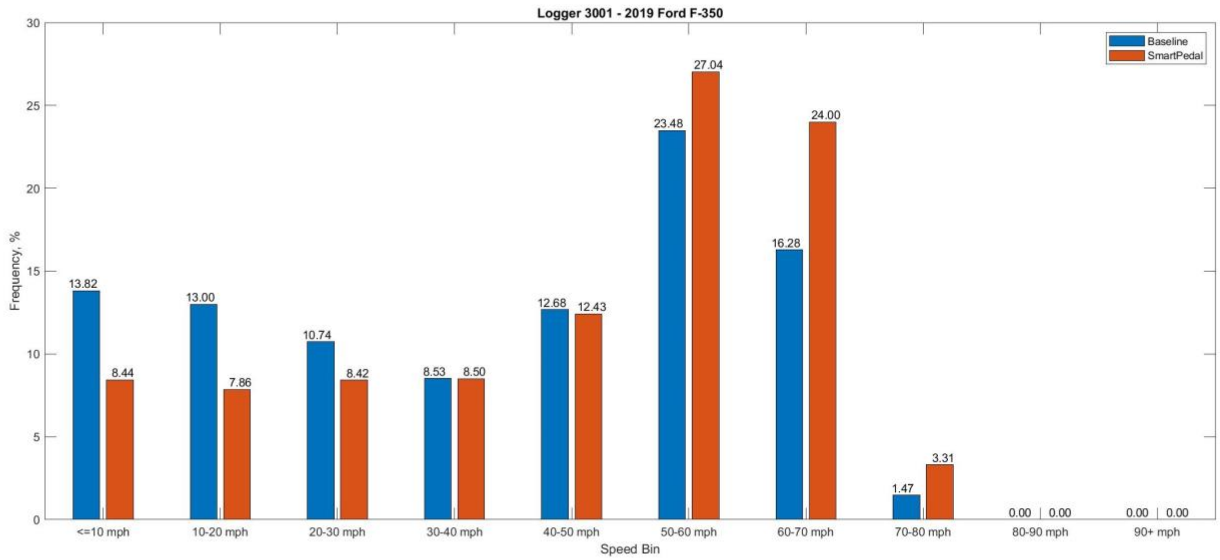

Figure 4-14. Activity frequency by speed bin for 2019 Ford F-350

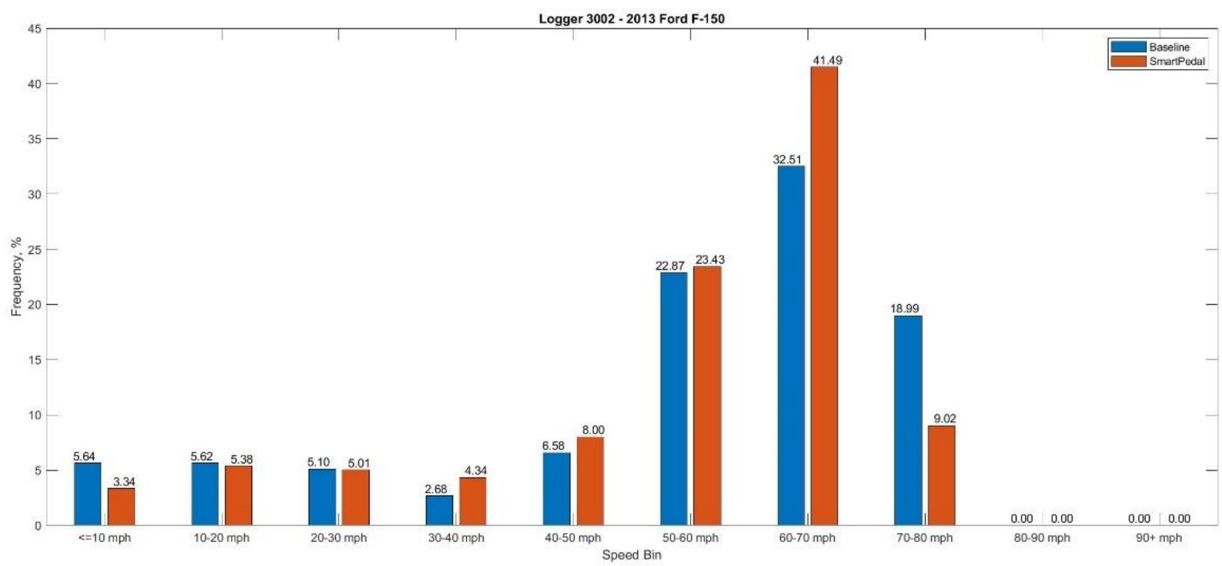

Figure 4-15. Activity frequency by speed bin for 2013 Ford F-150 (Logger 3002)

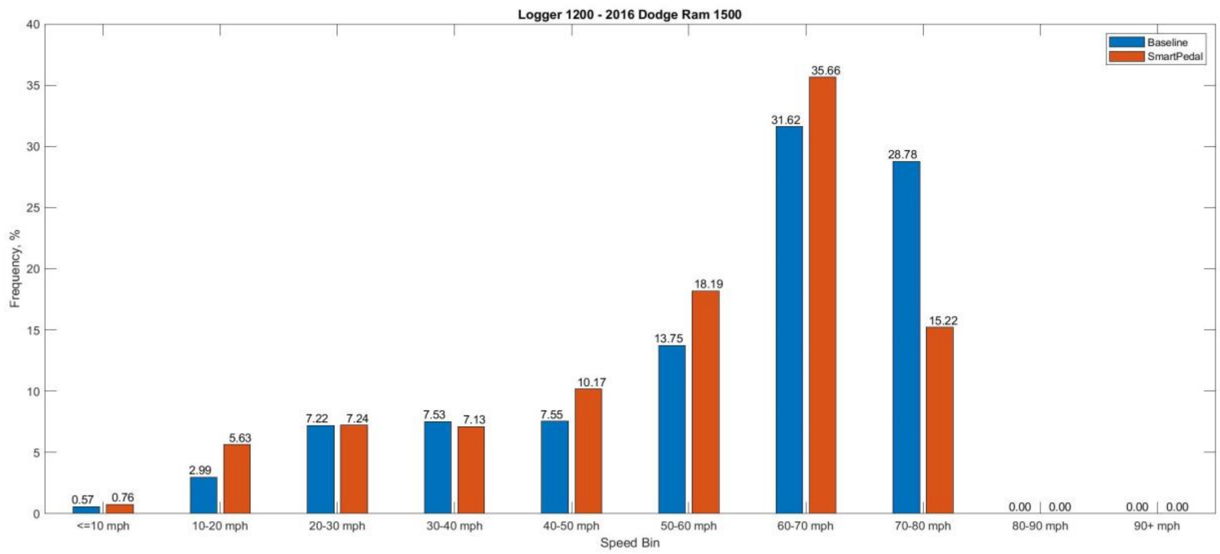

Figure 4-16. Activity frequency by speed bin for 2016 Dodge Ram 1500

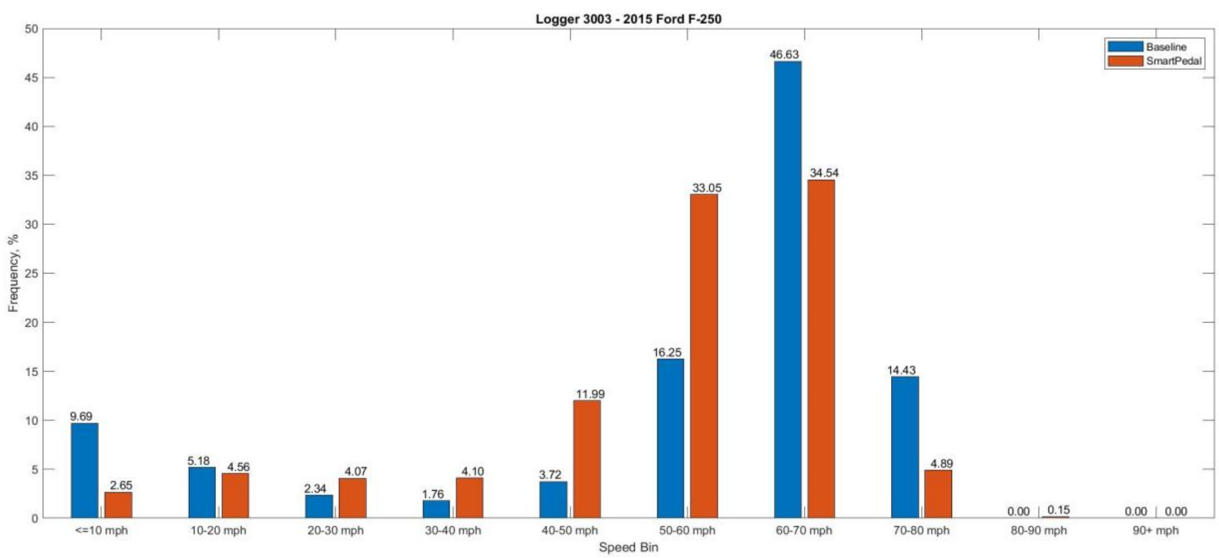

Figure 4-17. Activity frequency by speed bin for 2013 Ford F-250

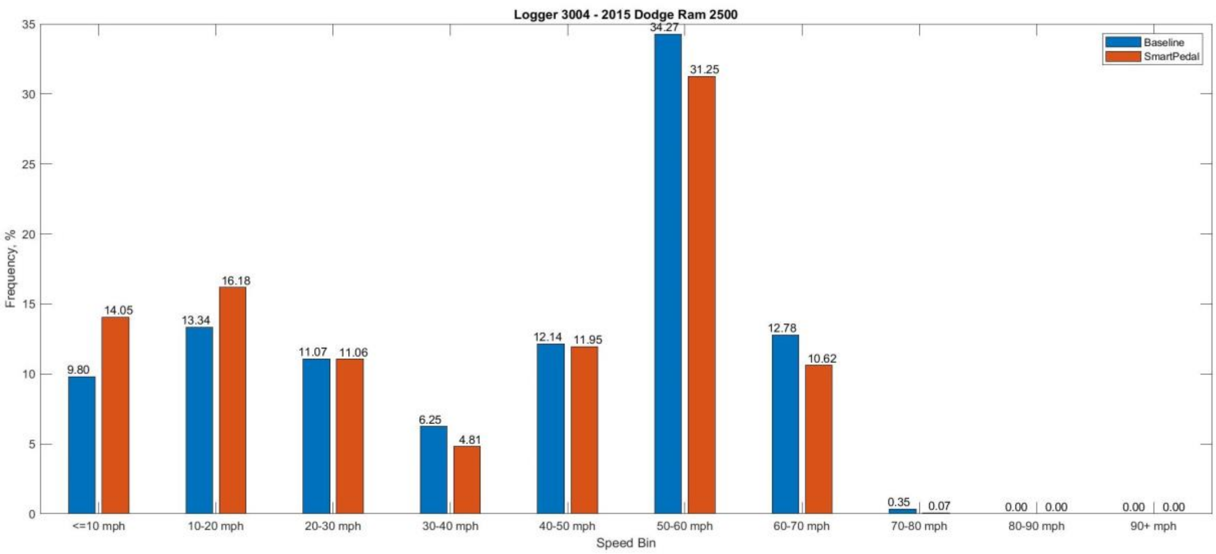

Figure 4-18. Activity frequency by speed bin for 2015 Dodge Ram 2500

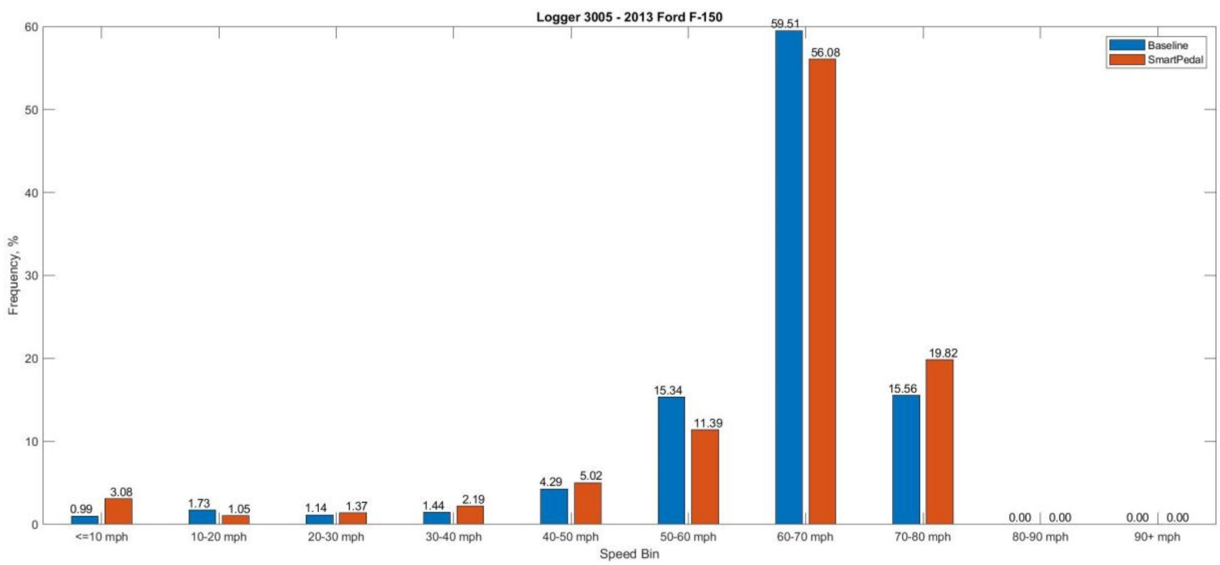

Figure 4-19. Activity frequency by speed bin for 2013 Ford F-150 (Logger 3005)

4.4 Technology Effectiveness

Comparison of baseline and SmartPedal^{TM} data was performed to investigate the potential effectiveness of the SmartPedal^{TM} device on improving fuel economy in the Caltrans fleet under real-world driving conditions. The average fuel economy value for each test vehicle during the baseline and SmartPedal^{TM} data collection period was calculated by filtering the test data and then dividing the cumulative distance traveled by the cumulative fuel used for the filtered data in each data collection period. Data filtering was included to help isolate the effect of the SmartPedal^{TM} technology and consisted of limiting the test data to non-zero vehicle speeds greater than 1 mph and non-negative road grade greater than zero percent grade. The percent change in fuel economy was calculated based on the baseline condition, where a positive change indicates an increase in fuel economy and a negative value indicates a decrease in fuel economy for the SmartPedal™ data. The results are presented in Table 4-1 and show that for the test data collected, the SmartPedal™ data showed an overall increase in fuel economy in four of the test vehicles, ranging from 0.47% to 6.3%. In two of the cases, the SmartPedal™ data showed a decrease in fuel economy from -0.52% to -1.72%. There is no known reason that the SmartPedal™ technology would hinder fuel economy and the small negative values are likely related to unknown contributions from factors influencing fuel economy as discussed in Section 4.1. The fuel economy improvements are in-line with the fuel economy improvements documented in the SmartPedal™ case studies presented in Section 2.2.1, which range from 1.5% to 16.8% improvement, with many of the fuel economy improvements in the 5% to 7% range. In Table 4-1 the Ford F-350 and the Dodge Ram 2500, both show unrealistically high average fuel economy numbers, as discussed in Section 3.2.4. This phenomenon persists throughout the dataset and the relative differences between the baseline and technology collection phase may not be impacted by an offset in the absolute MPG value occurring in both data sets.

Table 4-1. Comparison of Average Fuel Economy by Vehicle for Positive Road Grade

Vehicle	Year	Logger	Weight, lbs	Average MPG Baseline	Average MPG SmartPedal	Fuel Economy Increase, %
Ford F-150	2013	3002	6700	15.87	16.35	3.02
Ford F-150	2013	3005	6700	15.29	15.21	-0.52
Ford F-250	2015	3003	10000	12.88	13.69	6.29
Ford F-350	2019	3001	11500	23.62	24.62	4.23
Dodge Ram 1500	2016	1200	6800	21.22	21.32	0.47
Dodge Ram 2500	2015	3004	9000	24.96	24.53	-1.72

4.4.1 Speed Binned Fuel Economy Comparison

This section provides calculated fuel economy in 10mph speed bins for all of the test vehicles across both data collection periods. Figure 4-20 through Figure 4-25, show the comparison of fuel economy values calculated by speed bin for the baseline and SmartPedal™ data collection periods. These figures show that the trends found in the SmartPedal™ data collection period relative to the baseline are not consistent across speed bins. This relationship may depend on what extent factors impacting fuel economy are present in the data set and which data points those factors are impacting. The effect that an increase in fuel economy in a particular speed bin will have on the cumulative fuel use will depend on the frequency of activity in each speed bin. A large increase in fuel economy in a speed bin with little activity may result in little fuel savings, while a moderate increase in fuel economy in a speed bin with a large amount of activity may result in significant fuel savings. Vehicle activity is presented in Section 4.3.

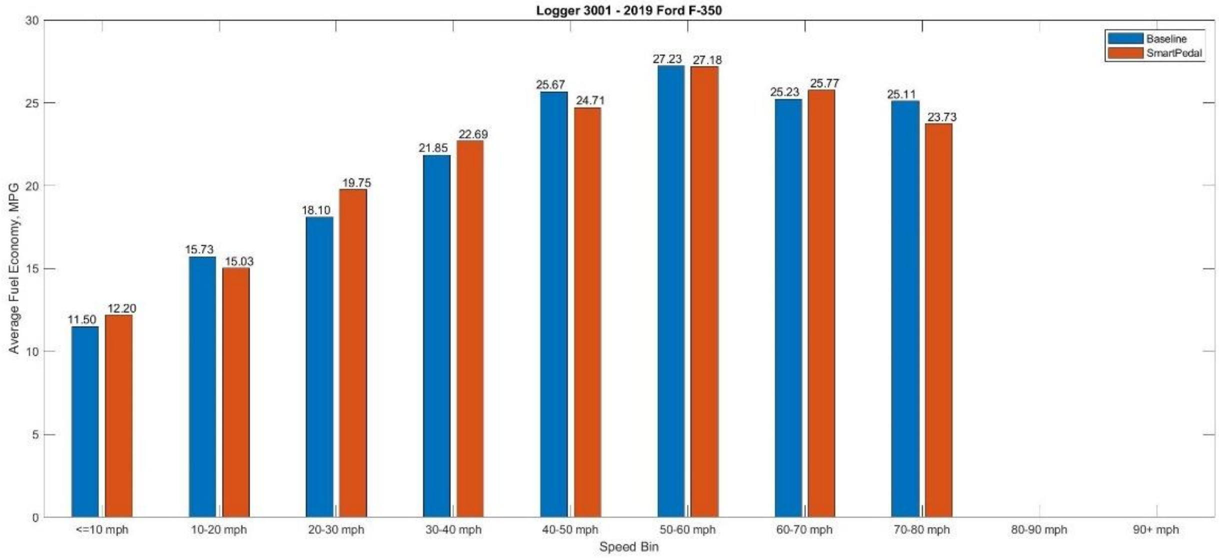

Figure 4-20. Average fuel economy calculated for 2019 Ford F-350

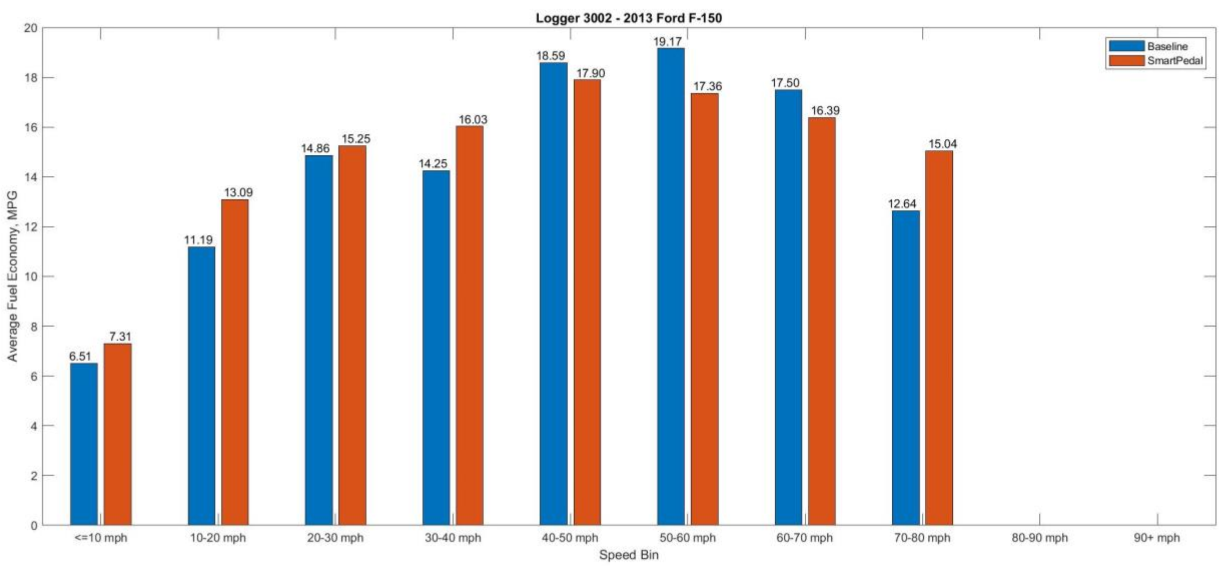

Figure 4-21. Average fuel economy calculated for 2013 Ford F-150 (Logger 3002)

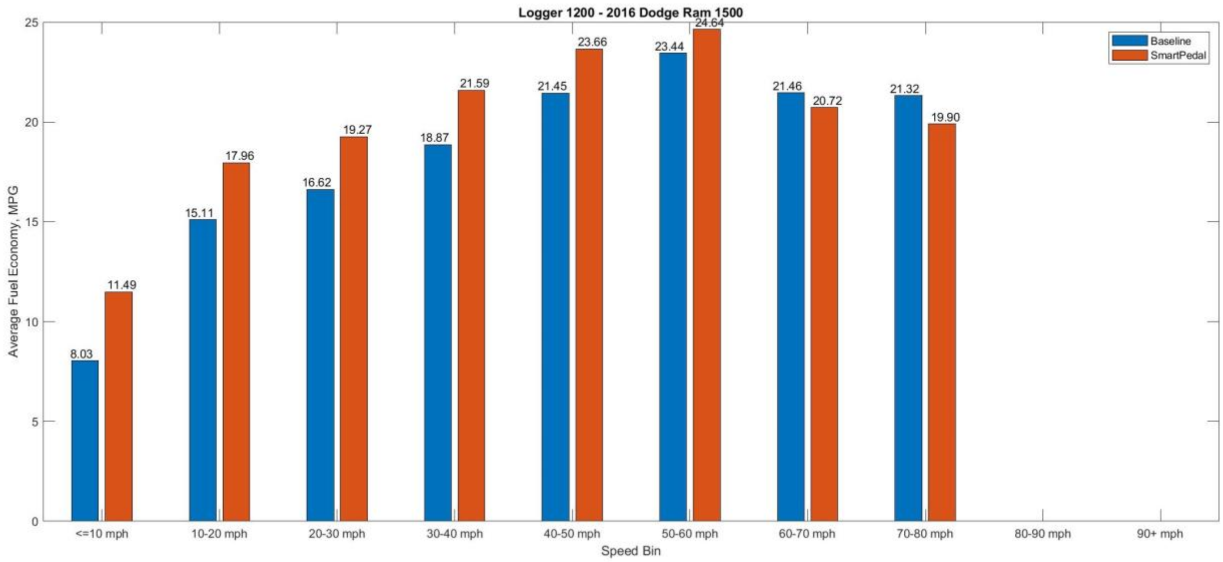

Figure 4-22. Average fuel economy calculated for 2016 Dodge Ram 1500

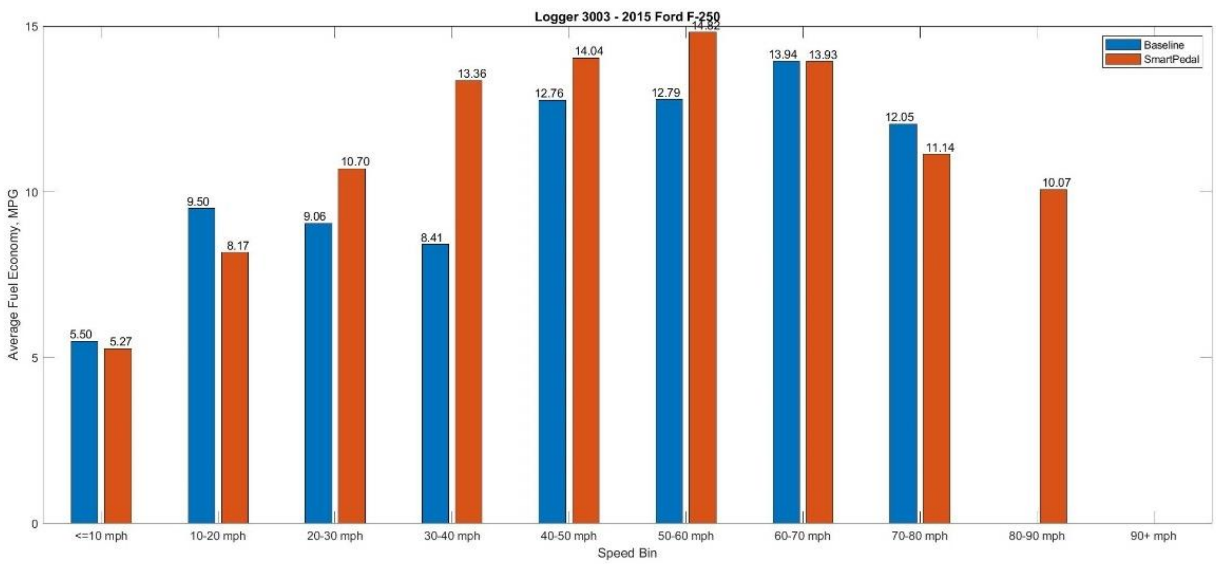

Figure 4-23. Average fuel economy calculated for 2013 Ford F-250

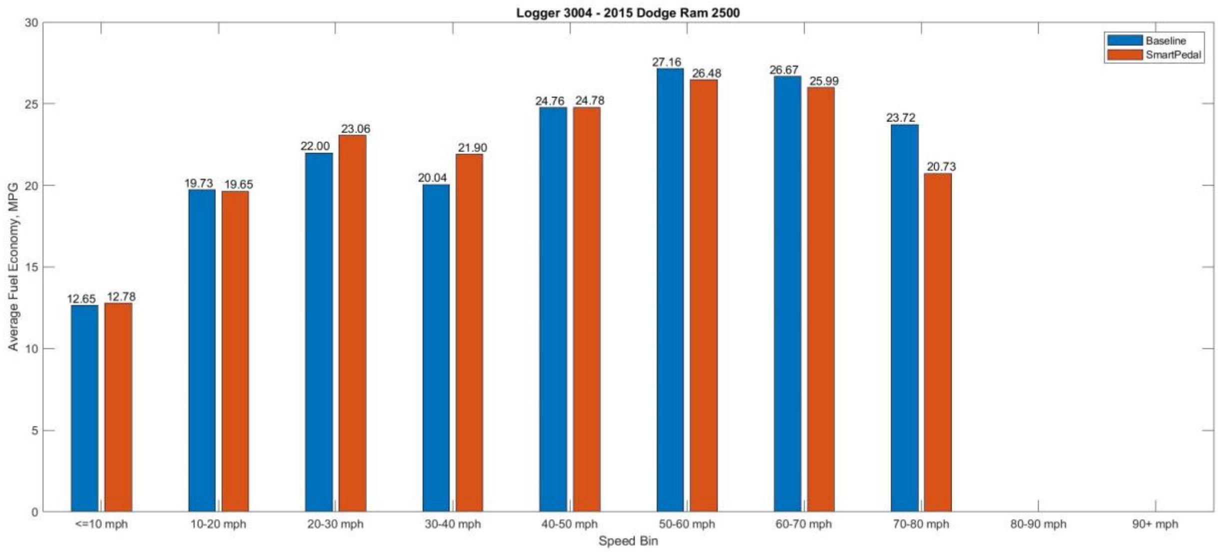

Figure 4-24. Average fuel economy calculated for 2015 Dodge Ram 2500

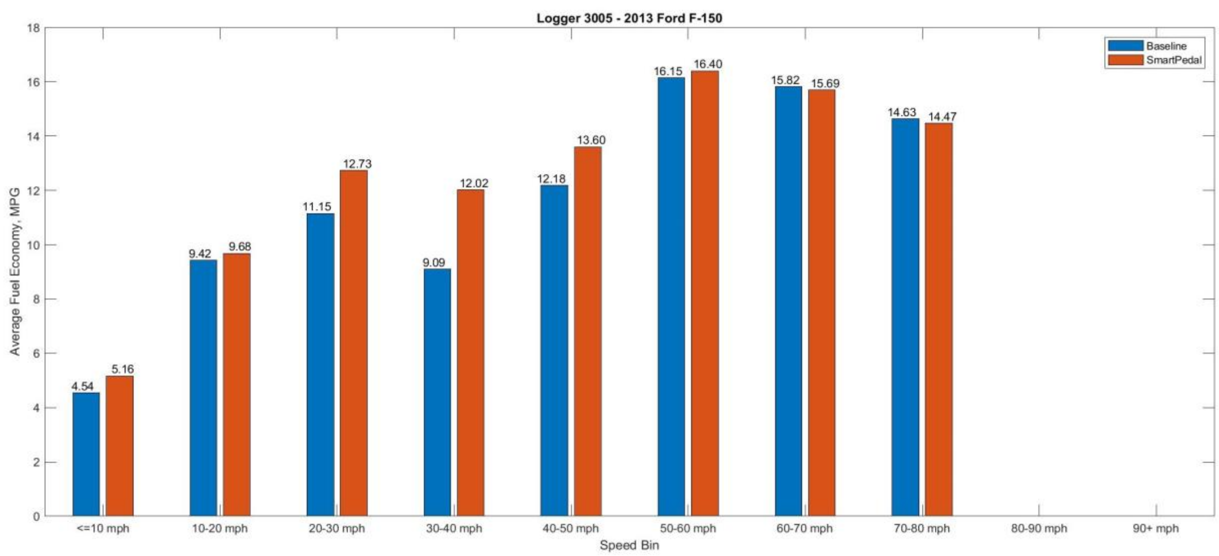

Figure 4-25. Average fuel economy calculated for 2013 Ford F-150

4.5 Cost Analysis

Lastly, the cost of implementation and the potential cost savings of the SmartPedal™ system was considered to determine the economic viability of the system. The unit cost for the SmartPedal™ system is $299 and the largest average fuel economy increase was 6.29% for the Ford F-250, which increased from an average 12.8 MPG for the baseline condition to 13.69 MPG with the SmartPedal™ system. During the study, the Ford F-250 was monitored for 128 days and in that time it operated on 37 of those days and traveled a total distance of 3,341.4 miles. Based on these numbers, the Ford F-250 drove an average of 26.10 miles per day during the study. At the baseline fuel economy of 12.8 MPG, the Ford F-250 consumes about 2.04

gallons of gas per day, and with the improved fuel economy of 13.69 MPG, the Ford F-250 consumes about 1.91 gallons of gas per day. The fuel savings using the SmartPedal^{TM} is roughly 0.13 gallons of gas per day or about 0.62 $/day assuming a gas price of 4.8 $/gallon. For this scenario, the payback period for the SmartPedal device is roughly 480 days or 15.76 months. This is comparable to the 18 month payback period that was reported in the St. Louis Missouri case study in Section 2.2.2.

5. Conclusions

The objective of this research was to evaluate the potential effectiveness of a "Smart Pedal" technology in vehicles in the Caltrans fleet. A literature review was performed on "Smart Pedal" technologies designed to improve fuel economy, such as throttle controllers and pedal systems, and a "Smart Pedal" device was chosen for evaluation; namely, the SmartPedal™ throttle controller from SmartPedal Labs. This device was selected for several reasons: it modifies the throttle signal based on motion sensor data to eliminate unwanted micro accelerations associated with bumps in the road or vibration on the accelerator pedal and does not simply scale back the accelerator signal as is common with other throttle controllers, it is dedicated to improving fuel economy and does not have performance modes which the user can access, and it has documented results in several large scale case studies. Following "Smart Pedal" device selection, six vehicles compatible with the "Smart Pedal" device from the Caltrans fleet were selected for testing and instrumented with GPS enabled ECU data loggers. ECU and activity data were collected from the test vehicles for a target period of two months and served as baseline data for comparison. Following collection of the baseline data, the test vehicles were instrumented with the SmartPedal™ device and data was collected for a target period of two months to generate the technology dataset for comparison with the baseline data.

Analysis from this study compared average fuel economy, in terms of miles per gallon, over non-negative grade and excluding idle, which resulted in an overall potential fuel economy savings of up to 6.3%. For two of the test vehicles, no fuel economy savings were observed and the difference in the compared fuel economy values between the baseline and technology data were -1.72% and -0.52%. These small negative differences in average fuel economy are not expected to be reflective of the performance of the SmartPedal™ device since there is no mechanism for this effect, but rather reflective of uncontrolled nature of this study. This study consisted of real-world operation and the contribution of unknown variables that could potentially impact fuel economy is unknown. Unknown factors that can impact fuel economy are discussed in Section 4.1, and include factors such as unknown payload, number of passengers, changes in driver, etc. The documented fuel economy savings from SmartPedal™ in case studies, described in Section 2.2.1, are between 1.5% and 16.8%. This study showed that at the low end of the case studies (1.5%), this effect could be difficult to detect in a smaller uncontrolled study using real-world conditions. In this study, the data sets ranged from 548 miles driven to roughly 2.8 thousand miles driven over longer periods of time. This is significantly less than the case studies, which are based on 255 thousand to 1.99 million miles of driving. Larger sample sizes reduce standard error and the chance of detecting an effect that exists in a population increases. In addition to the analysis of fuel economy over the total non-idle and non-negative grade data, fuel economy was also calculated for data grouped by speed bins for the baseline and SmartPedal™ data collection periods, which resulted in even smaller sample sizes in each of the speed bins and produced varied results; and no consistent trends in fuel economy were observed across speed bins. Despite the limitations of the study, the overall fuel savings for four out of the six test vehicles was positive (0.47%, 3.02%, 4.23%, and 6.29%), and three of the vehicles showed fuel-savings in-line with larger case studies (1.5% to 16.8%).

The F-250 test vehicle showed the largest fuel savings (6.29%) in the study and its results were used for the basis of a cost analysis. The Ford F-250 traveled an average of 26.1 miles/day and assuming a gas price of 4.80 $/gallon, the payback period was found to be roughly 15.76 months which is comparable to the 18 month payback period that was reported in the St. Louis Missouri case study

5.1 Recommendations and Future Research

Since the impact of the SmartPedal™ technology may be difficult to determine from a smaller sample size in an uncontrolled test under real-world conditions, additional testing would be needed to increase confidence in the effectiveness of the SmartPedal™ device and to characterize fuel savings with respect to other parameters such as vehicle speed. Two options for additional testing are a study with a much larger sample size performed under real-world conditions or a smaller study performed under more controlled conditions. In a controlled study, specific routes could be driven repeatedly, alternating between the baseline and the SmartPedal™ technology condition. The study could ensure that the driver, the number of passengers, vehicle payload, traffic conditions, road conditions, accessory usage, and other parameters that could potentially affect fuel economy, are as comparable as possible. Another area of study could also focus on driver behavior to determine if the SmartPedal™ device provides more value to drivers with certain behaviors.

6. References

[1] "Nissan Introduces Eco-Pedal Intelligent Accelerator Pedal System," 04 August 2008. [Online]. Available: https://www.greencarcongress.com/2008/08/nissan-introduc.html.

[2] S. Edelstein, "Haptic-Feedback Gas Pedal Tells Drivers When to Shift to Save Fuel," 2016. [Online]. Available: https://www.greencarreports.com/news/1102240_haptic-feedback-gas-pedal-tells-drivers-when-to-shift-to-save-fuel.

[3] "What is Pedal Commander?" [Online]. Available: https://pedalcommander.com/.

7. Data Summary

Products of Research

This research provides data that was collected for the evaluation of the SmartPedal^{TM} technology. Data was collected from six Caltrans vehicles, each monitored for two data collection periods: 1) without the SmartPedalTM device, to collect the baseline data sets, and 2) with the SmartPedalTM device, to collect a comparison data set with the "Smart Pedal" technology.

Data Format and Content

The dataset contains a README.md file that includes information on the data file name structure, test vehicle information, and a variable guide for the vehicle data files. The vehicle data files are in standard .csv format.

Data Access and Sharing

The data can be accessed on the Dryad system with the following https://doi.org/10.6086/D1Q10X

Reuse and Redistribution

The data can be reused with proper citation:

> Scora, George; Barth, Matthew (2023), Evaluating the Effectiveness of "Smart Pedal" Systems for Vehicle Fleets, Dryad, Dataset, https://doi.org/10.6086/D1Q10X