Title

Environmentally Friendly Driving Feedback Systems Research and Development for Heavy Duty Trucks

Authors
Boriboonsomsin, Kanok
Vu, Alexander
Barth, Matthew

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March 2016

A Research Report from the National Center for Sustainable Transportation

Kanok Boriboonsomsin, University of California at Riverside
Alexander Vu, University of California at Riverside
Matthew Barth, University of California at Riverside

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Disclaimer

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Environmentally Friendly Driving Feedback Systems Research and Development for Heavy Duty Trucks

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College of Engineering - Center for Environmental Research and Technology, University of California at Riverside

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EXECUTIVE SUMMARY

In the United States (U.S.), approximately 70% of freight is moved by commercial trucks. In typical commercial trucking operations, fuel costs are usually one of the largest expenses, accounting for about 30% to 40% of the total operating cost. Not only do freight trucks consume a large amount of fuel, they also produce a significant amount of greenhouse gas (GHG) and criteria pollutant emissions. For instance, medium-duty and heavy-duty trucks account for about 22% of the U.S. GHG emissions from transportation sector. Therefore, both the trucking industry and the government have sought ways to reduce fuel consumption and emissions from trucking operations. One such way is to improve the environmental performance of truck drivers. This can be achieved by providing them with necessary education, training, and technological support to help them reduce fuel consumption and emissions in their day-to-day trucking operations.

In this research project, the research team developed an environmentally-friendly (eco-friendly) driving feedback system for heavy-duty trucks, which was adapted from a similar system previously developed for light-duty cars. The system consists of:

1) *Eco-Routing Navigation* technology that provides route feedback by determining the most fuel-efficient route for any trip with consideration of historical and real-time traffic and roadway conditions;
2) *Eco-Driving Feedback* technology that provides a variety of driving feedback such as excessive speed warning, aggressive acceleration warning, recommended driving speed, etc., under different driving situations; and
3) *Eco-Score* and *Eco-Rank* technology that calculates a set of scores based on how eco-friendly one's driving is, and generates recommendation feedback for improving the driving performance and the scores.

The environmentally-friendly driving feedback system for heavy-duty trucks was tested by 22 truck driver participants. The Eco-Routing Navigation technology was implemented as a mobile app and used to study route choice preference comparing the shortest, the fastest, and the most fuel-efficient routes for 14 trip scenarios. Overall, the participants selected the shortest route for 44% of the time, the fastest route 18% of the time, and the most fuel-efficient route 38% of the time. These results do not follow conventional travel behavior theories, which suggest that travelers would try to minimize their overall travel costs, a big part of which is travel time. This could be because several participants are employed by companies as opposed to being independent owners/operators, so travel time spent on the job may not necessarily be regarded as their personal cost. It could also be that not every truck driver uses the same or even a similar rationale in making route choice decision. More research is needed to better understand route choice preference of truck drivers.

The Eco-Driving Feedback technology was integrated with the state-of-the-art truck driving simulator. A driving scenario that represents a typical freight trip in Southern California was programmed into the simulator and used as a driving course in an experiment with the same 22 truck driver participants for evaluating the impacts of the technology. The results show that the impacts for individual participants are different to varying degrees. When considering an average driver from this group of driver participants, the Eco-Driving Feedback technology has no adverse impact on travel time and carbon monoxide emission while reducing fuel consumption, oxides of nitrogen (NO_x) emission, and fine particulate matter ($PM_{2.5}$) emission by 11%, 8%, and 8%, respectively. Although the Eco-Driving Feedback technology results in an increase in hydrocarbon emission by 3%, it is not a major concern for heavy-duty diesel trucks as on-road emission inventories of this pollutant are more dominated by contribution from gasoline vehicles. On the other hand, diesel vehicles, most of which are heavy-duty trucks, are the major contributor of on-road emission inventories of NO_x and $PM_{2.5}$.

The impacts of the Eco-Score and Eco-Rank technology were not evaluated as it would involve a long-term study beyond the scope of this research project. However, the eco-scores were calculated for all the participants in the experiment of the Eco-Driving Feedback technology. The results show that the technology improves the acceleration score by 9%, the braking score by 7%, the speed score by 3%, and the overall score by 4%.

Based on the promising results from this research project that was conducted in a simulator environment, a follow-on study in a real-world environment is warranted. In the real-world study, route choice preference of truck drivers can be analyzed based on actual route choice decisions made in the day-to-day operations through the use of the Eco-Routing Navigation technology. Also, the fuel consumption and emission reduction benefits of the Eco-Driving Feedback technology can be validated under a variety of real-world driving scenarios. Ideally, this real-world study will be several months long and involve truck drivers from the same fleet(s) so that the impacts of the Eco-Score and Eco-Rank technology can also be evaluated.

Introduction

Freight movement has become an important economic factor in the ever-increasing international trade and global supply chain. In the United States (U.S.), approximately 70% of freight is moved by commercial trucks (*1*). In typical commercial trucking operations, fuel costs are usually one of the largest expenses, accounting for about 30% to 40% of the total operating cost (*2*). Not only do freight trucks consume a large amount of fuel, they also produce a significant amount of greenhouse gas (GHG), especially carbon dioxide (CO_2), and criteria pollutant emissions. Between 1990 and 2011, medium-duty and heavy-duty trucks, most of which are used for freight movement, account for about 22% of the U.S. GHG emissions from transportation sector (*3*). Therefore, both the trucking industry and government agencies have good reasons to improve fuel efficiency and reduce GHG emissions from commercial trucking operations.

Among several strategies to reduce fuel consumption and GHG emissions from freight trucks, eco-driving is one that has the potential to be very cost effective. Eco-driving can be defined as "the practice of driving in such a way as to minimize fuel consumption and the emission of carbon dioxide" (*4*). In a broader sense, eco-driving may also include non-driving activities such as pre-trip planning (of route and schedule) and vehicle maintenance. The core of eco-driving programs is to provide drivers with education and training regarding ways to reduce fuel consumption and CO_2 emissions from the operation of their vehicles. The driver education and training can be augmented by driving advice and feedback provided periodically through report cards or in real-time through in-vehicle systems.

Environmentally-Friendly Driving Feedback System

Researchers at the University of California at Riverside (UCR) have developed a next-generation environmentally-friendly (eco-friendly) driving feedback system for light-duty cars as part of a three-year U.S. Department of Energy (DOE) research program (*5*). The developed system consists of several technology components including: 1) Eco-Fleet Planning, 2) Eco-Routing Navigation, 3) Eco-Driving Feedback, and 4) an Eco-Score and Eco-Rank. The driving feedback system and its technology components are depicted in Figure 1 and briefly described below.

1. *Eco-Fleet Planning* – One of the eco-driving practices is to plan driving trips in advance. The Eco-Fleet Planning technology provides trip feedback by finding the minimum cost path between a set of stops or destinations by incorporating time schedules and road networks into a solution. The cost considered could be trip distance, trip travel time, trip fuel consumption, or a combination of these. In the case of commercial vehicles, the technology can also account for driver and vehicle costs, vehicle capacity, and other constraints. Pre-planning trips helps to reduce time, fuel consumption, and the need for vehicle maintenance.

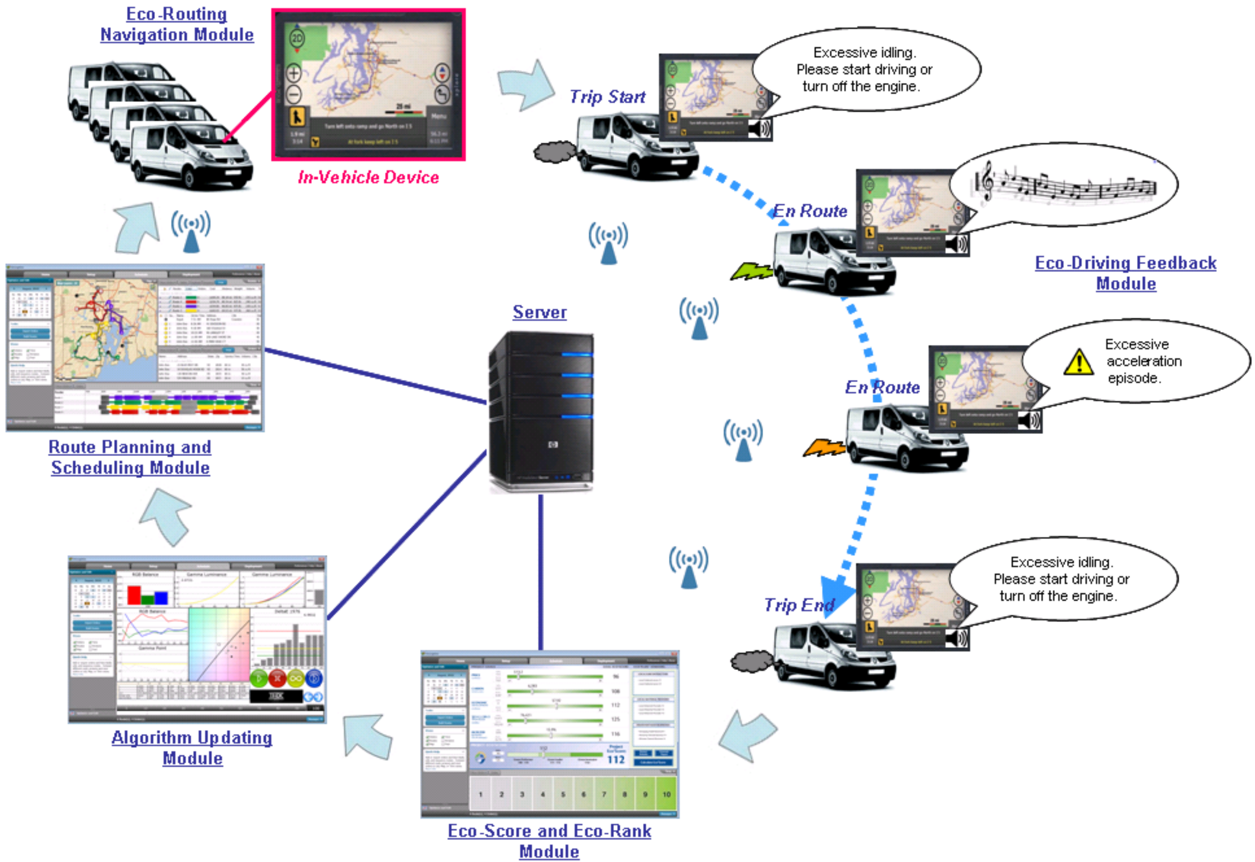

Figure 1. Technology components of the environmentally-friendly driving feedback system

2. *Eco-Routing Navigation* – Current roadway navigation systems can determine a shortest-distance or a shortest-time route for any trip. However, these routes are not necessarily the most fuel-efficient route for the trip, and thus, fuel savings can be gained with the help of a fuel-optimized navigation system. The Eco-Routing Navigation technology provides route feedback by determining the most fuel-efficient route for each of the pre-planned trips with consideration of historical and real-time traffic, and roadway conditions. The driver can elect to use the most fuel-efficient route if the estimated time of arrival is still within the planned schedule or at his/her discretion.

3. *Eco-Driving Feedback* – Once the trip is underway, vehicle fuel consumption can be further reduced by adopting a variety of eco-driving practices such as keeping moderate speed, accelerating and braking mildly, and minimizing idling time. The Eco-Driving Feedback technology provides a variety of driving feedback such as excessive speed warning, aggressive acceleration warning, recommended driving speed, etc., under different driving situations. The feedback is selectively provided through visual and/or audio cues in a way that minimizes driver distraction.

4. *Eco-Score and Eco-Rank* – The Eco-Score and Eco-Rank technology analyzes driving data of the driver to determine how eco-friendly his/her driving is in each driving mode (i.e., cruising, accelerating, braking, and idling). The technology also determines a score for each driving mode as well as a combined score. In addition, the technology generates recommendation feedback for improving the driving performance and the scores. These scores can be compared across the different driving modes for the driver so that he/she can prioritize area(s) for improvement. The scores can also be used to compare and rank drivers.

Research Goal and Objectives

The goal of this research project is to evaluate potential fuel savings and emission reductions of the environmentally-friendly driving feedback system for heavy-duty trucks. In order to achieve this goal, specific project objectives are set forth as follows: 1) adapt the Eco-Routing Navigation, Eco-Driving Feedback, and Eco-Score and Eco-Rank technologies from the previously developed environmentally-friendly driving feedback system for light-duty cars for use with heavy-duty trucks; 2) integrate the technologies with a state-of-the-art truck driving simulator located at UCR; and 3) evaluate fuel saving and emission reduction benefits of the technologies through a set of experiments with professional truck drivers.

Driving Feedback Technologies for Heavy-Duty Trucks

Eco-Routing Navigation

The research team has been developing the Eco-Routing Navigation technology since 2006, starting with an eco-routing navigation system for light-duty cars (*6*). It consists of several components, including: (a) a Dynamic Roadway Network database, which is a digital map of a roadway network that integrates historical and real-time traffic information from multiple data sources through an embedded data fusion algorithm; (b) an Energy/Emissions Operational Parameter Set, which is a compilation of energy/emission factors for a variety of vehicle types under various roadway characteristics and traffic conditions; (c) a routing engine, which contains shortest-path algorithms used for optimal route calculation; and (d) user interfaces that receive origin-destination inputs from users and display route maps to the users (*7*).

In 2011, we expanded the technology to include an eco-routing navigation system for heavy-duty trucks. The expansion involved the integration of 3D information (i.e., road grade), which is critical for truck routing, into the Dynamic Roadway Network database as well as the development of the Energy/Emissions Operational Parameter Set for a truck. The truck Energy/Emissions Operational Parameter Set includes loaded weight as a variable, which allows the routing engine to account for the total truck weight in calculating the most fuel-efficient route for the trip. Therefore, it is possible that the most fuel-efficient route may be different for a fully loaded truck compared to an empty truck. Figure 2 shows the web application of the truck eco-routing navigation system (*8*).

The truck eco-routing navigation system was used to perform over 500,000 simulated route calculations across multiple total truck weights, origin/destination points, and days using real-world traffic data for the Greater Los Angeles Metropolitan Area (*9*). The results showed that for most trips the eco-route has lower fuel consumption but longer travel time when compared to the fastest route, meaning that there is a tradeoff between fuel savings and travel time increase. The tradeoff varies greatly depending on origin/destination points, trip distance, traffic condition, time of day, day of week, and total truck weight. Therefore, the next step in truck eco-routing research is to understand how real truck drivers would respond to the different levels of the tradeoff between fuel savings and travel time increase.

In this project, we designed an experiment to study truck drivers' route choice preferences. We asked truck drivers to select the route that they would take for 14 trip scenarios represented by the blue dots in Figure 3. These dots indicate percent fuel savings and percent travel time increase of the eco-route as compared to the fastest route. For example, the dot at (0, 0) means that the eco-route and the fastest route are essentially the same. The dot at (15, 5) means that the eco-route would save 15% of fuel but would take 5% longer travel time as compared to the fastest route. This experimental design was aimed at analyzing what level of tradeoff the truck drivers would be willing to give to take an eco-route.

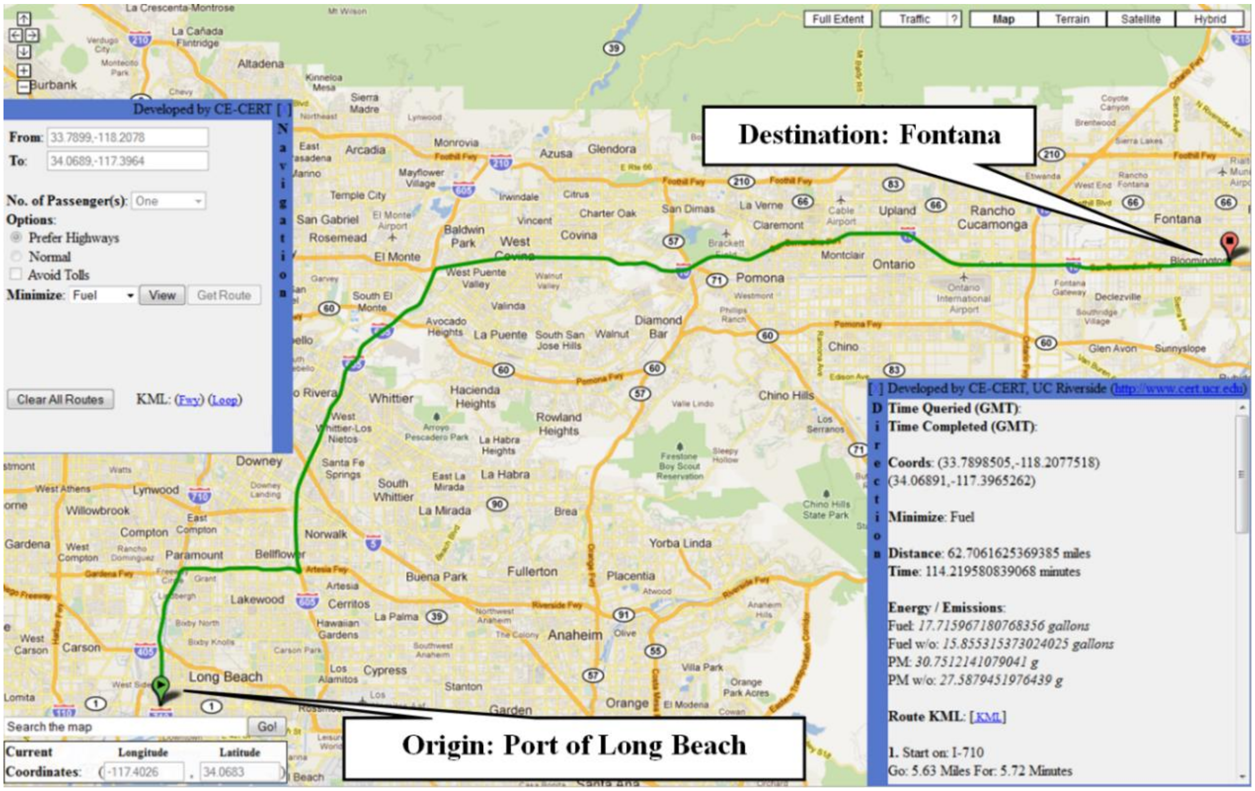

Figure 2. Web application of UCR's truck eco-routing navigation system

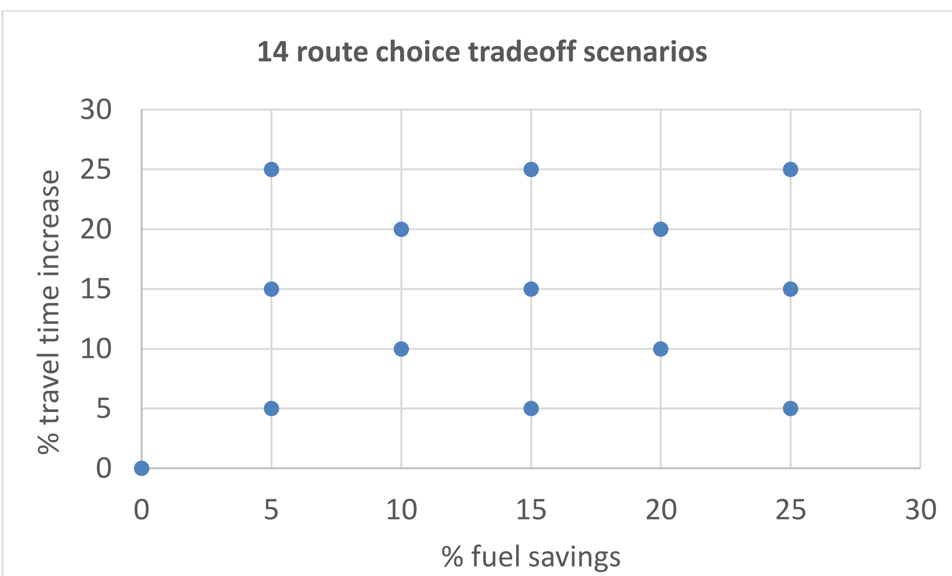

Figure 3. Tradeoff scenarios for truck driver route choice preference experiment

In the three-year DOE research program on driving feedback technologies for light-duty cars, we implemented the Eco-Routing Navigation technology in the form of an Android app and ran it on a smart device (Nexus 7 tablet). In this project, we adapted the previously developed Eco-Routing Navigation app for use in the study of truck drivers' route choice preferences. Figure 4 shows example screenshots of the app. The driver was first presented with a description of the trip scenario, followed by the map and information for three route options. The route option selected by the driver was recorded by the app for later analyses.

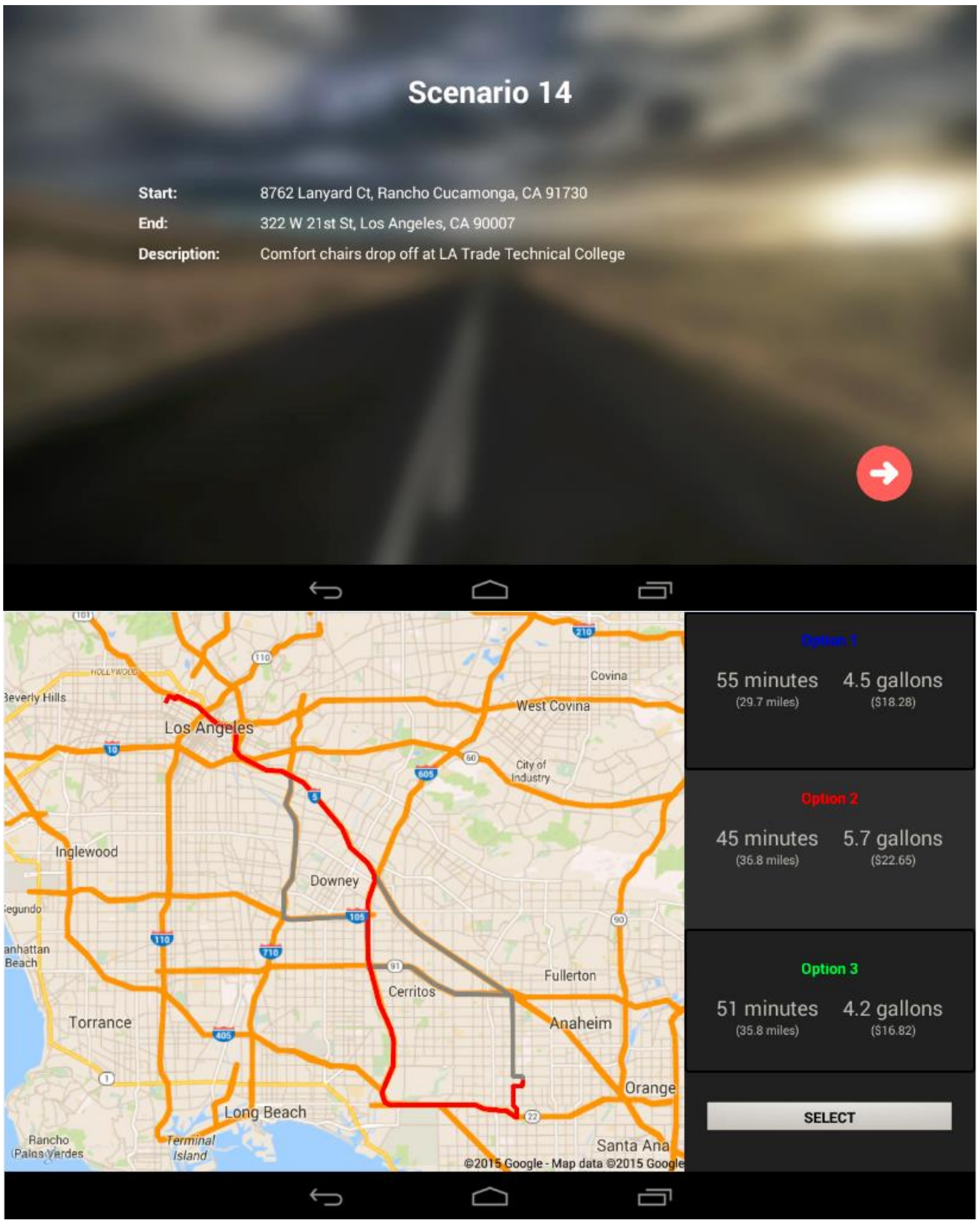

Figure 4. Screenshots of the Eco-Routing Navigation app adapted for heavy-duty trucks

Eco-Driving Feedback

In the DOE research program on driving feedback technologies, we designed the eco-driving feedback interface as shown in Figure 5. It is intentionally designed to look similar to the typical vehicle dashboard so that it can be used in place of the dashboard (e.g., the in-vehicle device is placed in front of the dashboard). This is aimed to reduce the length of "eyes off road" time—a measure of driver's distraction—when glancing at the interface. While there is still a speedometer in this simple and intuitive design, the tachometer is replaced by a fuel economy gauge that presents miles per gallon (MPG) values. Other features of the interface are:

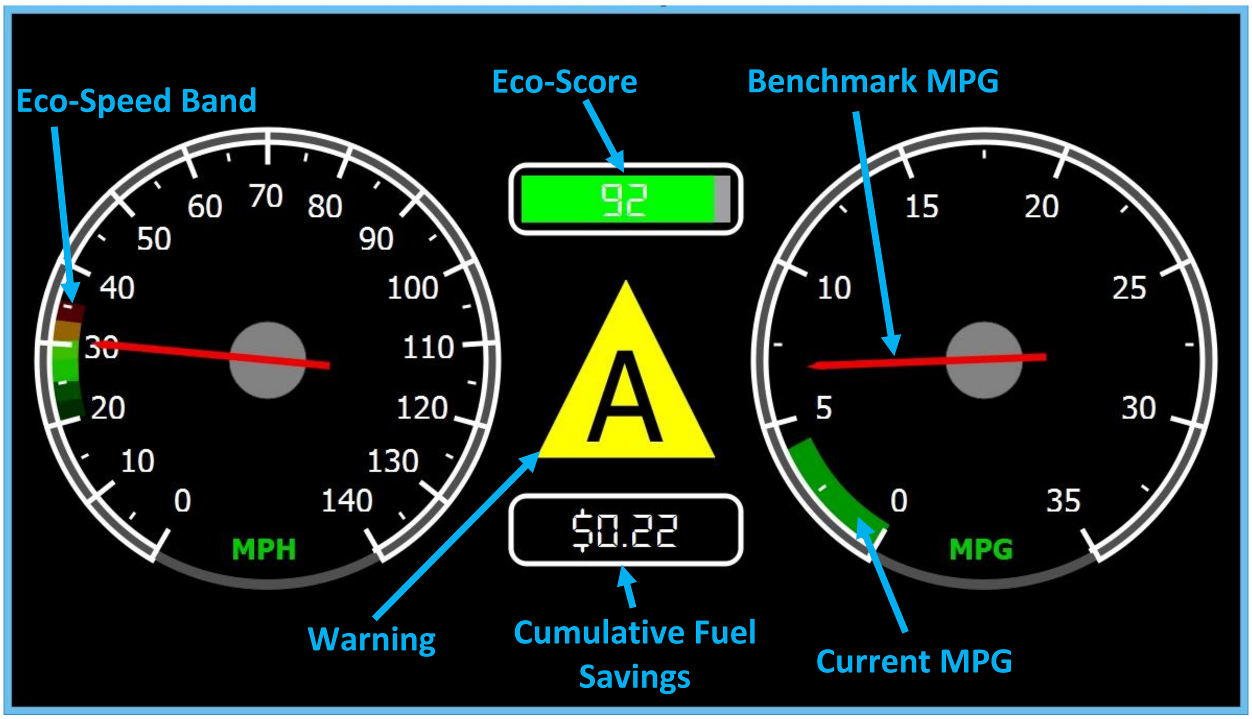

Figure 5. Design of eco-driving feedback interface

- *Eco-Speed Band* – The location of this colorful band is dynamically changed depending on the prevailing traffic speed and road grade on the current roadway link. The goal for the driver is to stay within the bright green zone of the band, which is the range of recommended driving speed. It is not advised to exceed the bright green zone and go into the orange or red zone of the band. While dropping below the bright green zone is not desirable, it is acceptable as it is sometime unavoidable. For example, the driver may need to drive at a speed below the recommended driving speed range when the vehicle in front slows down or brakes.

- *Warning* – This multi-purposed warning sign pops up when accelerating too aggressively (A), braking too abruptly (B), or idling for too long (I). The driver or fleet manager can set the warning sign to have it be accompanied by a beep sound, if desirable.

- *Benchmark MPG* – The benchmark MPG value is customizable. It can be set to the average MPG value of the last trip, over the last 5 minutes, or any value entered by the driver or fleet manager (e.g., the fleet-wide target fuel economy for the truck).

- *Current MPG* – This is also customizable. The driver can elect to show the average MPG value for the current trip, over the last 5 minutes, or the instantaneous MPG value. The goal for the driver is to stay above the benchmark MPG as much as possible.

- *Eco-Score* – This ranges from 0 to 100, where 100 is the most fuel-efficient driving. The Eco-Score to be displayed can be set to the average score over the last 5 minutes or for the current trip.

- *Cumulative Fuel Savings* – The cumulative fuel savings value is calculated based on the benchmark and the current MPG values, as well as the assumed diesel fuel price of $4 per gallon, which can be modified by the driver or fleet manager. This feature directly presents an economic incentive for eco-driving.

Eco-Score and Eco-Rank

In the DOE research program on driving feedback technologies, we developed algorithms for calculating various types of Eco-Scores. These include: 1) speed score, 2) acceleration score, 3) braking score, 4) idling score, and 5) overall score. In this project, we have adapted all but the idling score for use in the evaluation of the fuel-efficient driving performance of each truck driver since idling behavior is difficult to evaluate in a driving simulator environment. Each score is represented by a point, which ranges from 0 (worst) to 100 (best). The calculation algorithms of these scores and their logics are described below.

Speed Score

In general, vehicles are most fuel-efficient when operating at moderate speeds around 40-50 mph. Thus, one might want to give the maximum point to the driver who drives within this speed range, and deduct some points when driving outside of the speed range. However, driving at a lower speed than 40 mph is usually not by choice but rather because of traffic congestion. Although the Eco-Driving Feedback technology provides a range of recommended driving speeds that are most fuel efficient for any driving conditions including when under traffic congestion, it is not possible for the driver to stay within the recommended speed range at all times. For instance, sometimes the driver may have to slow down significantly as another vehicle cuts in from the adjacent lane. Therefore, no point should be deducted from the Speed Score under this circumstance.

Similarly, driving above 50 mph may sometime be necessary especially on highways. In fact, when traffic is moving at highway speed, driving at a significant lower speed is unsafe and considered a hazard to other vehicles. Therefore, no point should be deducted from the Speed

Score under this circumstance, as well. Therefore, the Speed Score will be the maximum possible of 100 as long as the vehicle speed stays within the speed limit (v_{limit}). In California, the maximum speed limit on highways for cars is 65 mph while it is 55 mph for trucks.
On the other hand, excessive speed is always a safety concern and speeding is illegal. In addition, driving at a speed exceeding speed limits on highways is often not fuel efficient. Therefore, in the Speed Score calculation algorithm, points are deducted from the maximum possible of 100 whenever the vehicle speed exceeds the speed limit. The amount of points deducted is a function of the speed threshold, which can be set by the driver or fleet manager. Figure 6 shows the Speed Score curve for a maximum speed threshold of 10 mph above the speed limit. The Speed Score is 100 when the vehicle speed is lower than or equal to the speed limit. Then, it decreases as the vehicle speed increases towards the speed threshold. Beyond the threshold, the Speed Score becomes zero.

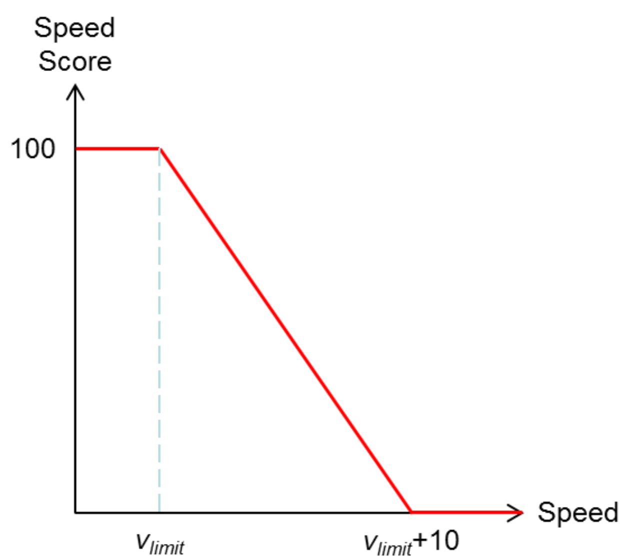

Figure 6. Speed Score curve

Acceleration Score

A typical acceleration rate (i.e., mean) for any drivers and its variation (i.e., standard deviation) vary by vehicle speed (see examples in Figures 7 and 8). Given the mean (μ) and standard deviation (σ) of the acceleration rate for any vehicle speed, the range of vehicle acceleration rate can be divided into three regions: 1) desirable, 2) acceptable, and 3) unacceptable.

Taking Figure 9 as an example, a vehicle acceleration rate is *desirable* if it is less than or equal to μ-σ. In this region, the Acceleration Score is the maximum possible of 100. A vehicle acceleration rate is *acceptable* if it is greater than μ-σ but less than μ+2σ. In this region, the Acceleration Score decreases from 100 to 0 as the vehicle acceleration rate increases from μ-σ towards μ+2σ. Finally, a vehicle acceleration rate is *unacceptable* if it is equal to or greater than μ+2σ. In this case, the Acceleration Score is zero. Note that the thresholds of the acceptable acceleration rate region can be set by the driver or fleet manager.

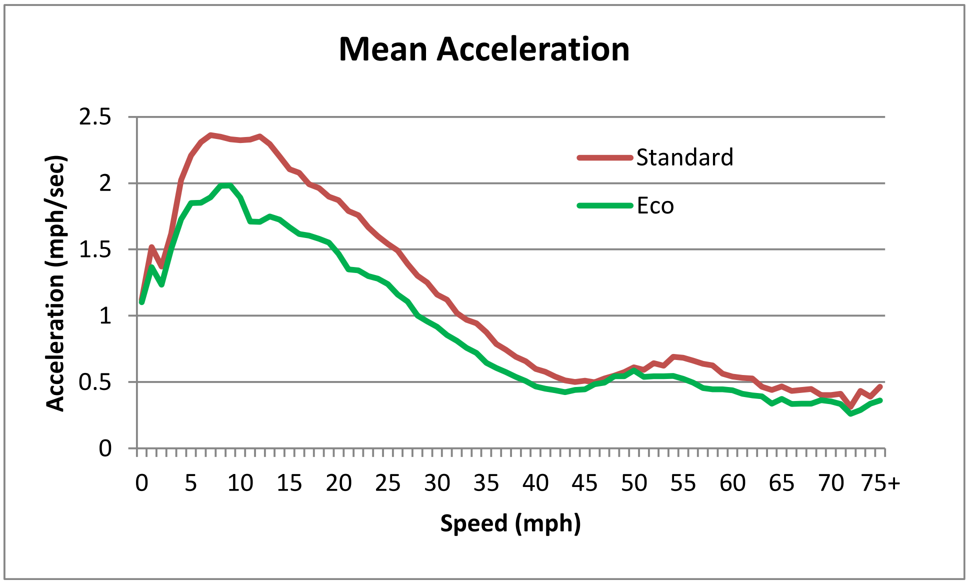

Figure 7. Mean acceleration as a function of vehicle speed

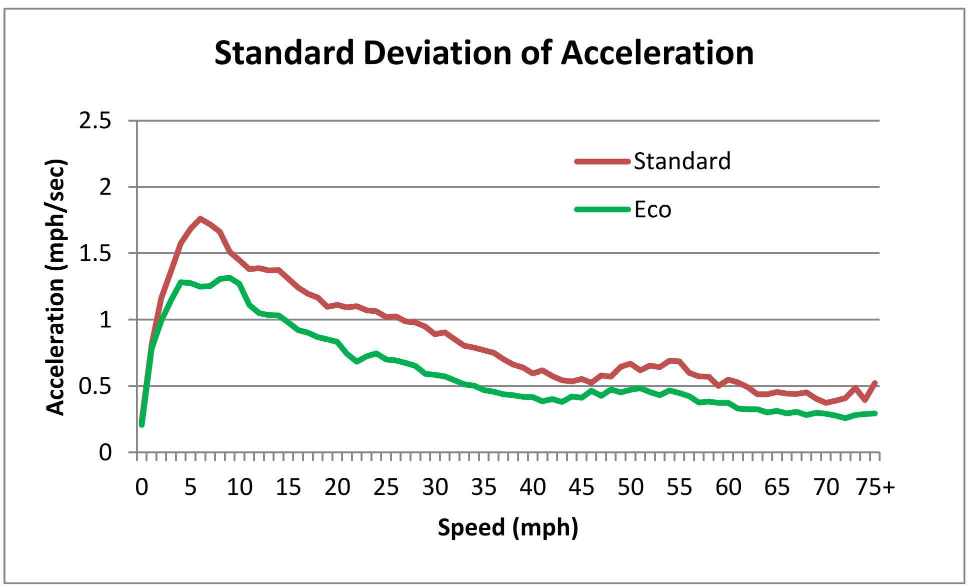

Figure 8. Standard deviation of acceleration as a function of vehicle speed

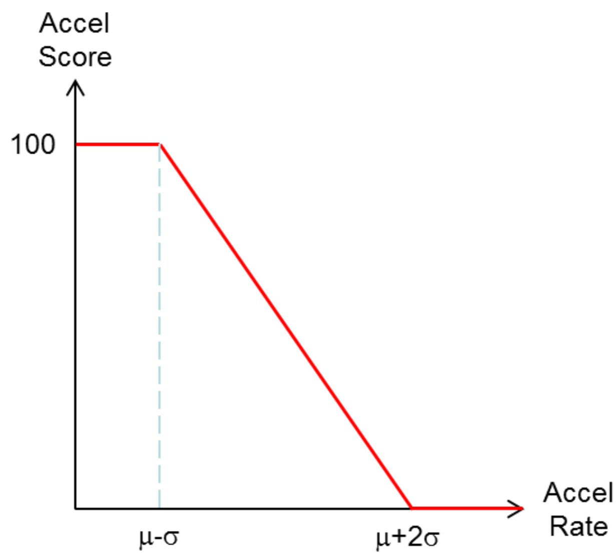

Figure 9. Acceleration Score curve

Braking Score

The calculation of the Braking Score is similar to that of the Acceleration Score. Given the mean (μ) and standard deviation (σ) of the deceleration rate for any vehicle speed, the range of vehicle deceleration rate can also be divided into three regions: 1) desirable, 2) acceptable, and 3) unacceptable. Note that arithmetically, the value of vehicle deceleration rates is negative.

Based on Figure 10, a vehicle deceleration rate is *desirable* if its value is higher than or equal to $\mu+\sigma$. In this region, the Deceleration Score is the maximum possible of 100. A vehicle deceleration rate is *acceptable* if its value is lower than $\mu+\sigma$ but higher than μ-2σ. In this region, the Deceleration Score decreases from 100 to 0 as the value of vehicle deceleration rate decreases from $\mu+\sigma$ towards μ-2σ. Finally, a vehicle deceleration rate is *unacceptable* if its value is equal to or lower than μ-2σ. In this case, the Deceleration Score is zero. Note that the thresholds of the acceptable deceleration rate region can be set by the driver or fleet manager.

Overall Score

The Overall Score is an aggregation of the three modal scores into one score. This is useful for evaluating the overall driving performance in all aspects. The Overall Score is calculated as a weighted average of the three modal scores. The weights are customizable, allowing the driver or fleet manager to emphasize one behavior over another. For example, one may give more weight to the Acceleration Score than the Braking Score as acceleration behavior has a greater impact on vehicle fuel consumption than braking behavior. Similar to other scores, the Overall Score is also calculated on a second-by-second basis. Thus, it can be aggregated for any time period (e.g., 5 minutes) by calculating the simple average of the score values over that time period. The same method can be applied to the individual modal scores as well. The aggregated scores over the entire driving scenario are displayed to the driver at the end of the trip and are used to rank drivers by their fuel-efficient driving performance.

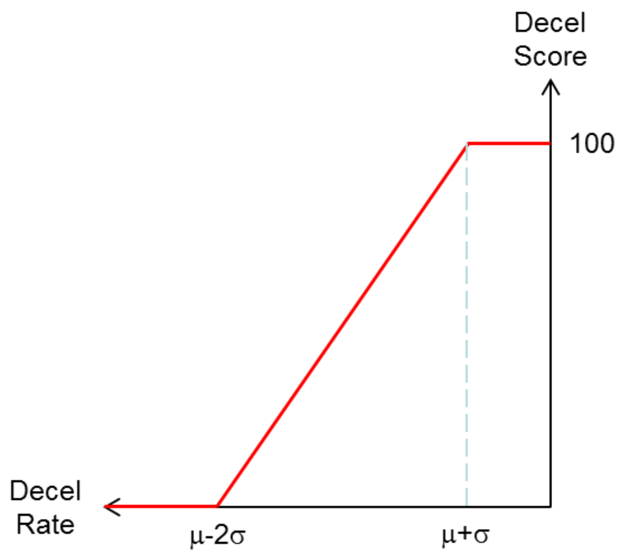

Figure 10. Braking Score curve

Experiment

Truck Driving Simulator

In 2012, we acquired a state-of-the art truck driving simulator, called Minisim^{TM}, from the National Advanced Driving Simulator. It is a sophisticated PC-based driving simulator that is configured to have multiple displays, instrument panel, and high-quality steering wheel and pedals built into a system the size of a quarter cab. As shown in Figure 11, the simulator's visual graphics are displayed on three 42'' plasma screens, and there is a separate LCD screen immediately below that replicates the instrument panel. The simulator conveys sound (e.g., engine noise, horn) through a 2.1 audio system. The drivers use an adjustable steering wheel, gas and brake pedals, and gear shift lever (8 gears) when they drive in the simulator, the same way as driving in a real truck.

Figure 11. Minisim^{TM} truck driving simulator at UCR

The simulator comes with several software tools including Tile Mosaic Tool (TMT) and Interactive Scenario Authoring Tool (ISAT) that are used to create driving scenarios. TMT allows roadmaps to be built using a database of premade tiles. ISAT uses the roadmap built in TMT and places objects and coordinators on it. The objects include static ones, such as signs and obstacles, as well as Autonomous Dynamic Objects (ADOs) and Dependent Dynamic Objects (DDOs), such as vehicles. ADOs can be simply placed on a roadmap, and will drive autonomously while obeying preset controls, including lane deviation, maximum and minimum speed, acceleration, and gap between vehicles. DDOs require a designated path, and will not move unless given a set of nodes to travel to on the roadmap. Coordinators, including traffic signals, global time triggers, and road pads, provide a way to control large groups of ADOs. On the other hand, DDOs are not affected by coordinators. Once a driving scenario has been created and the external driver has been given a spawn point on the roadmap, the scenario can be run by Minisim^{TM}.

In this project, the Eco-Driving Feedback technology was integrated with the truck driving simulator as a parallel system that interfaces with Minisim™ in real time. As shown in Figure 12, a data acquisition and processing computer is connected to the truck driving simulator. It collects real-time driving and traffic data from the simulator, and uses these data as inputs for determining eco-driving feedback, which is displayed to the driver on a 7-inch automotive-grade monitor that sits atop the instrument panel (this monitor replicates the tablet used in the DOE research program). A significant amount of work was performed to migrate the computer codes from the Android platform previously used in the DOE research program to the Windows platform used by the truck driving simulator.

Figure 12. Integration of Eco-Driving Feedback technology with truck driving simulator

We adapted the same features of the Eco-Driving Feedback technology interface (i.e., Eco-Speed Band, Warning, Benchmark MPG, Current MPG, Eco-Score, and Cumulative Fuel Savings), but customized them for heavy-duty trucks. For example, we changed the range of the MPG gauge from 0-70 to 0-14. We also adjusted the thresholds for triggering acceleration and braking warnings to the levels that are appropriate for trucks. In addition, we removed the idling warning as it is difficult to study truck drivers' idling behavior with a driving simulator. Generally, truck drivers idle the engine to heat/cool the cab or to use electronic devices; those situations are difficult to replicate in a driving simulator environment.

Since the truck driving simulator does not have a real truck engine, real-time fuel consumption while driving the simulator (which is used to calculate Current MPG and Cumulative Fuel Savings) is estimated using fuel consumption rate data from the U.S. Environmental Protection Agency's Motor Vehicle Emission Simulator (MOVES) model (*10*) for a 2009 model year heavy-duty truck with a diesel engine. The estimation is based on second-by-second speed and acceleration of the driving as captured by the simulator. In addition to fuel consumption, various types of emissions were also estimated using emission rate data from the MOVES model. These include carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_X), and fine particulate matter ($PM_{2.5}$). Of particular interest are NO_X and $PM_{2.5}$, which are major pollutants generated by diesel engines.

Driving Scenario

The driving scenario developed in this project represents a typical freight trip in Southern California where a truck hauls a container from a warehouse in the Inland Empire to the Port of Los Angeles. During the trip, the truck goes through four driving conditions:

1. *Uncongested arterial* – from the warehouse to the nearest freeway
2. *Uncongested highway* – on an outer Los Angeles freeway
3. *Congested highway* – on an inner Los Angeles freeway
4. *Congested arterial* – from the freeway to the Port

The initial driving scenario that was coded was tested by UCR staff members who have experience driving heavy-duty trucks and hold commercial driver license. The feedback received from the test drives was used in the refinement of the driving scenario. Figure 13 shows an overview of the final driving scenario in the TMT. Then, Figure 14 through Figure 17 show scenes from each of the four driving conditions. Each driving condition is about 7 minutes long, so it would take about 28 minutes on average to complete the trip in the driving simulator. The length of the trip helps ensure that the amount of driving data collected would be sufficient for the characterization of driving behavior under each driving condition.

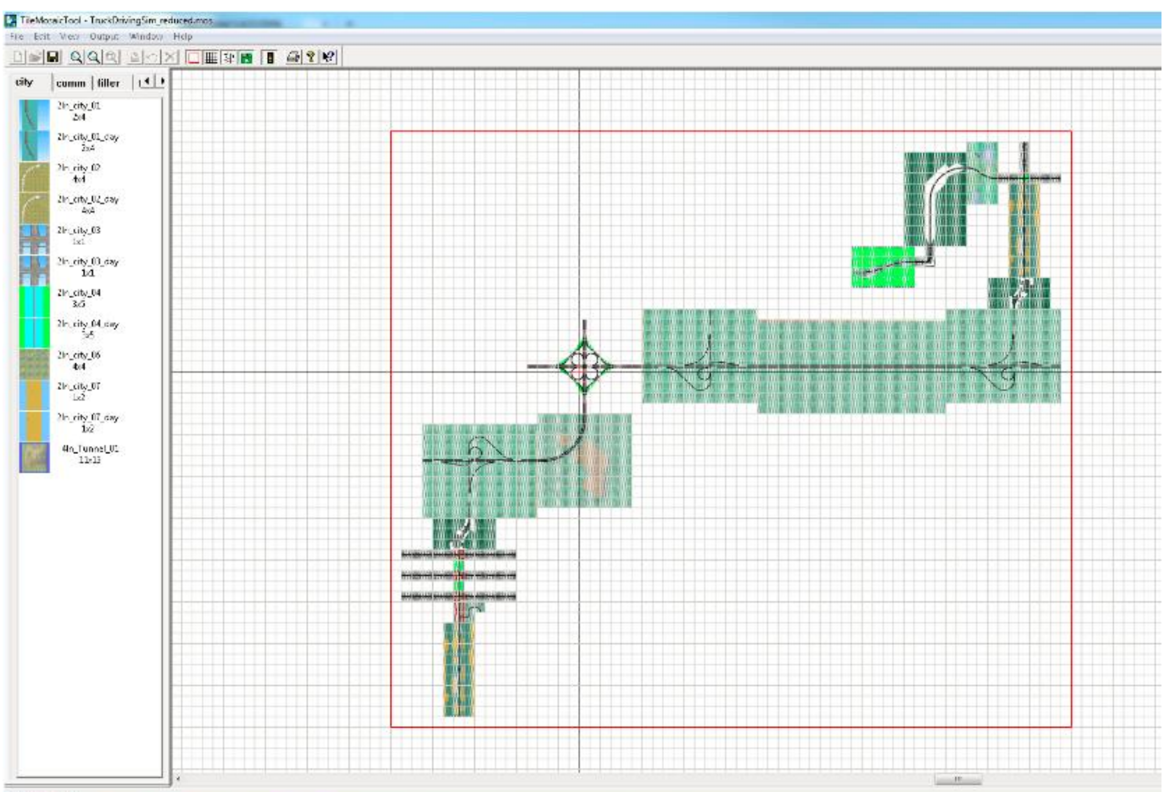

Figure 13. Overview of the driving scenario in the Tile Mosaic Tool

Figure 14. Scene during uncongested arterial condition

Figure 15. Scene during uncongested highway condition

Figure 16. Scene during congested highway condition

Figure 17. Scene during congested arterial condition

Procedures

Once the truck driving simulator was configured and programmed with the developed driving scenario, truck driver participants were recruited from local truck fleets to take part in the driving experiment. The experiment consisted of several steps as described below.

1. *Pre-Survey* – First, the participants were asked to fill out a pre-survey. This survey contains questions about their truck and fleet, typical trucking operations, driving habits, knowledge about fuel-efficient driving, and demographics. A copy of the pre-survey is provided in Appendix A.

2. *Eco-Routing Experiment* – The participants were asked to complete the eco-routing experiment on a tablet where they were presented with 14 trip scenarios. There are three route options for each scenario (i.e., shortest distance, shortest travel time, and most fuel-efficient) and they must select one of them. The selected route option in each scenario was recorded for later analyses.

3. *Introduction to Driving Simulator* – The participants were introduced to the truck driving simulator, and given a chance to test drive it using a sample driving scenario that comes with the simulator (not the one developed in this project). They would practice driving the simulator until they felt comfortable with it.

4. *Baseline Driving* – The participants were asked to drive the driving scenario developed in this project in a way that they would normally drive in real life.

5. *Introduction to Eco-Driving Feedback Technology* – The participants were introduced to the Eco-Driving Feedback technology and its interface, and were explained all the features on the interface. Then, they were given a chance to try the Eco-Driving Feedback technology in another test drive using a sample driving scenario that comes with the simulator (not the one developed in this project).

6. *Driving with Feedback* – The participants were asked to drive the driving scenario developed in this project with the use of the Eco-Driving Feedback technology.

7. *Post-Survey* – Lastly, the participants were asked to fill out a post-survey. This survey contains questions about their experience with and opinion of the Eco-Driving Feedback technology. A copy of the post-survey is provided in Appendix B.

Data Collection and Processing

Driving data were automatically recorded through the Minisim™ DAQ (Data Acquisition) tool. Several parameters such as truck speed, position, engine speed, etc., were recorded at the frequency of 60 Hz. The data were aggregated into 1 Hz and then used to calculate acceleration/deceleration rate, instantaneous fuel consumption, and eco-scores that drive the different features of the Eco-Driving Feedback interface. The aggregated data were also used to calculate the various emissions (i.e., CO_2, CO, HC, NO_x, and $PM_{2.5}$) based on the emission rates of a 2009 model year heavy-duty diesel truck from the U.S. Environmental Protection Agency's MOVES model. MOVES defines 23 different operating mode (OpMode) bins for a vehicle in operation based on its second-by-second speed and vehicle specific power (VSP), as shown in Figure 18. Each OpMode bin is associated with a fuel consumption or emission rate. Figure 19 shows the fuel consumption rates by OpMode bin for the truck assumed in this project.

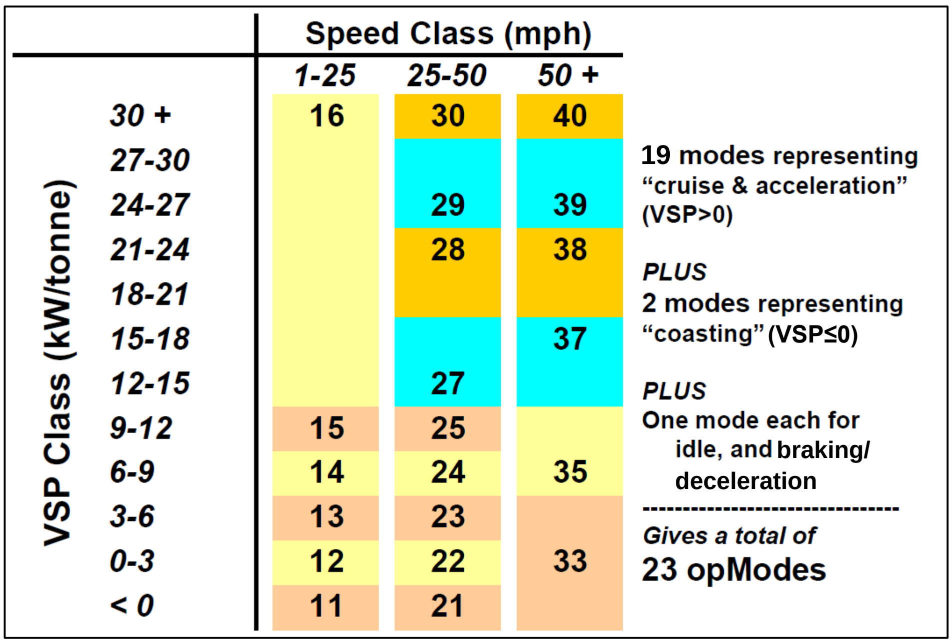

Figure 18. Definition of vehicle operating mode bins in MOVES model

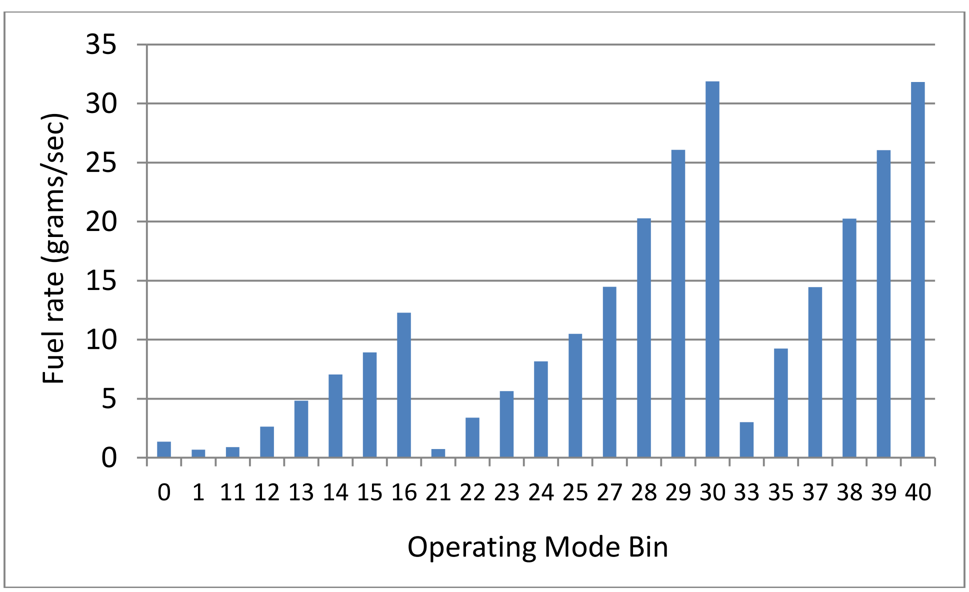

Figure 19. Fuel consumption rate of 2009 model year heavy-duty diesel truck

Results

This section presents the experiment results for 22 truck driver participants. Twenty of them are male and two are female. The age of the participants ranges from 23 to 68 years old, with the median of 48 years. The length of professional driving experience ranges from 6 months to 30 years, with the median of 17 years.

Pre-Survey

The pre-survey asks questions about the participants' trucks and fleets, typical trucking operations, driving habits, knowledge about fuel-efficient driving, and demographics. Based on the survey responses:

- Fifteen out of 22 participants (68%) operate regionally with a typical trip being no more than 100 miles.
- Seven out of 22 participants (32%) work in distribution and warehousing and another seven (32%) provides truckload and less-than-truckload services. The remaining participants do freight forward, drayage, and others.
- Seven out of 22 participants (32%) are either an independent owner/operator or from a small fleet with no more than five trucks in the fleet. Four participants (18%) are from a medium-sized fleet with 6-25 trucks in the fleet. Eleven participants (50%) are from a large fleet with more than 25 trucks in the fleet.
- As shown in Figure 20, half of the participants answer that they generally maintain a speed of 55 mph on highway, which is the maximum speed limit for trucks on California highways. The remaining participants except one report maintaining a speed higher than the speed limit.

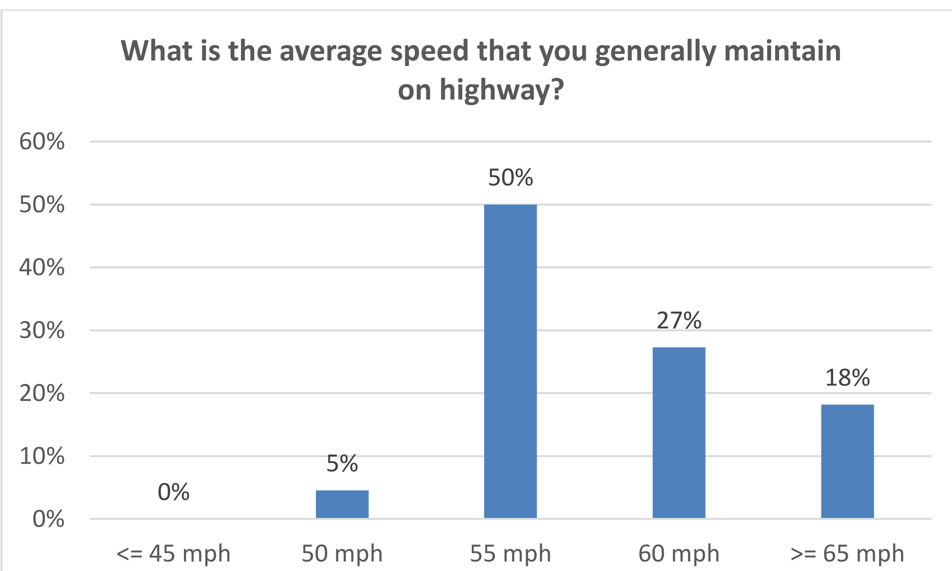

Figure 20. Responses to question "What is the average speed that you generally maintain on highway?"

In terms of prior training and knowledge on fuel-efficient driving:

- Seven out of 22 participants (32%) indicates that they receive training or feedback on how to improve fuel economy. Two of those seven report receiving it once, another two report receiving it annually, and the other three report receiving it quarterly. Measures that the participants are trained to take include:
    - Accelerate mildly (3 out of 7 participants)
    - Decelerate gradually (4 out of 7)
    - Use moderate highway driving speed (2 out of 7)
    - Maintain constant driving speed (3 out of 7)
    - Avoid unnecessary idling (4 out of 7)
    - Use progressive gear shifting technique (1 out of 7)

  None is trained to change gear with double-clutching technique.
- As shown in Figure 21, 13 participants (59%) think that the training on how to improve fuel economy definitely is or would definitely be useful to them. Another 8 participants (36%) think that it probably is or would probably be useful to them.

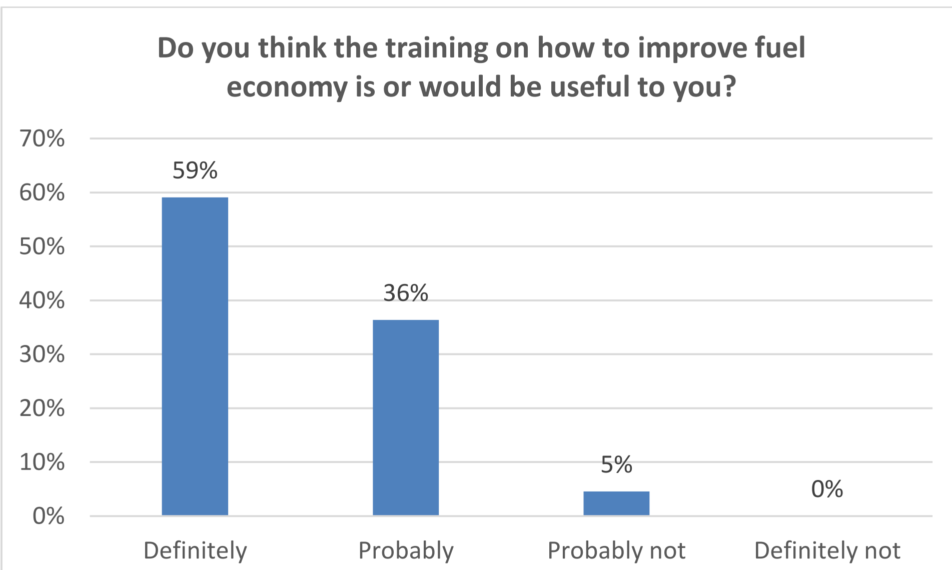

Figure 21. Responses to question "Do you think the training on how to improve fuel economy is or would be useful to you?"

As for the current efforts to improve fuel economy:

- As shown in Figure 22, all but one participant indicates currently taking one or more measure to improve fuel economy.
- Two of the 22 participants (9%) work for companies that provide incentives to save fuel. Both of them indicate that they probably do not try to drive more fuel efficiently in order to earn these incentives.
- Figure 23 shows that all but one participant uses one or more tools to provide driving directions while Figure 24 shows how much the participants are willing to pay for an in-vehicle device that can help guide them to improve fuel economy of their driving by 5%.

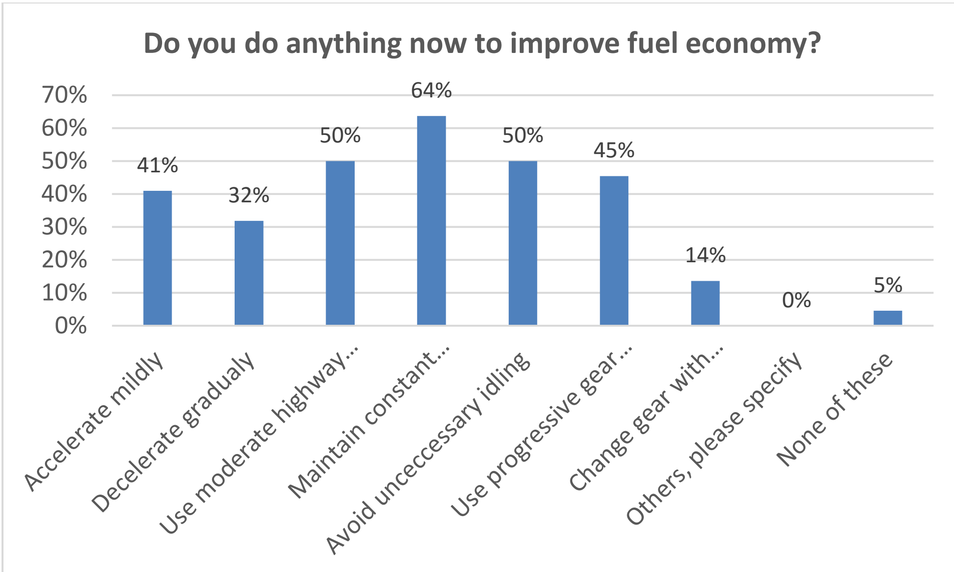

Figure 22. Responses to question "Do you do anything now to improve fuel economy?"

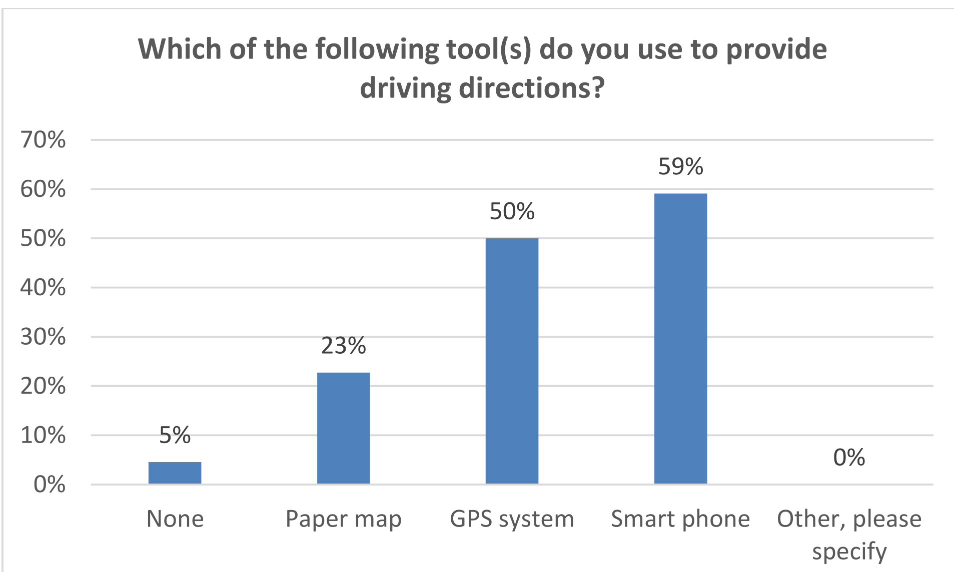

Figure 23. Responses to question "Which of the following tool(s) do you use to provide driving directions?"

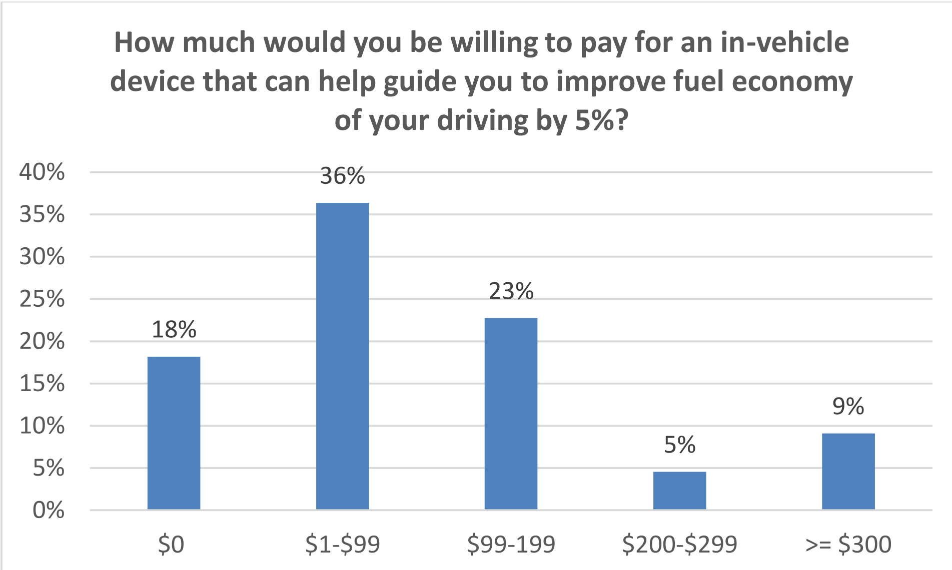

Figure 24. Responses to question "How much would you be willing to pay for an in-vehicle device that can help guide you to improve fuel economy of your driving by 5%?"

Eco-Routing Navigation

Table 1 presents the distance, travel time, and fuel use of each route option in each trip scenario. Taking trip scenario 1 as an example, for this trip the fastest route and the most fuel-efficient route would take the same amount of time and consume the same amount of fuel. While the shortest route would be shorter in terms of distance as compared to the other two routes, it would take longer time and consume more fuel. Taking trip scenario 4 as another example, for this trip it was purposefully designed so that the most fuel-efficient route would take about 5% longer time but consume approximately 25% less fuel as compared to the fastest route. For this same trip, the shortest route would naturally have the shortest distance, take longer time than the fastest route, and consume more fuel than the most fuel-efficient route.

Table 2 tabulates the tally of route options selected by the 22 truck driver participants for each of the 14 trip scenarios. Overall, the participants selected the shortest route for 44% of the time (134 out of 308), the fastest route 18% of the time (56 out of 308), and the most fuel-efficient route 38% of the time (118 out of 308). When examining the individual trip scenarios, it is found that the fastest route is selected the least in most scenarios. The most fuel-efficient route is selected the most in trip scenario 14 where the route would consume 25% less fuel than the fastest route albeit taking 25% longer travel time.

While travel behavior theories often suggest that travelers would try to minimize their overall travel costs, a big part of which is travel time, the results from this experiment are not necessarily aligned with such suggestion. One potential explanation may be that several participants are employed by companies as opposed to being independent owners/operators, so travel time spent on the job may not necessarily be regarded as their personal cost. The same may be true with fuel use. Normally, truck drivers employed by companies are not responsible for the fuel cost as the companies manage all aspects of the truck fleets. Therefore, they may not have motivation to save fuel. Another potential explanation for the results of this experiment may be that not every driver uses the same or even a similar rationale in making route choice decision. Some may follow their instinct and feel that the shortest route is always the best. Some may prioritize other attributes, such as familiarity with the route, over the attributes included in the experiment.

Table 1. Attributes of each route option in each trip scenario

Trip Sce-nario	% Time In-crease	% Fuel Sav-ings	Shortest Route			Fastest Route			Most-Fuel Efficient Route		
			Dist. (mi)	Time (min)	Fuel (gal)	Dist. (mi)	Time (min)	Fuel (gal)	Dist. (mi)	Time (min)	Fuel (gal)
1	0	0	57.8	70.4	9.6	59.7	67.0	9.2	58.2	67.0	9.2
2	5	5	39.9	61.7	7.1	46.0	56.0	7.1	49.5	58.8	6.7
3	5	15	29.7	49.6	5.1	36.8	45.0	5.7	35.8	47.3	4.8
4	5	25	24.4	36.4	3.1	25.3	33.0	3.9	27.4	34.7	2.9
5	10	10	13.5	41.6	3.0	20.9	36.0	3.2	20.9	39.6	2.9
6	10	20	16.3	25.4	2.5	19.0	22.0	2.9	21.7	24.2	2.3
7	15	5	12.2	21.7	2.2	14.1	18.0	2.2	13.0	20.7	2.1
8	15	15	30.5	49.5	4.6	33.2	41.0	5.1	32.1	47.2	4.3
9	15	25	35.8	55.5	5.2	42.7	46.0	6.6	49.5	52.9	4.9
10	20	10	10.0	26.5	1.5	10.5	21.0	1.6	11.0	25.2	1.5
11	20	20	8.2	18.9	1.2	9.1	15.0	1.4	10.6	18.0	1.1
12	25	5	31.3	59.1	4.9	31.8	45.0	4.9	35.7	56.3	4.6
13	25	15	34.2	60.4	4.7	34.5	46.0	5.3	35.2	57.5	4.5
14	25	25	41.6	64.3	5.4	44.5	49.0	6.8	42.0	61.3	5.1

Table 2. Number of participants who selected each route option in each trip scenario

Trip Scenario	Number of Participants Who Selected			
	Shortest Route	Fastest Route	Most Fuel-Efficient Route	*Total*
1	10	2	10	*22*
2	10	6	6	*22*
3	11	4	7	*22*
4	7	5	10	*22*
5	8	3	11	*22*
6	12	2	8	*22*
7	8	5	9	*22*
8	14	3	5	*22*
9	14	3	5	*22*
10	10	4	8	*22*
11	6	8	8	*22*
12	10	4	8	*22*
13	11	4	7	*22*
14	3	3	16	*22*
Total	*134*	*56*	*118*	*308*

Eco-Driving Feedback

The driving data over the 12-mile driving scenario collected from the truck driving simulator were processed and then used to calculate a number of driving metrics, including:

- Time – total travel time for the trip (minutes)
- Fuel – total fuel consumption for the trip (gallons)
- NO_x – total oxides of nitrogen emission for the trip (grams)
- $PM_{x2.5}$ – total fine particulate matter emission for the trip (grams)
- CO – total carbon monoxide emission for the trip (grams)
- HC – total hydrocarbon emission for the trip (grams)
- Speed – trip average speed (miles per hour)
- MPG – trip average fuel economy (miles per gallon)
- ESA – eco-score for acceleration
- ESB – eco-score for braking
- ESS – eco-score for speed
- ESO – overall eco-score

Tables 3 presents the results for the baseline driving, while Table 4 presents the results for the driving with Eco-Driving Feedback technology.

Table 3. Driving simulator results of baseline driving

ID	Time (min)	Fuel (gal)	NO_x (g)	$PM_{2.5}$ (g)	CO (g)	HC (g)	Speed (mph)	MPG	ESA	ESB	ESS	ESO
01	22.8	1.98	96.7	0.37	4.84	1.16	31.5	6.1	75	80	98	88
02	22.8	1.82	89.8	0.33	4.61	1.14	31.6	6.6	73	86	97	88
03	25.3	1.85	92.2	0.32	4.95	1.25	28.5	6.5	78	83	95	88
04	26.4	1.66	85.0	0.29	4.85	1.30	27.2	7.2	87	92	100	95
05	32.6	2.53	121.3	0.43	5.35	1.45	22.1	4.7	50	72	93	80
06	26.5	2.05	100.9	0.36	5.09	1.29	27.2	5.9	76	80	96	88
07	32.0	1.59	86.7	0.29	5.25	1.50	22.5	7.6	97	93	100	98
08	26.2	1.75	89.1	0.30	4.93	1.28	27.5	6.9	88	89	95	92
09	36.6	1.76	96.8	0.33	5.63	1.75	19.7	6.8	92	97	100	97
10	34.1	1.82	97.1	0.35	5.76	1.56	21.1	6.6	92	92	100	97
11	31.4	1.71	91.3	0.31	5.44	1.49	22.9	7.0	91	91	99	95
12	27.9	1.87	94.7	0.33	5.33	1.37	25.8	6.4	86	83	99	93
13	25.6	1.93	96.6	0.34	5.05	1.24	28.1	6.2	75	79	95	87
14	25.9	1.97	98.5	0.35	5.10	1.28	27.8	6.1	76	79	96	87
15	30.4	1.74	91.3	0.32	5.44	1.47	23.7	6.9	89	93	99	95
16	25.3	1.79	87.8	0.30	4.95	1.27	28.4	6.7	86	87	94	91
17	25.4	2.10	101.1	0.35	5.15	1.25	28.4	5.7	79	71	93	85
18	25.8	1.95	95.9	0.34	4.88	1.23	27.9	6.2	70	81	91	84
19	25.0	1.88	91.7	0.31	4.89	1.22	28.8	6.4	83	83	93	89
20	24.8	2.11	98.1	0.36	4.61	1.11	29.1	5.7	65	76	86	81
21	21.0	2.10	95.6	0.33	4.44	1.02	34.2	5.7	74	71	74	75
22	26.3	1.81	90.9	0.32	4.86	1.21	27.3	6.6	75	84	97	89
Avg	*27.3*	*1.90*	*95.0*	*0.33*	*5.06*	*1.31*	*26.4*	*6.3*	*80*	*84*	*95*	*89*

Table 4. Driving simulator results of driving with Eco-Driving Feedback technology

ID	Time (min)	Fuel (gal)	NO_x (g)	$PM_{2.5}$ (g)	CO (g)	HC (g)	Speed (mph)	MPG	ESA	ESB	ESS	ESO
01	25.7	1.73	87.6	0.30	4.97	1.29	28.0	6.9	87	90	100	94
02	24.8	1.65	85.0	0.30	4.78	1.25	29.0	7.3	87	91	99	94
03	26.8	1.59	85.6	0.30	4.94	1.31	26.8	7.5	82	87	97	91
04	32.7	1.55	85.0	0.29	5.20	1.59	22.0	7.8	95	96	100	98
05	28.3	1.85	93.0	0.32	5.14	1.37	25.4	6.5	86	89	97	93
06	23.5	1.77	88.7	0.31	4.83	1.19	30.7	6.8	82	86	99	91
07	29.2	1.55	84.1	0.28	5.11	1.42	24.7	7.8	97	89	98	96
08	24.8	1.66	84.4	0.29	4.83	1.25	29.0	7.2	85	90	96	92
09	29.9	1.71	90.9	0.32	5.23	1.46	24.0	7.0	86	95	100	96
10	37.7	1.81	99.9	0.35	6.00	1.84	19.1	6.6	96	92	99	97
11	31.9	1.61	86.8	0.32	5.46	1.56	22.6	7.5	95	95	100	97
12	28.3	1.68	88.0	0.29	5.26	1.42	25.5	7.2	93	89	100	96
13	27.7	1.62	84.7	0.31	5.19	1.37	26.0	7.4	92	92	99	96
14	27.6	1.45	78.6	0.26	4.84	1.38	26.1	8.3	95	94	100	97
15	28.1	1.64	85.5	0.32	5.33	1.42	25.6	7.3	93	93	99	96
16	27.5	1.51	80.3	0.27	4.92	1.39	26.2	8.0	96	93	100	98
17	26.8	1.99	98.4	0.35	5.31	1.30	26.8	6.0	81	79	97	89
18	23.8	1.96	94.8	0.33	4.73	1.18	30.2	6.1	67	77	87	80
19	24.6	1.53	80.4	0.27	4.81	1.24	29.3	7.9	89	91	100	95
20	26.5	1.66	85.3	0.30	5.10	1.30	27.1	7.2	89	91	100	95
21	22.4	1.82	88.6	0.31	4.53	1.10	32.1	6.6	73	80	84	81
22	23.7	1.84	90.1	0.33	4.59	1.18	30.4	6.5	67	87	95	86
Avg	*27.4*	*1.69*	*87.5*	*0.31*	*5.05*	*1.35*	*26.3*	*7.1*	*87*	*89*	*98*	*93*

On average, driving with the Eco-Driving Feedback technology helps reduce fuel consumption over the 12-mile trip from 1.90 gallons to 1.69 gallons. Assume that the same level of fuel savings is achieved in a typical commercial truck that travels 100,000 per year, the total fuel savings from the use of the Eco-Driving Feedback technology would be 1,750 gallons annually. Table 5 presents the percentage changes in the results of the driving feedback as compared with the baseline driving. They are calculated as:

$$\% \text{ change} = 100\% \times (v_f - v_b)/v_b$$

where v_f is value from the driving with feedback, and v_b is value from the baseline driving.

According to this table, the driving feedback seems to provide energy and emission benefits. Specifically, the total fuel consumption for the trip when driving with feedback is reduced across all the drivers by up to 27%. The total emissions for the trip are also reduced for most drivers by up to 23%, 26%, 7%, and 17% for NO_x, $PM_{2.5}$, CO, and HC, respectively. While the total CO and HC emissions for the trip noticeably increase for some drivers (up to 11% for CO and 22% for HC), these two pollutants are of less concern for heavy-duty diesel trucks as on-road emission inventories of these pollutants are more dominated by contribution from gasoline vehicles. On the other hand, diesel vehicles, most of which are heavy-duty trucks, are the major contributor of on-road emission inventories of NO_x and $PM_{2.5}$.

The impact of the driving feedback on trip travel time is varied. The changes range from 18% reduction to 24% increase in travel time. As for the eco-scores, the changes are mostly in the positive direction, with the driving feedback having a greater impact on acceleration behavior (up to 72% improvement) followed by braking behavior (up to 24% improvement) and speed behavior (up to 16% improvement), respectively. When considering an average driver from this group of driver participants, the Eco-Driving Feedback technology has no impact on trip travel time and CO emission (0% change) while reducing fuel consumption, NO_x emission, and $PM_{2.5}$ emission for the trip by 11%, 8%, and 8%, respectively. The Eco-Driving Feedback technology also improves the acceleration behavior of the average driver by 9%, the braking behavior by 7%, and the speed behavior by 3%.

Table 5. Percentage changes in the results of driving with feedback as compared to baseline

ID	Time (min)	Fuel (gal)	NO_x (g)	$PM_{2.5}$ (g)	CO (g)	HC (g)	Speed (mph)	MPG	ESA	ESB	ESS	ESO
01	12%	-13%	-9%	-17%	3%	11%	-11%	14%	16%	13%	2%	7%
02	9%	-10%	-5%	-10%	4%	9%	-8%	11%	19%	6%	2%	7%
03	6%	-14%	-7%	-6%	0%	5%	-6%	16%	5%	5%	2%	3%
04	24%	-7%	0%	0%	7%	22%	-19%	7%	9%	4%	0%	3%
05	-13%	-27%	-23%	-25%	-4%	-6%	15%	37%	72%	24%	4%	16%
06	-11%	-14%	-12%	-14%	-5%	-8%	13%	16%	8%	8%	3%	3%
07	-9%	-3%	-3%	-3%	-3%	-5%	10%	3%	0%	-4%	-2%	-2%
08	-5%	-5%	-5%	-3%	-2%	-2%	5%	6%	-3%	1%	1%	0%
09	-18%	-3%	-6%	-3%	-7%	-17%	22%	3%	-7%	-2%	0%	-1%
10	11%	0%	3%	0%	4%	18%	-10%	0%	4%	0%	-1%	0%
11	1%	-6%	-5%	3%	0%	5%	-1%	6%	4%	4%	1%	2%
12	1%	-10%	-7%	-12%	-1%	3%	-1%	11%	8%	7%	1%	3%
13	8%	-16%	-12%	-9%	3%	10%	-7%	19%	23%	16%	4%	10%
14	6%	-26%	-20%	-26%	-5%	8%	-6%	36%	25%	19%	4%	11%
15	-7%	-6%	-6%	0%	-2%	-3%	8%	6%	4%	0%	0%	1%
16	9%	-16%	-8%	-10%	-1%	10%	-8%	19%	12%	7%	6%	8%
17	6%	-5%	-3%	-1%	3%	4%	-5%	6%	3%	11%	4%	5%
18	-8%	1%	-1%	-3%	-3%	-4%	8%	-1%	-4%	-5%	-4%	-5%
19	-2%	-19%	-12%	-13%	-2%	2%	2%	23%	7%	10%	8%	7%
20	7%	-21%	-13%	-17%	11%	17%	-7%	27%	37%	20%	16%	17%
21	6%	-13%	-7%	-6%	2%	7%	-6%	15%	-1%	13%	14%	8%
22	-10%	2%	-1%	3%	-6%	-2%	11%	-2%	-11%	4%	-2%	-3%
Avg	*0%*	*-11%*	*-8%*	*-8%*	*0%*	*3%*	*0%*	*12%*	*9%*	*7%*	*3%*	*4%*

To demonstrate the impact that the Eco-Driving Feedback technology has on driving behaviors, the driving data for Driver # 14 are used as an example. Figure 25 shows the speed profiles of the baseline driving and the driving with feedback over the course of the 12-mile driving scenario. The figure also shows the recommended driving speed given through the Eco-Speed Band along the driving course. The first 2.5-mile segment is the uncongested arterial condition, followed by the uncongested highway condition up to about the 8th mile. From about the 8th to the 10th mile, it is the congested highway condition. Finally, the last 2-mile segment is the congested arterial condition.

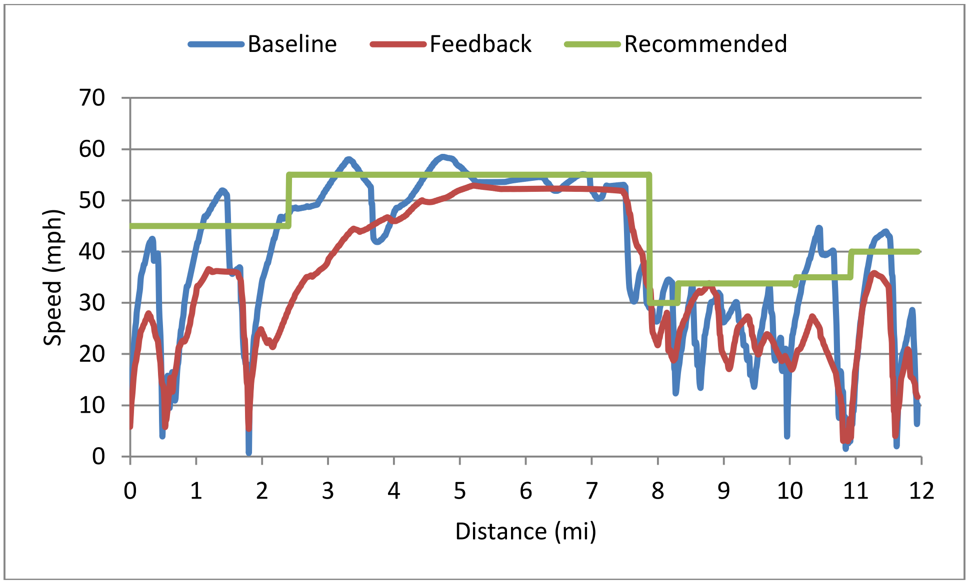

Figure 25. Driving speed profiles for Driver # 14

According to Figure 25, the speed profile for the baseline driving exceeds the recommended driving speed profile a several times. Since the Eco-Speed Band was actually not shown to the driver during the baseline driving, it means that the driver's personal choice of driving speed was not always at or below an appropriate level. On the other hand, the speed profile for the driving with feedback never exceeds the recommended speed profile, implying that the Eco-Speed Band was able to guide the driver to keep the driving speed at or below an appropriate level throughout the driving course. Not only did the Eco-Speed Band help the driver keep an appropriate level of driving speed, but it also helped the driver better maintain a constant speed. An example is the portion from the 5th to the 7.5th mile where the speed profile for the driving with feedback is smoother with less fluctuation than the one for the baseline driving.

The impact of the Eco-Driving Feedback technology on driving speed can also be viewed in the form of a speed histogram as shown in Figure 26 for the arterial portions and in Figure 27 for the highway portions of the driving course. In both figures, it can be seen that the range of speed for the driving with feedback is narrower where the frequency of speeds at the high and low ends is reduced as compared to the baseline driving.

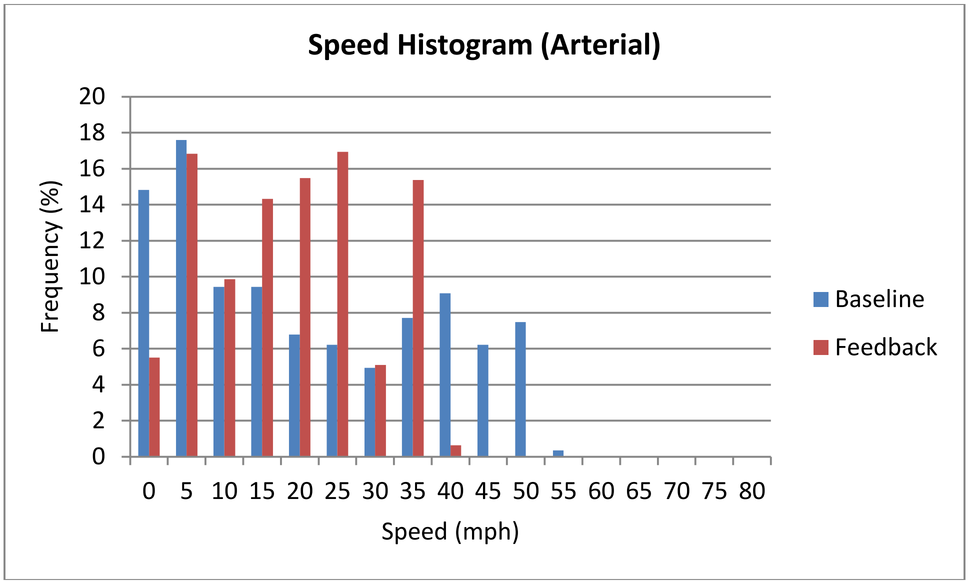

Figure 26. Speed histogram on arterial for Driver # 14

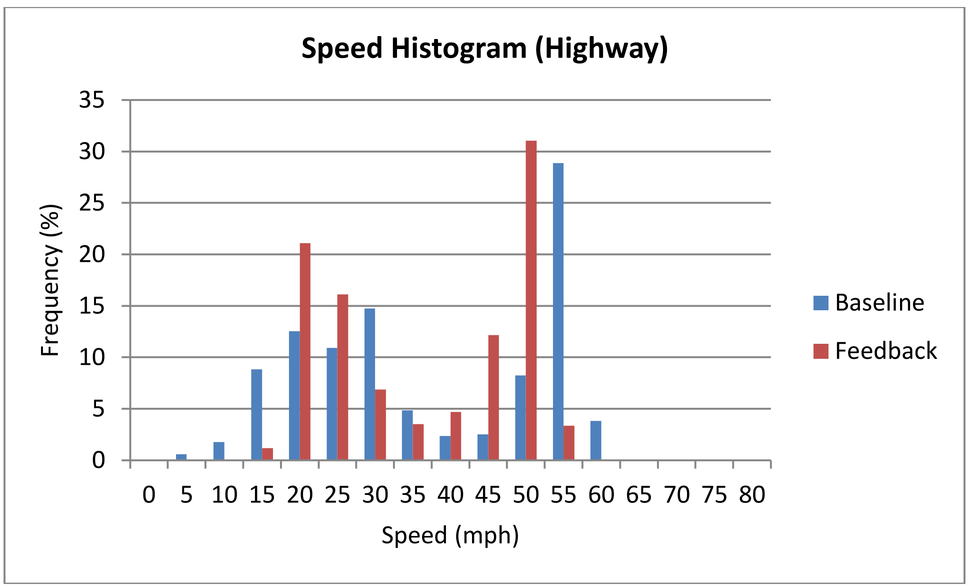

Figure 27. Speed histogram on highway for Driver # 14

In addition to the impact on speed, the plots in Figure 25 also show that the driving with feedback tends to have milder acceleration (e.g., the portion from the 2nd to the 5th mile). This could partly be attributed to the aggressive acceleration warning of the Eco-Driving Feedback technology where the driver was aware of the warning and tried to avoid triggering it. The impact of the warning on the driver's acceleration behavior can also be seen in Figures 28 and 29, which show the mean acceleration rates at different levels of speed for arterial driving and highway driving, respectively. In both figures, the mean acceleration profiles for the driving with feedback are much lower than the ones for the baseline driving.

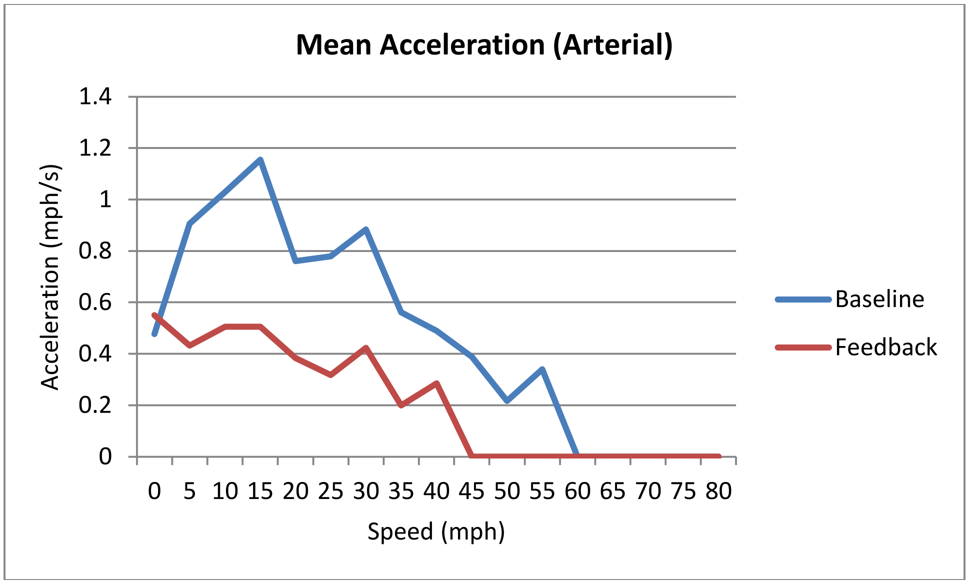

Figure 28. Mean acceleration profile on arterial for Driver # 14

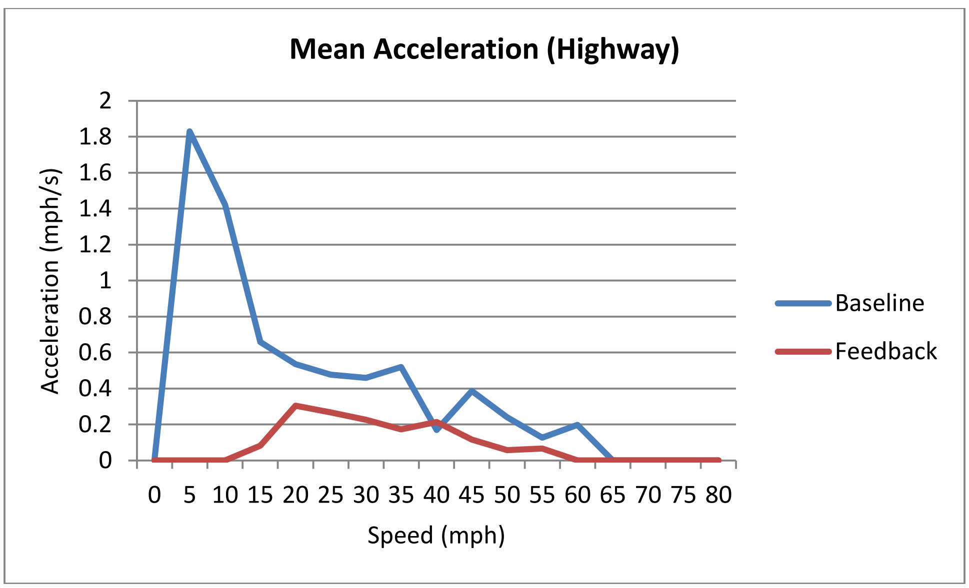

Figure 29. Mean acceleration profile on highway for Driver # 14

Similarly, the plots in Figure 25 also indicate that the driver was easier on the brake during the driving with feedback (e.g., the portion from the 7.5th to the 8th mile). This could partly be attributed to the hard braking warning of the Eco-Driving Feedback technology where the driver was aware of the warning and tried to avoid triggering it. The impact of the warning on the driver's braking behavior can also be seen in Figures 30 and 31, which show the mean deceleration rates at different levels of speed for arterial driving and highway driving, respectively. In both figures, the mean deceleration profiles for the driving with feedback are much lower than the ones for the baseline driving.

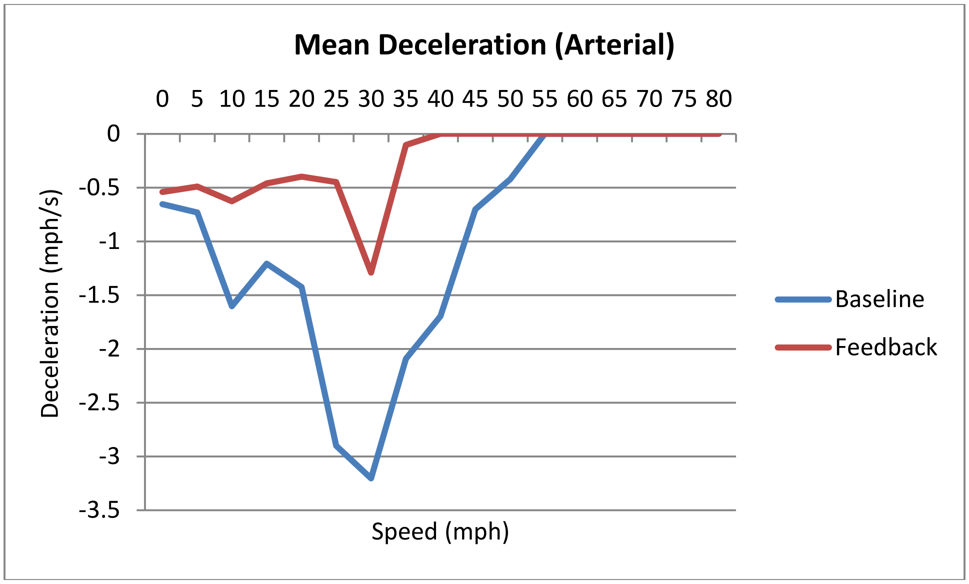

Figure 30. Mean deceleration profile on arterial for Driver # 14

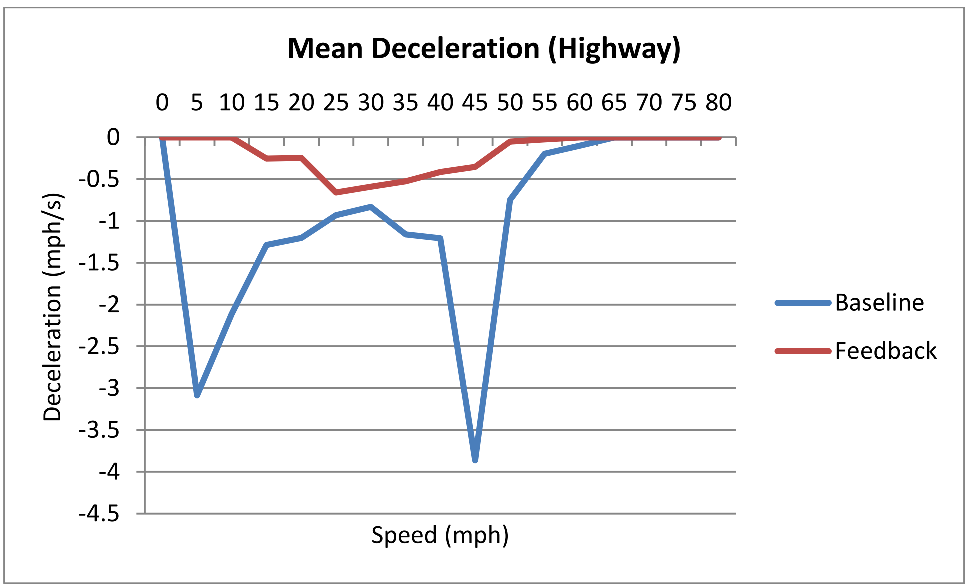

Figure 31. Mean deceleration profile on highway for Driver # 14

Plots similar to Figures 25 through 31 for each driver participant are provided in Appendix C.

Post-Survey

The post-survey asks questions about the driver participants' experience with and opinion of the Eco-Driving Feedback technology. In Figures 32 through 35, the number immediately above each bar is the percent of the 22 participants who select that option. The number in the bracket is the average fuel economy improvement when driving with the Eco-Driving Feedback technology of the participants who select that option.

Taking Figure 32 as an example, 23% of the participants (i.e., 5 out of 22) indicate that they have a lot of knowledge about fuel-efficient driving practices before participating in this study. These five participants have an average fuel economy improvement when driving with the Eco-Driving Feedback technology of 13%. Similarly, 50% of the participants (i.e., 11 out of 22) think that they have some knowledge about fuel-efficient driving practices before participating in the study, and these 11 participants have an average fuel economy improvement of 9%. The results in this figure show that the Eco-Driving Feedback technology can lead to similar levels of fuel economy improvement irrespective of the drivers' prior knowledge about fuel-efficient driving practices, implying that such knowledge is not a pre-requisite for an effective use of the technology.

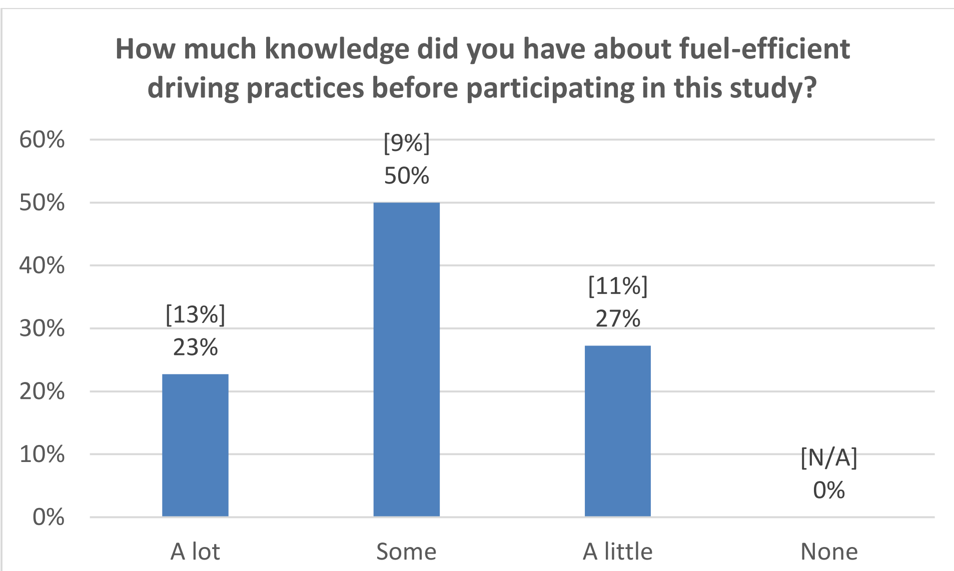

Figure 32. Responses to question "How much knowledge did you have about fuel-efficient driving practices before participating in this study?"

Figure 33 show the reported level of effort in following the recommended speed during the second drive (i.e., driving with the Eco-Driving Feedback technology). According to the figure, 5%, 32%, and 50% of the participants tried to follow the recommended speed sometimes, most of the time, and all the time, respectively. The associated fuel economy improvement results show that in general the more often the drivers followed the recommended speed, the more their fuel economy improved.

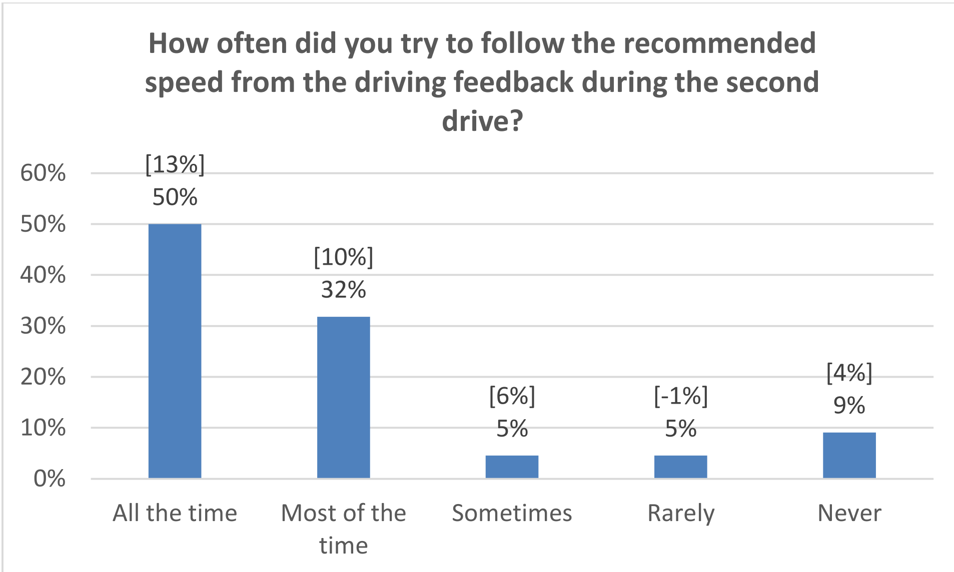

Figure 33. Responses to question "How often did you try to follow the recommended speed from the driving feedback during the second drive?"

Figure 34 shows how the participants perceive the change in their fuel economy during the second drive (i.e., driving with the Eco-Driving Feedback technology). All but two participants feel that their fuel economy improved either moderately or significantly during the second drive. The associated fuel economy improvement results show that the participants in general have a correct perception of their fuel economy changes. The participants who felt that their fuel economy improved significantly do indeed gain the most fuel economy improvement.

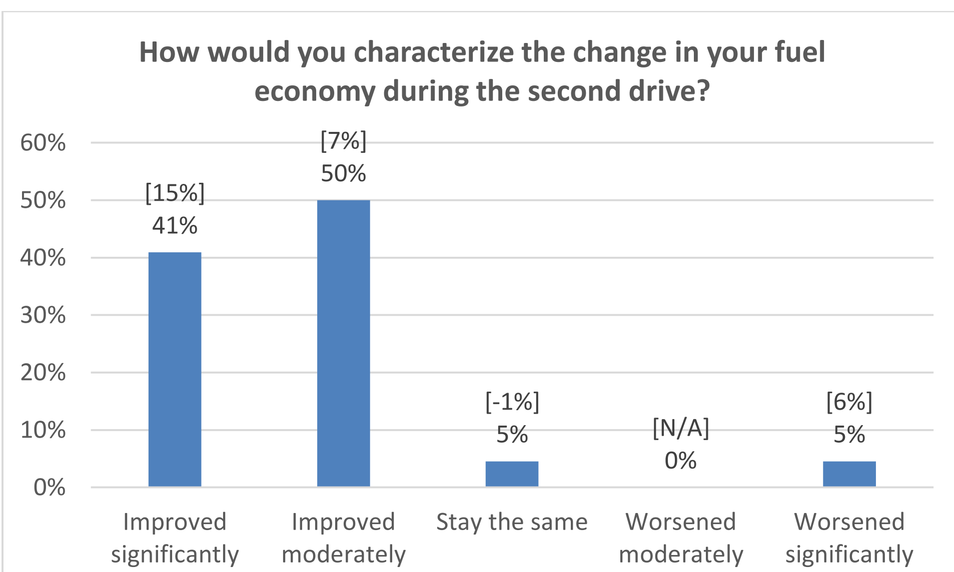

Figure 34. Responses to question "How would you characterize the change in your fuel economy during the second drive?"

The post-survey also asks a few questions regarding the visual feedback of the Eco-Driving Feedback technology. Figure 35 shows that 50% of the participants look at the driving feedback interface every few seconds while another 32% look at it every 10-15 seconds. These results are probably due to the fact that the recommended speed is constantly updated in response to the traffic condition ahead, which prompts the participants to glance at the driving feedback interface often.

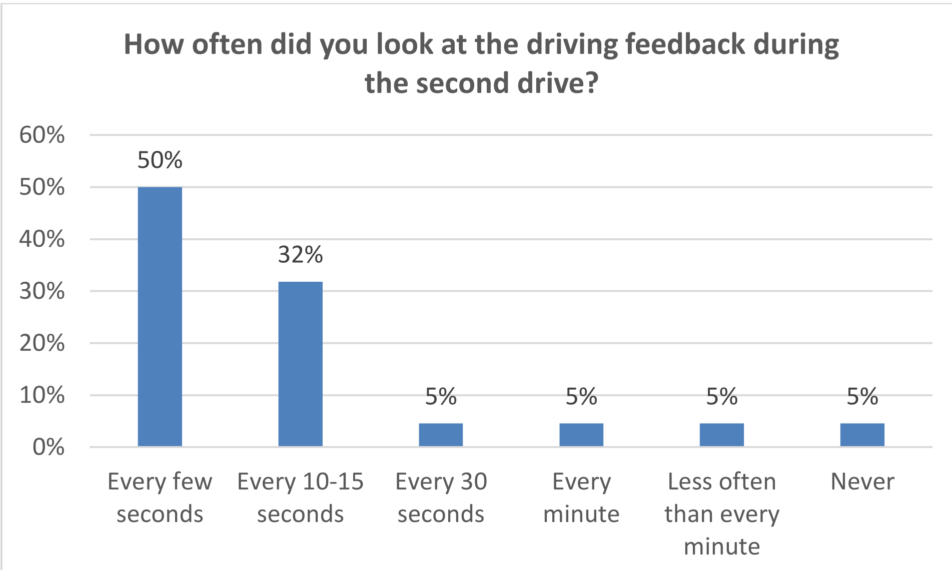

Figure 35. Responses to question "How often did you look at the driving feedback during the second drive?"

Figure 36 shows the reported length of time that the participants look at the driving feedback interface. The results show an almost normally distributed response across a wide range of glancing period from less than one second to more than 10 seconds. Note that a glancing period of more than 5 seconds is overly long and would make the driving difficult. It could be that some participants overestimated the frequency of their glances at the driving feedback interface and the length of each glance. In future research, these data may be collected directly through the use of eye-tracking device and software.

Nevertheless, Figure 37 shows that 9% of the participants found the driving feedback to be a lot of distraction, 36% found it to cause some distraction, and 23% found it to be just a little distractive. Although 32% of the participants found the driving feedback to be not distractive at all, more research is needed to design driving feedback interfaces that will be as or more effective at improving fuel economy while not being distractive to most drivers.

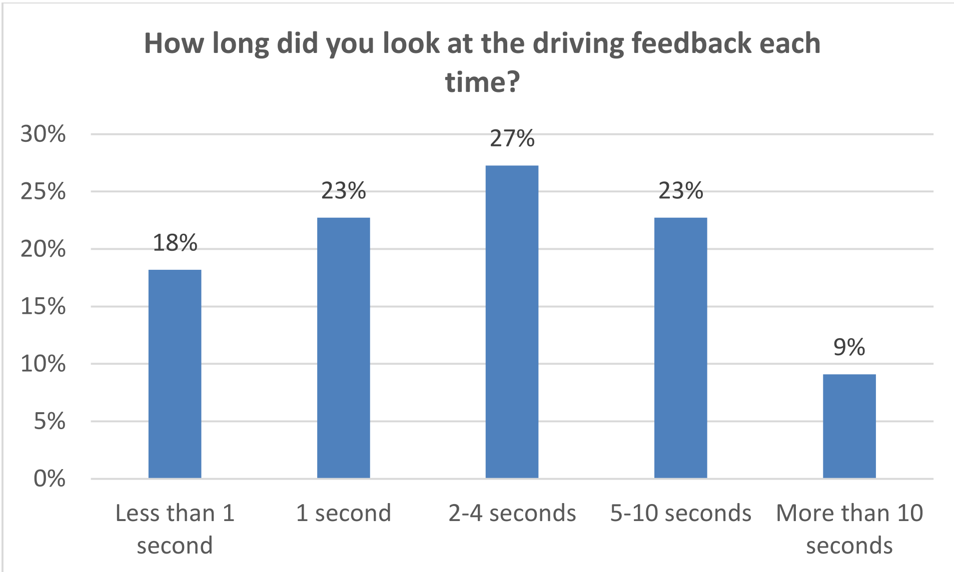

Figure 36. Responses to question "How long did you look at the driving feedback each time?"

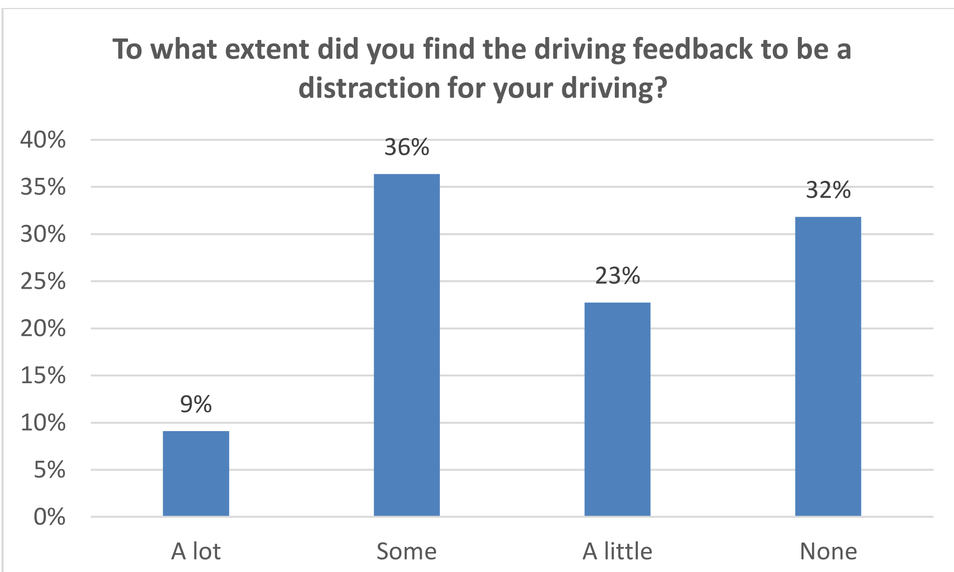

Figure 37. Responses to question "To what extent did you find the driving feedback to be a distraction for your driving?"

In addition, the post-survey also asks questions about the impact of participating in this study. Figure 38 shows that 50% of the participants think that the changes in their driving behaviors will persist without the Eco-Driving Feedback technology. This is a positive effect of the knowledge and experience gained from participating in the study. On the other hand, the other 50% think that the changes may be, may not, or will not persist without the aid of the technology. Nevertheless, 77% of the participants indicate that the participation in this study will help them be somewhat or much more fuel efficient in the future, as shown in Figure 39.

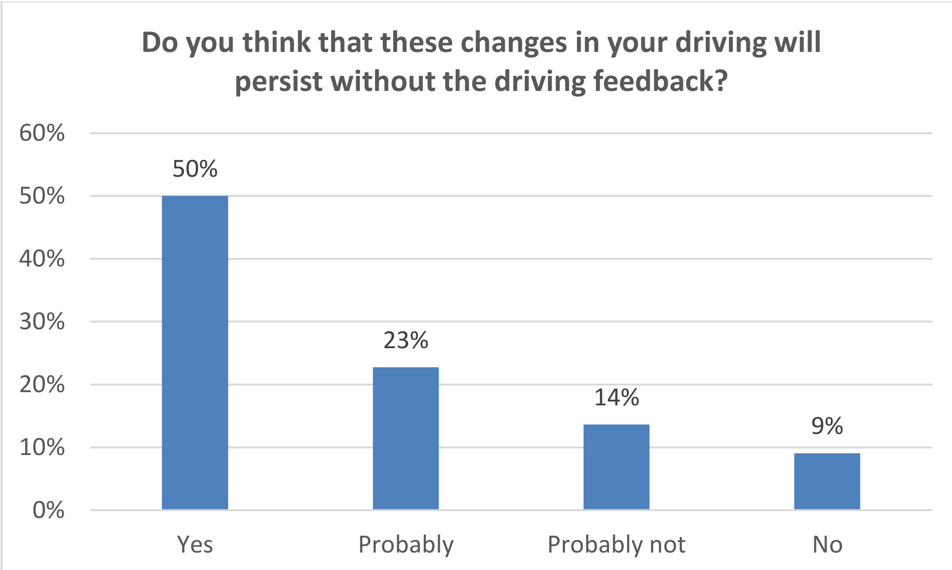

Figure 38. Responses to question "Do you think that these changes in your driving will persist without the driving feedback?"

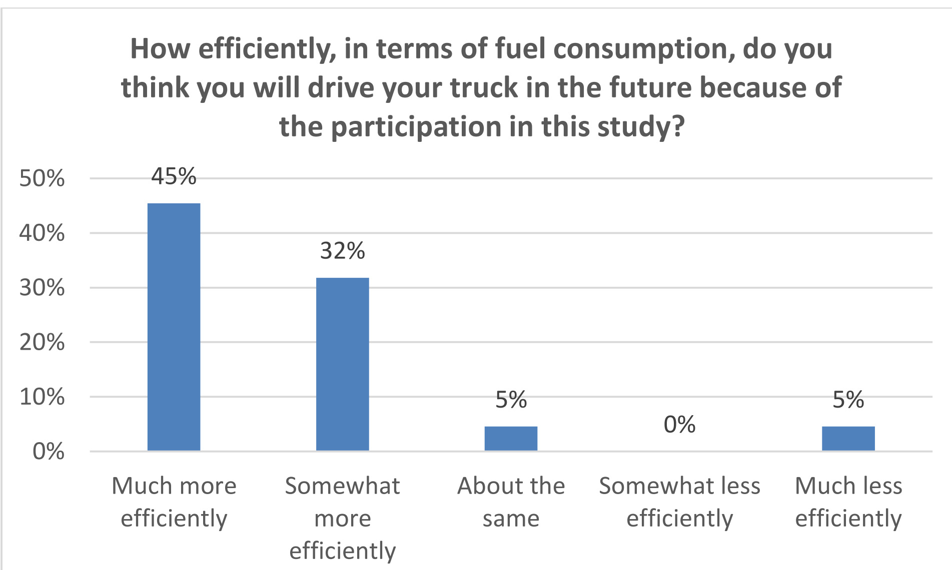

Figure 39. Responses to question "How efficiently, in terms of fuel consumption, do you think you will drive your truck in the future because of the participation in this study?"

The positive experience with the Eco-Driving Feedback technology during the study is also reflected in Figure 40 where 82% of the participants would probably want or would definitely want to get an eco-driving device to use with their current trucks. And if their current trucks have already been equipped with such a device, 55% of the participants say that they would use it all the time, 18% most of the time, and 14% sometime, as shown in Figure 41.

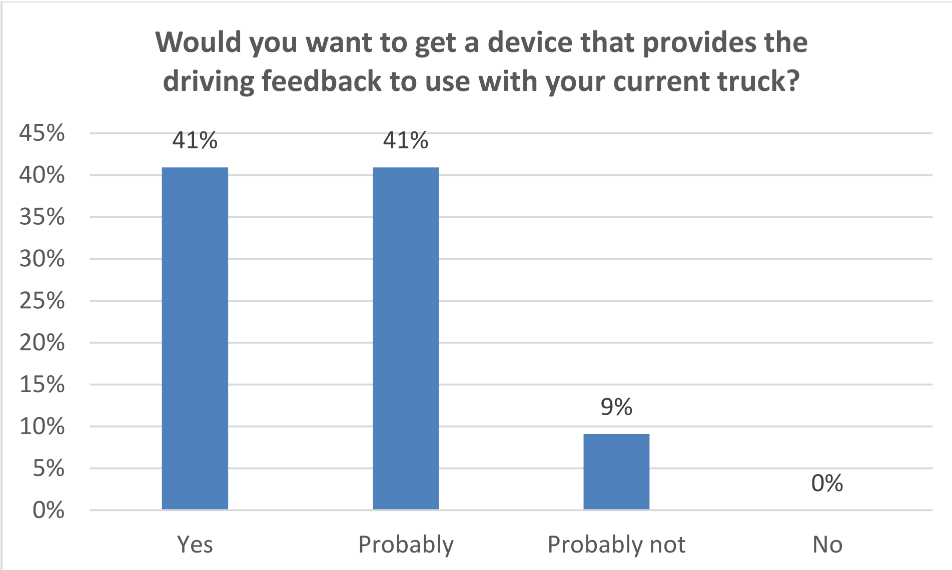

Figure 40. Responses to question "Would you want to get a device that provides the driving feedback to use with your current truck?"

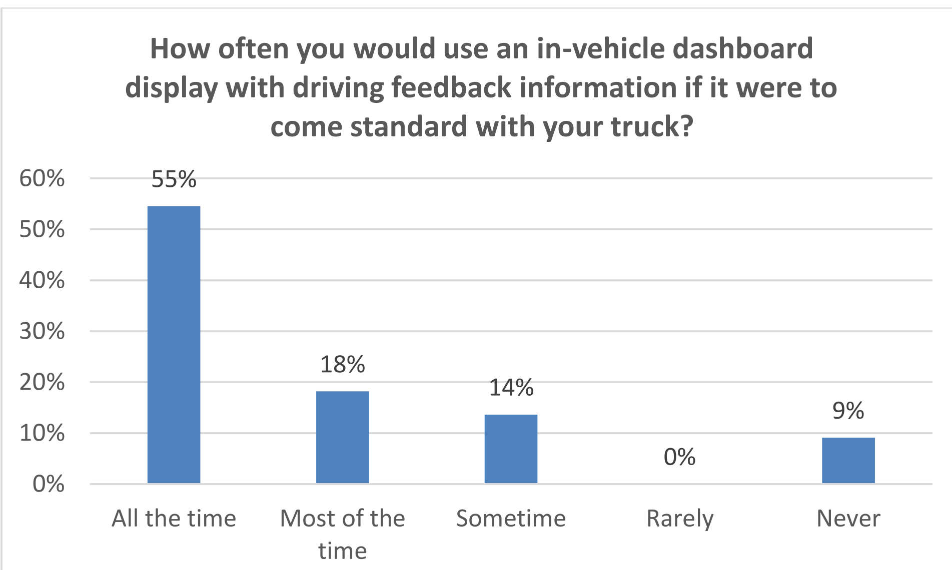

Figure 41. Responses to question "How often you would use an in-vehicle dashboard display with driving feedback information if it were to come standard with your truck?"

When asked about what driving feedback information are desirable, many participants selected multiple types of information. According to Figure 42, the three most popular driving feedback information are recommended driving speed (68%), real-time fuel economy (64%), and trip summary statistics (50%). The two least desirable driving feedback information are excessive idling warning (27%) and historical fuel economy (32%).

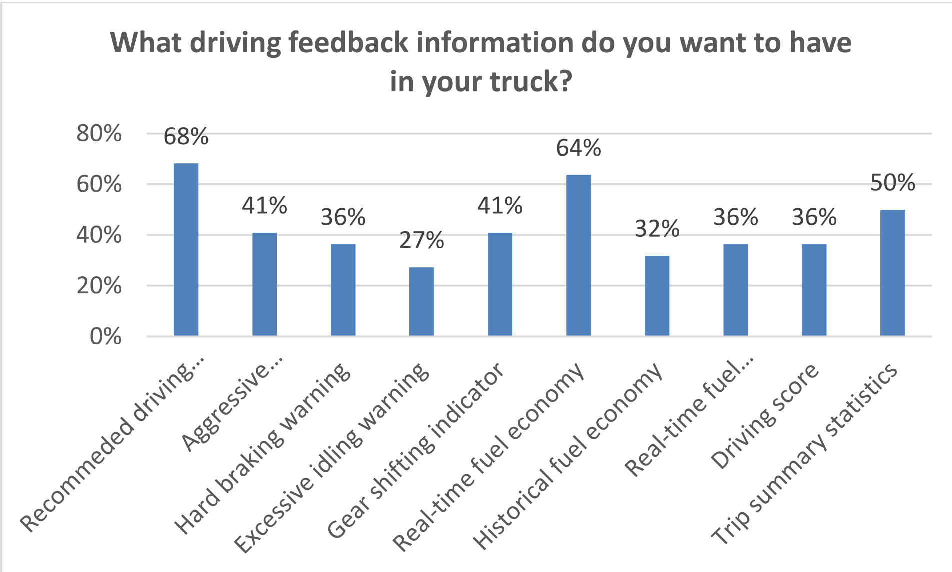

Figure 42. Responses to question "What driving feedback information do you want to have in your truck?"

Concluding Remarks

In this research project, the research team developed an environmentally-friendly driving feedback system for heavy-duty trucks, which was adapted from a similar system previously developed for light-duty cars. The system consists of:

1) *Eco-Routing Navigation* technology that provides route feedback by determining the most fuel-efficient route for any trips with consideration of historical and real-time traffic and roadway conditions,
2) *Eco-Driving Feedback* technology that provides a variety of driving feedback such as excessive speed warning, aggressive acceleration warning, recommended driving speed, etc., under different driving situations, and
3) *Eco-Score and Eco-Rank* technology that calculates a set of scores based on how eco-friendly one's driving is, and generates recommendation feedback for improving the driving performance and the scores.

The environmentally-friendly driving feedback system for heavy-duty trucks was tested by 22 truck driver participants. The Eco-Routing Navigation technology was implemented as a mobile app and used to study route choice preferences comparing the shortest, the fastest, and the most fuel-efficient routes for 14 trip scenarios. Overall, the participants selected the shortest route for 44% of the time, the fastest route 18% of the time, and the most fuel-efficient route 38% of the time. These results do not follow conventional travel behavior theories, which suggest that travelers would try to minimize their overall travel costs, a large part of which is travel time. This could be because several participants are employed by companies as opposed to being independent owners/operators, so travel time spent on the job may not necessarily be regarded as their personal cost. It could also be that not every truck driver uses the same or even a similar rationale in making route choice decision. More research is needed to better understand route choice decisions of truck drivers.

The Eco-Driving Feedback technology was integrated with the state-of-the-art truck driving simulator. A driving scenario that represents a typical freight trip in Southern California was programmed into the simulator and used as a driving course in an experiment with the same 22 truck driver participants for evaluating the impacts of the technology. The results show that the impacts for individual participants are different to varying degrees. When considering an average driver from this group of driver participants, the Eco-Driving Feedback technology has no adverse impact on travel time and CO emission while reducing fuel consumption, NO_x emission, and $PM_{2.5}$ emission by 11%, 8%, and 8%, respectively. Although the Eco-Driving Feedback technology results in an increase in hydrocarbon emission by 3%, it is not a major concern for heavy-duty diesel trucks as on-road emission inventories of this pollutant are more dominated by contribution from gasoline vehicles. On the other hand, diesel vehicles, most of which are heavy-duty trucks, are the major contributor of on-road emission inventories of NO_x and $PM_{2.5}$.

The impacts of the Eco-Score and Eco-Rank technology were not evaluated as it would involve a long-term study beyond the scope of this research project. However, the eco-scores were calculated for all the participants in the experiment of the Eco-Driving Feedback technology. The results show that the technology improves the acceleration score by 9%, the braking score by 7%, the speed score by 3%, and the overall score by 4%.

Based on the promising results from this research project conducted in a simulator environment, a follow-on study in a real-world environment is warranted. In the real-world study, route choice preference of truck drivers can be analyzed based on actual route choice decisions made in the day-to-day operations through the use of the Eco-Routing Navigation technology. Also, the fuel consumption and emission reduction benefits of the Eco-Driving Feedback technology can be validated under a variety of real-world driving scenarios. And ideally, this real-world study will be several months long and involve truck drivers from the same fleet(s) so that the impacts of the Eco-Score and Eco-Rank technology can also be evaluated.

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Appendix A: Pre-Survey

<u>**ECO-Driving Technology and Behavior Research for Heavy-Duty Trucks**</u>
"Before" Survey

Thank you for your participation. This is the first of two surveys you will take in this study. This survey will ask questions about your current driving practices and your knowledge about fuel-efficient driving techniques. The survey should take about 10-15 minutes to complete. You are not required to answer any question that you'd prefer not to answer. All responses are confidential and you may withdraw from the study at any time.

Please enter your participant ID. If you have forgotten it, please ask Research Staff for help.

Survey Questions

1. What is the make/model/year (if known) of the truck you drive?______________________________________

2. Approximately how many miles per gallon do you get driving this truck?_________________

3. In what city and state is your company?____

4. How far is a typical trip with a single load?
   □$_1$ Less than 50 miles　□$_2$ 51-100 miles　□$_3$ 101-250 miles　□$_4$ More than 250 miles

5. What type(s) of services do you perform? (please check all that apply)
   □$_1$ Truckload　□$_2$ Less-Than-Truckload　□$_3$ Distribution and warehousing　□$_4$ Parcel
   □$_5$ Freight forward　□$_6$ Drayage　□$_7$ Others (please specify)_____________________

6. Approximately how many miles a year do you drive a commercial truck? _____________________________

7. What size is the fleet of your company?
   □$_1$ Small (1-5 trucks)　□$_2$ Medium (6-25 trucks)　□$_3$ Large (more than 25 trucks)

8. What is the average speed that you generally maintain on highway?
   □$_1$ 45 mph or lower　□$_2$ 50 mph　□$_3$ 55 mph　□$_4$ 60 mph　□$_5$ 65 mph or higher

9. Has your company provided any training or feedback on how to improve fuel economy?
   □$_1$ Yes　□$_2$ No (skip to Q10)

   A. How often do you get training or feedback?
      □$_1$ Once every few years　□$_2$ Every year　□$_3$ Every 6 months
      □$_4$ Every 3 months　□$_5$ Every month or less

B. What measures have you been trained to take? (please check all that apply)

☐1 Accelerate mildly ☐2 Decelerate gradually
☐3 Use moderate highway driving speed ☐4 Maintain constant driving speed
☐5 Avoid unnecessary idling
☐6 Use progressive gear shifting technique
☐7 Change gear with double-clutching technique
☐8 Other, please specify: ______________________________
☐9 None of these

C. Do you think these measures save fuel?

☐1 Definitely ☐2 Probably ☐3 Probably not ☐4 Definitely not

10. Do you think the training on how to improve fuel economy is or would be useful to you?

☐1 Definitely ☐2 Probably ☐3 Probably not ☐4 Definitely not

11. Do you do anything now to improve fuel economy? (please check all that apply)

☐1 Accelerate mildly ☐2 Decelerate gradually
☐3 Use moderate highway driving speed ☐4 Maintain constant driving speed
☐5 Avoid unnecessary idling
☐6 Use progressive gear shifting technique
☐7 Change gear with double-clutching technique
☐8 Other, please specify: ______________________________
☐9 None of these (Skip to Q12)

A. Which measure do you think saves the **most** fuel? (**please select only one**)

☐1 Accelerate mildly ☐2 Decelerate gradually
☐3 Use moderate highway driving speed ☐4 Maintain constant driving speed
☐5 Avoid unnecessary idling
☐6 Use progressive gear shifting technique
☐7 Change gear with double-clutching technique
☐8 Other, please specify: ______________________________

12. Do you manage or do maintenance on the truck that you drive?

☐1 Yes, I do the maintenance myself ☐2 No, the company manages it (skip to Q13)

A. What type of maintenance work do you do?

☐1 Change engine oil and filter ☐2 Inflate tires ☐3 Tune electronic control unit settings
☐4 Other, please specify: ______________________________
☐5 Other, please specify: ______________________________
☐6 Other, please specify: ______________________________

B. Do you have any aerodynamic fittings on your tractor or trailer? □1 Yes □2 No (skip to Q13)

C. Where are these fittings located? (please check all that apply)
□1 On top of the tractor □2 Below trailer between the axles □3 At the back of the trailer
□4 Elsewhere, please explain: ____

13. Does your company provide any incentives to save fuel? □1 Yes □2 No (skip to Q14)

A. What incentives are you provided?____
____

B. Do you try to drive more fuel efficiently in order to earn these incentives?
□1 Definitely □2 Probably □3 Probably not □4 Definitely not

14. Which of the following tool(s) do you use to provide driving directions? (please check all that apply)
□1 None □2 Paper map □3 GPS system □4 Smart phone
□5 Other, please specify ____

15. How much would you be willing to pay for an in-vehicle device that can help guide you to improve fuel economy of your driving by 5%?
□1 $0 □2 $1-$99 □3 $99-$199 □4 $200-$299 □5 $300 or more

16. How many years have you been a professional truck driver?_______________

17. What is your gender? □1 Male □2 Female

18. What is your age?___________________

19. We have a number of projects related to truck travel, technology, and parking. If you would be interested in participating in further research with us, please provide your email.

You would only be contacted regarding truck research and your email address will not be shared with another party. Giving us your email does not obligate you to participate in further studies, but it does allow us to contact you and give you the option.

There may or may not be compensation associated with additional research projects.

Email address (optional):____(Please print clearly)

Appendix B: Post-Survey

<u>ECO-Driving Technology and Behavior Research for Heavy-Duty Trucks</u>
"After" Survey

Thank you for your participation. This is the second and last survey you will take in this study. This survey will ask questions about your experience with the fuel-efficient driving feedback in the driving simulator. The survey should take about 10-15 minutes to complete. You are not required to answer any question that you'd prefer not to answer. All responses are confidential and you may withdraw from the study at any time.

Please enter your participant ID. If you have forgotten it, please ask Research Staff for help.

Survey Questions

1. How much knowledge did you have about fuel-efficient driving practices before participating in this study?
   □$_1$ A lot □$_2$ Some □$_3$ A little □$_4$ None

2. How often did you try to follow the recommended speed from the driving feedback during the second drive?
   □$_1$ All the time □$_2$ Most of the time □$_3$ Sometime □$_4$ Rarely □$_5$ Never

3. How would you characterize the change in your fuel economy during the second drive?
   □$_1$ Improved significantly □$_2$ Improved moderately □$_3$ Stayed the same (skip to Q3)
   □$_4$ Worsened moderately □$_5$ Worsened significantly

   A. How much would you say the change in your fuel economy during the second drive was due to the driving feedback?
      □$_1$ A lot □$_2$ Some □$_3$ A little □$_4$ None

4. How often did you look at the driving feedback during the second drive?
   □$_1$ Every few seconds □$_2$ Every 10-15 seconds □$_3$ Every 30 seconds
   □$_4$ Every minute □$_5$ Less often than every minute □$_6$ Never (skip to Q5)

   A. How long did you look at the driving feedback each time?
      □$_1$ Less than 1 second □$_2$ 1 second □$_3$ 2-4 seconds
      □$_4$ 5-10 seconds □$_5$ More than 10 seconds

5. To what extent did you find the driving feedback to be a distraction for your driving?
   □$_1$ A lot □$_2$ Some □$_3$ A little □$_4$ None (skip to Q6)

   A. To what extent do you think that the distraction was significant enough to impair your driving?
      □$_1$ A lot □$_2$ Some □$_3$ A little □$_4$ None

6. Please state whether you Strongly Agree, Agree, Disagree or Strongly Disagree with the following statements during the second drive.

	Strongly Agree	Agree	Disagree	Strongly Disagree
A. Because of the driving feedback, I accelerated more mildly.	❑	❑	❑	❑
B. Because of the driving feedback, I braked more gradually.	❑	❑	❑	❑
C. Because of the driving feedback, I drove at appropriate driving speeds.	❑	❑	❑	❑
D. Overall, the driving feedback changed how I drove during the second drive.	❑	❑	❑	❑

If stating Strongly Agree or Agree in one of the above (otherwise, skip to Q7):

A. Do you think that these changes in your driving will persist without the driving feedback?
□1 Yes □2 Probably □3 Probably not □4 No (skip to Q7)

B. How long do you think these changes in your driving will persist without the driving feedback?
□1 Less than 1 month □2 1-3 months □3 4-6 months □4 More than 6 months

7. How efficiently, in terms of fuel consumption, do you think you will drive your truck in the future because of the participation in this study?
□1 Much more efficiently □2 Somewhat more efficiently □3 About the same
□4 Somewhat less efficiently □5 Much less efficiently

8. Would you want to get a device that provides the driving feedback to use with your current truck?
□1 Yes □2 Probably □3 Probably not □4 No
Please specify the reason(s):
____
____
____
____

9. How much will you be willing to pay for the device?____________________________________

10. How often do you think you would use an in-vehicle dashboard display with driving feedback information if it were to come standard with your truck?
□1 All the time □2 Most of the time □3 Sometime □4 Rarely □5 Never

11. What driving feedback information do you want to have in your truck (check all that apply)?

- □$_{1}$ Recommended driving speed (optimal driving speed based on traffic condition and road slope)
- □$_{2}$ Aggressive acceleration warning (warning sign or sound when accelerating too fast)
- □$_{3}$ Hard braking warning (warning sign or sound when braking too hard)
- □$_{4}$ Excessive idling warning (warning sign or sound when idle too long)
- □$_{5}$ Gear shifting indicator (light indicating an optimal point for shifting gear)
- □$_{6}$ Real-time fuel economy (instantaneous fuel economy in miles per gallon)
- □$_{7}$ Historical fuel economy (average fuel economy for the last 5 or 15 minutes)
- □$_{8}$ Real-time fuel consumption cost (cumulative fuel consumption cost for the current trip)
- □$_{9}$ Driving score (score indicating fuel-efficient driving performance)
- □$_{10}$ Trip summary statistics (distance, travel time, average speed, average fuel economy, fuel consumed, fuel cost, and average driving score provided at the end of each trip)
- □$_{11}$ Other, please specify:______________________________
- □$_{12}$ Other, please specify:______________________________
- □$_{13}$ Other, please specify:______________________________
- □$_{14}$ Other, please specify:______________________________

12. Do you have any other comments about the driving feedback provided in this study?

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13. Do you have any other comments about this study?

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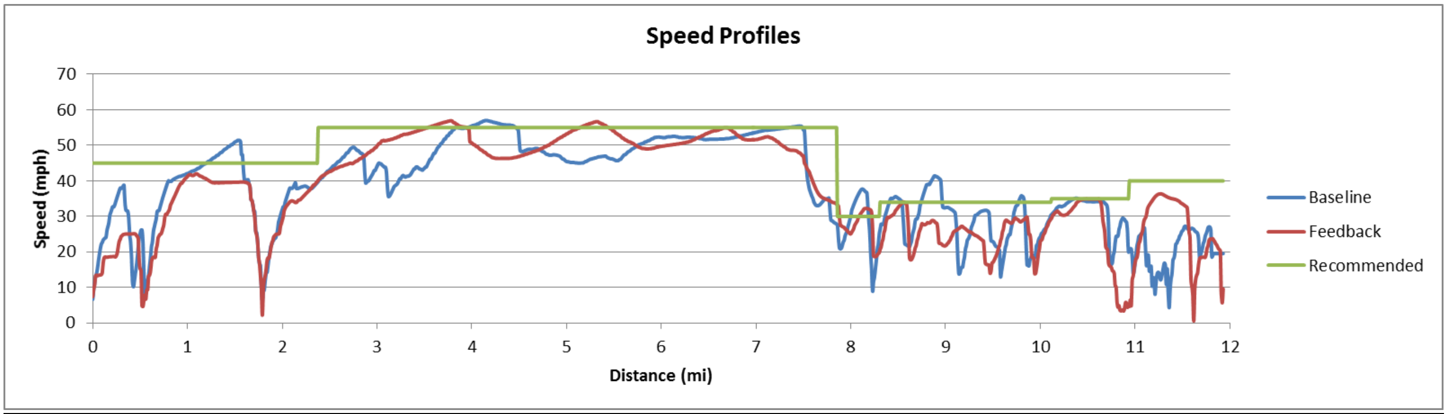
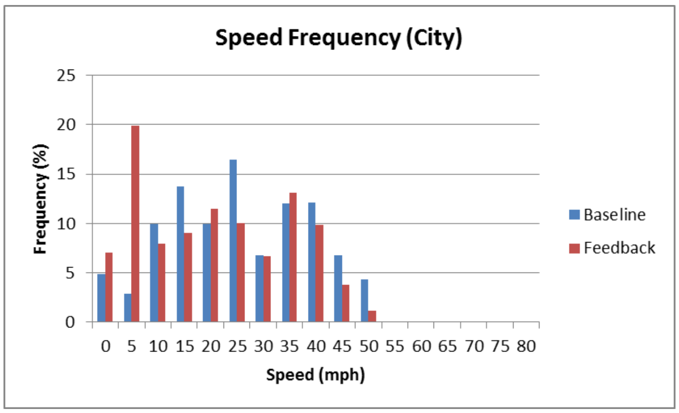
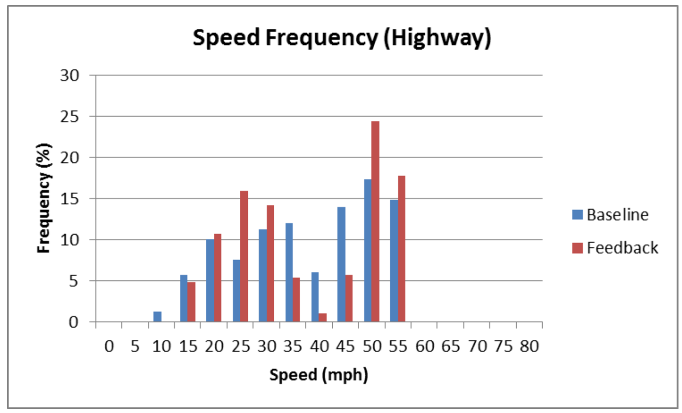
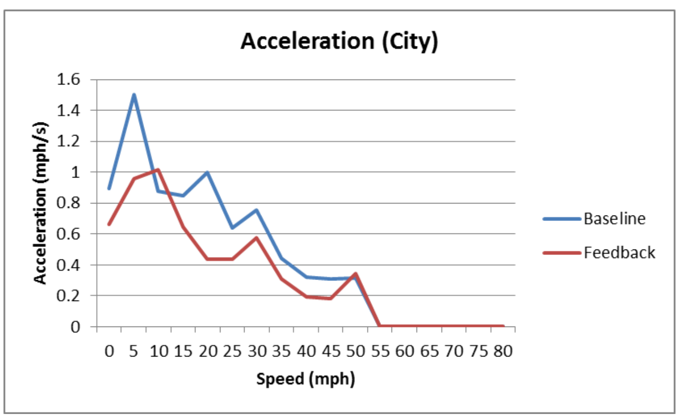
Appendix C: Driving Behavior Comparison

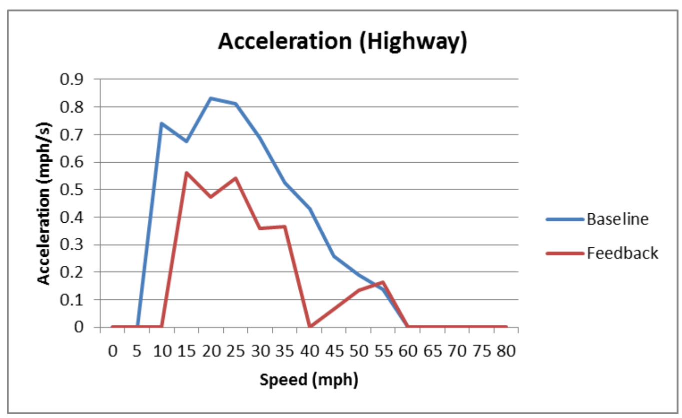
Driver #01

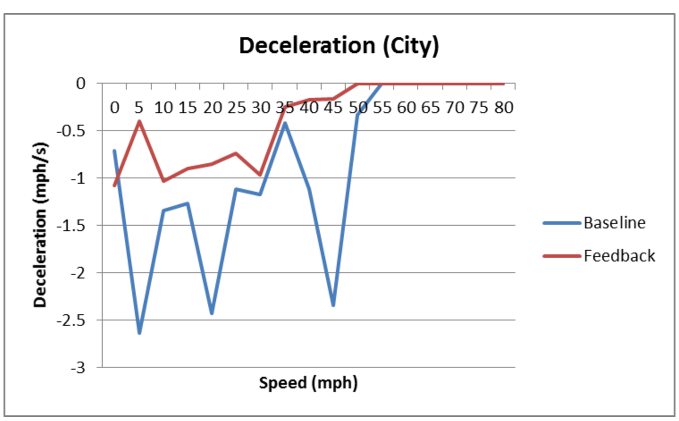

Speed Profiles
Speed (mph)
Distance (mi)
0 10 20 30 40 50 60 70
0 1 2 3 4 5 6 7 8 9 10 11 12
Baseline
Feedback
Recommended

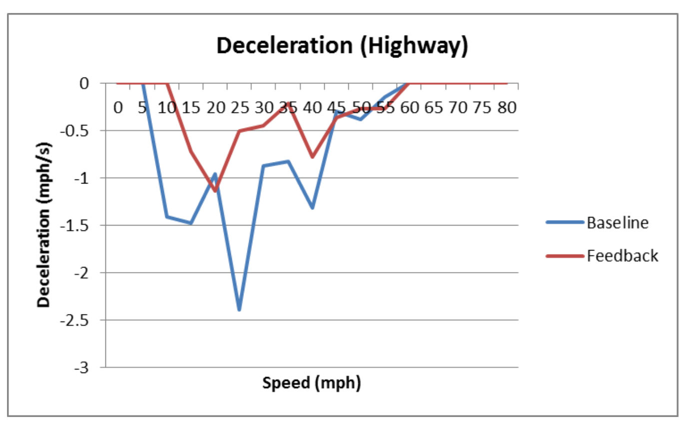

Speed Frequency (City)
Frequency (%)
0 5 10 15 20 25
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
0 5 10 15 20 25 30
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback


Acceleration (City)
Acceleration (mph/s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

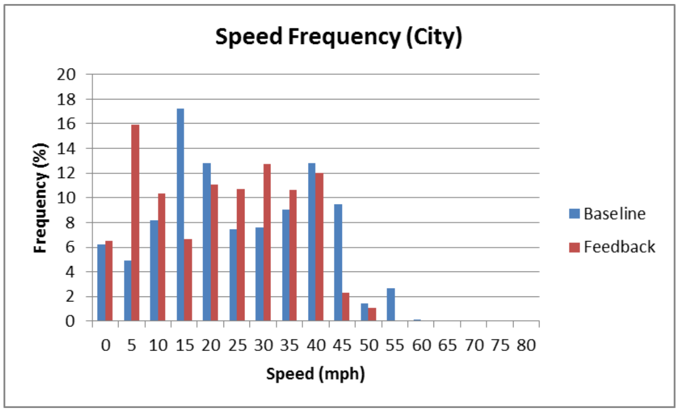

Acceleration (Highway)
Acceleration (mph/s)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback


Deceleration (City)
Deceleration (mph/s)
0 -0.5 -1 -1.5 -2 -2.5 -3
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

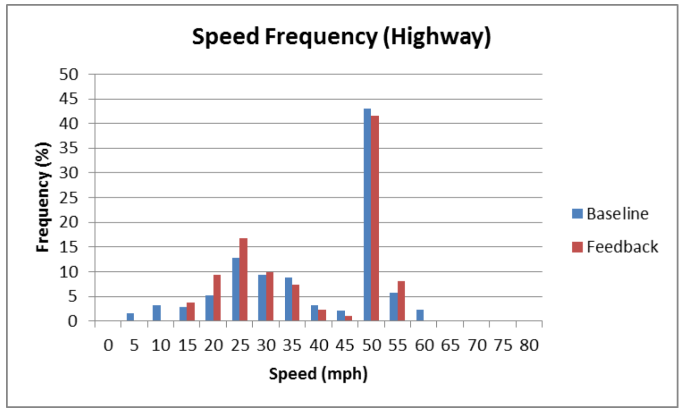

Deceleration (Highway)
Deceleration (mph/s)
0 -0.5 -1 -1.5 -2 -2.5 -3
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

Driver #02

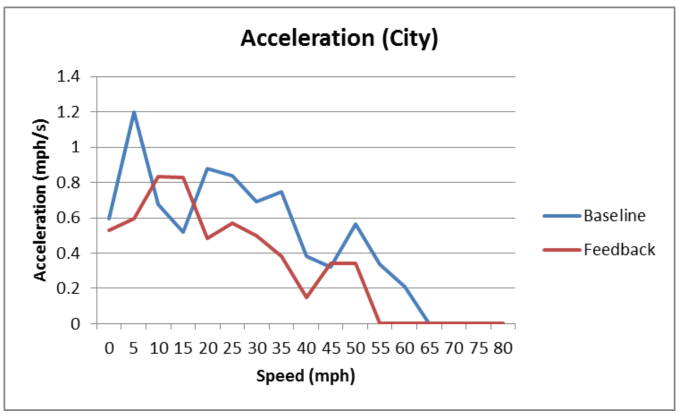
Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended



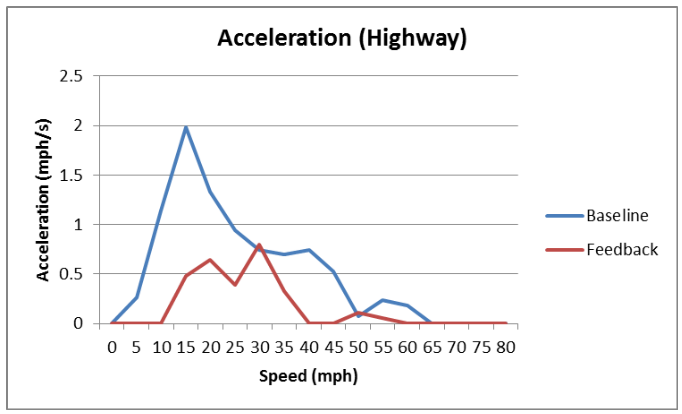
Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback



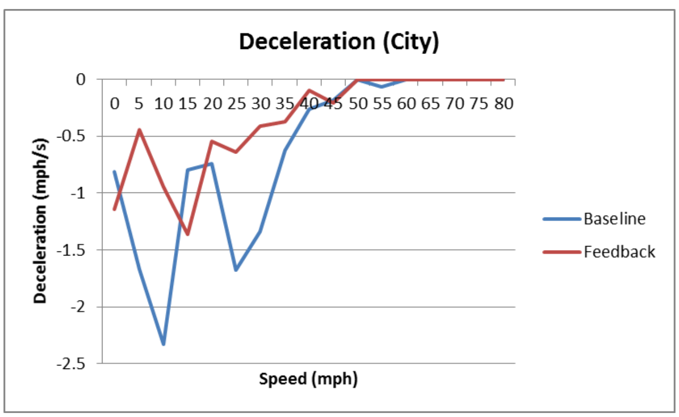
Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback



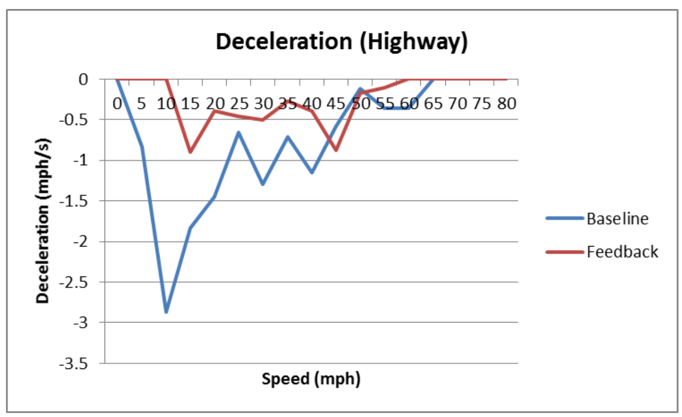
Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback



Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

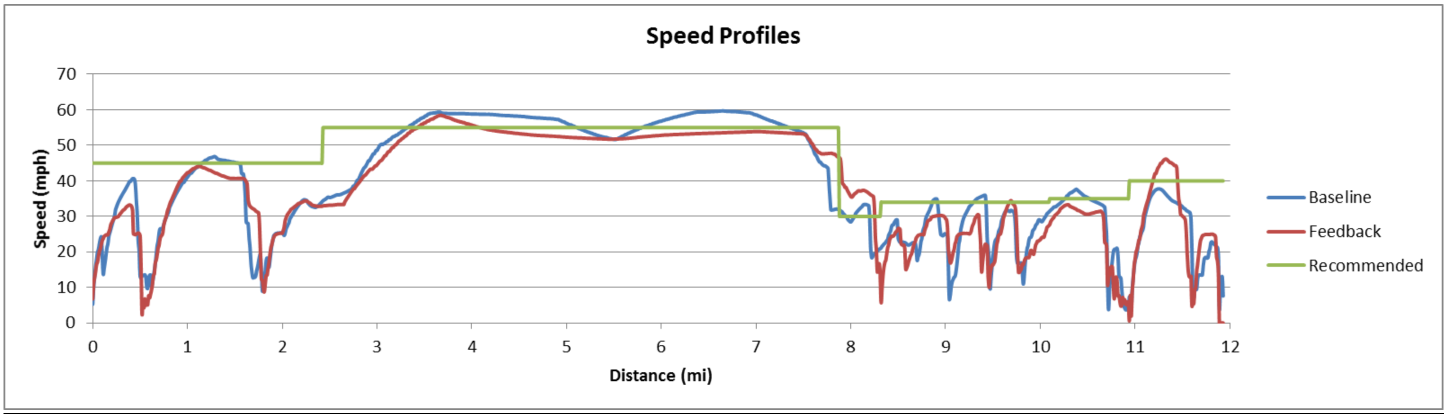


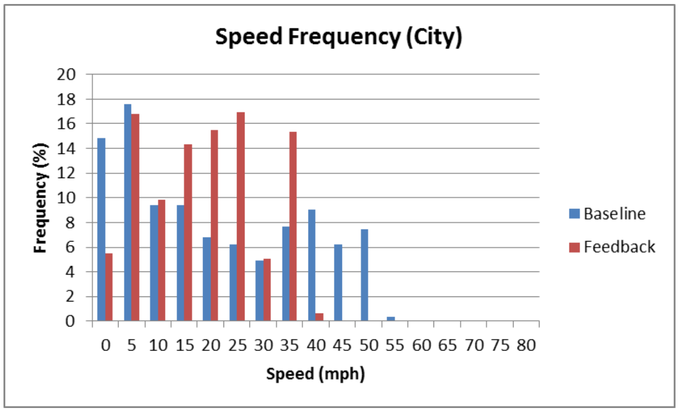
Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

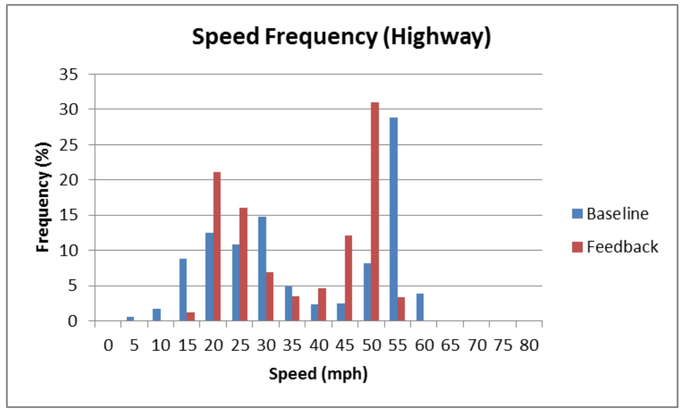


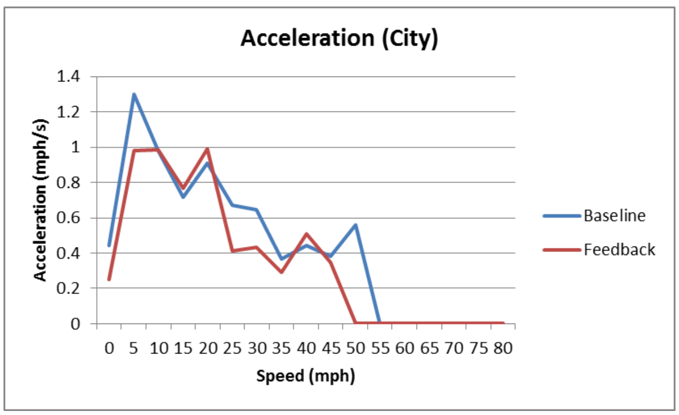
Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

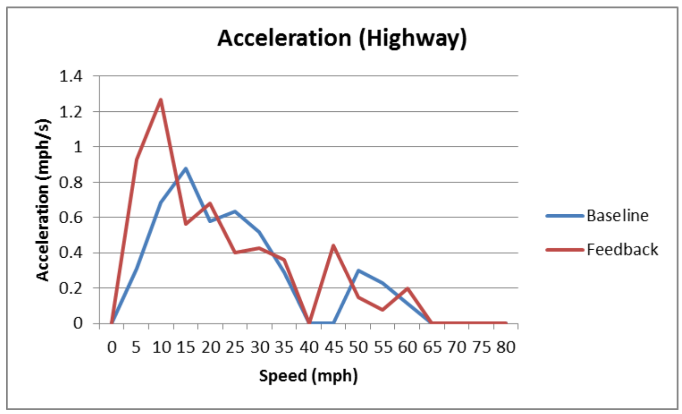
Driver #03

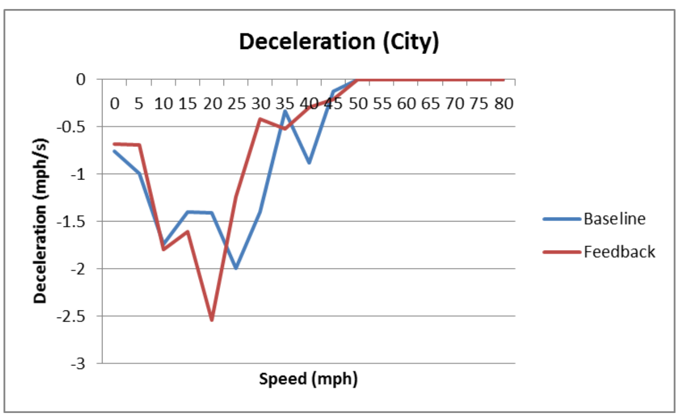

Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended

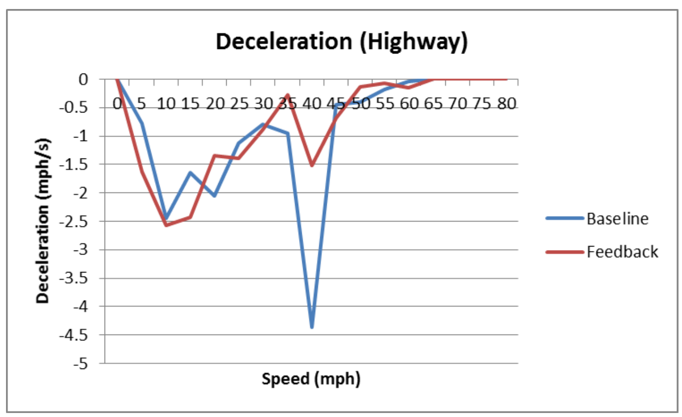

Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback

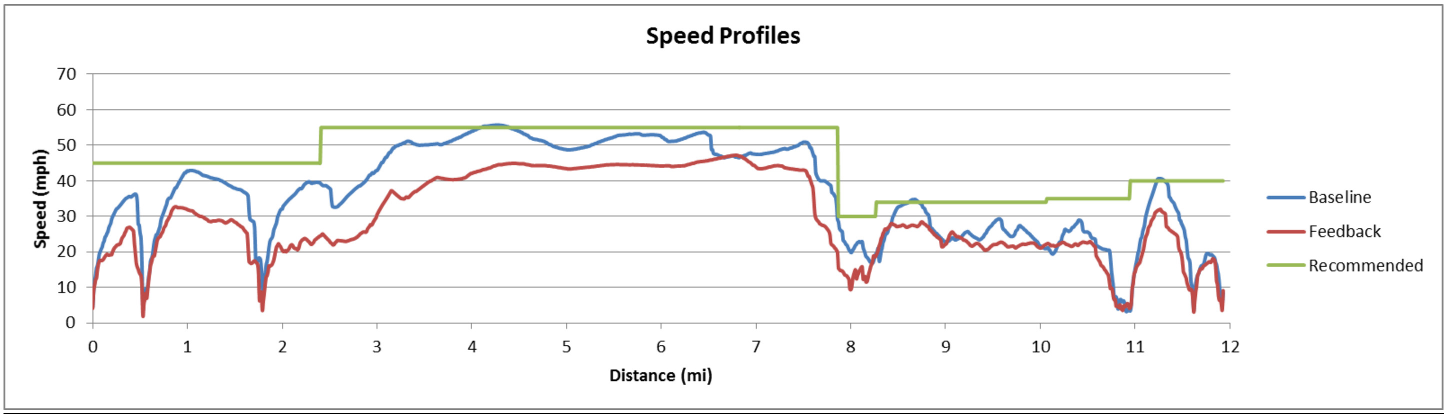

Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

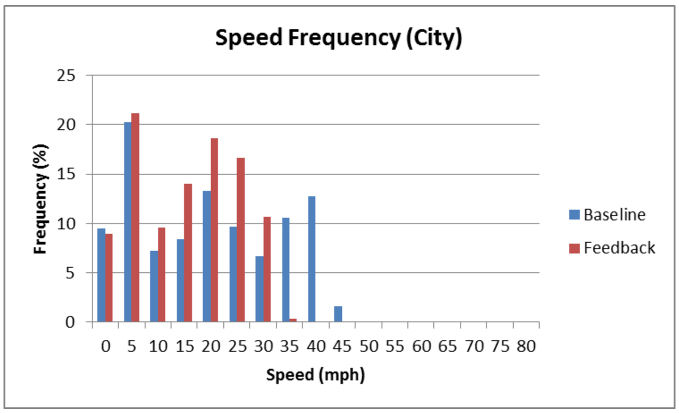

Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

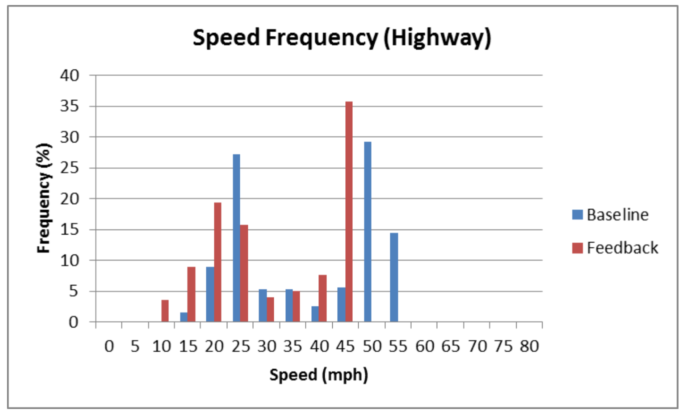

Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

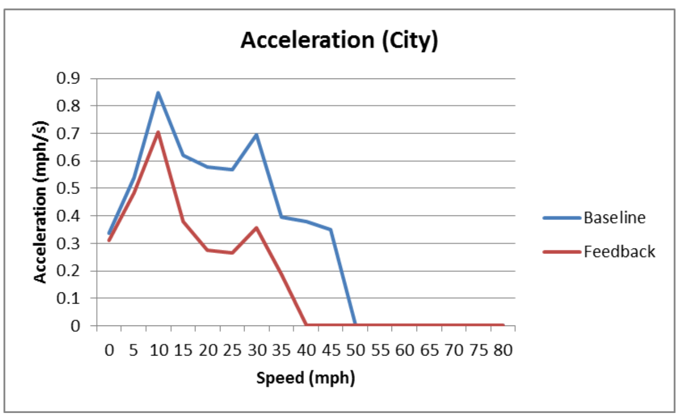

Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

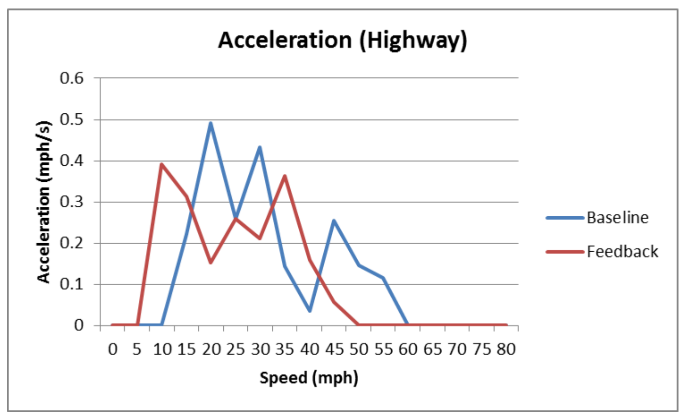
Driver #04

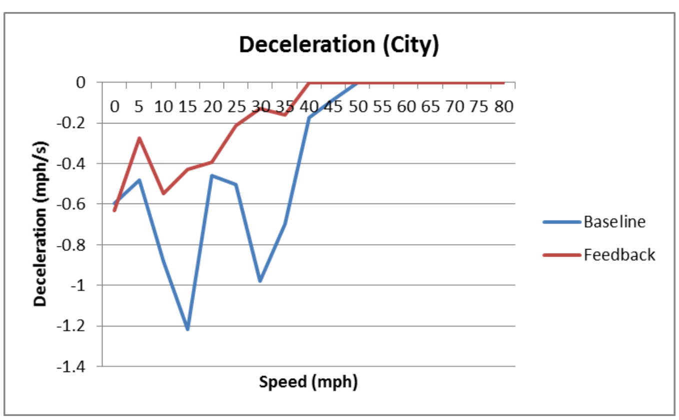

Speed Profiles
Speed (mph)
0 10 20 30 40 50 60 70
0 1 2 3 4 5 6 7 8 9 10 11 12
Distance (mi)
Baseline
Feedback
Recommended

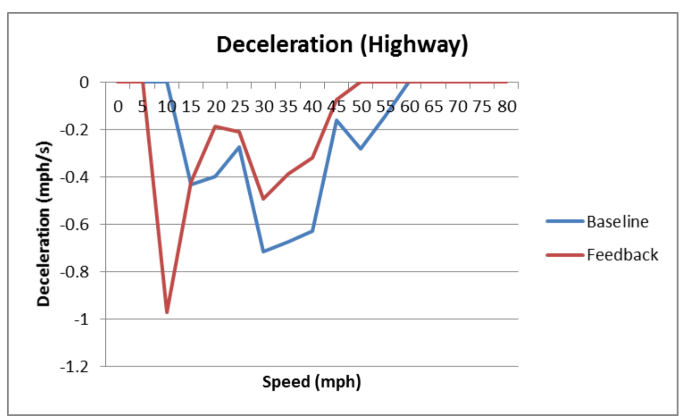

Speed Frequency (City)
Frequency (%)
0 5 10 15 20 25
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
0 5 10 15 20 25 30 35 40
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

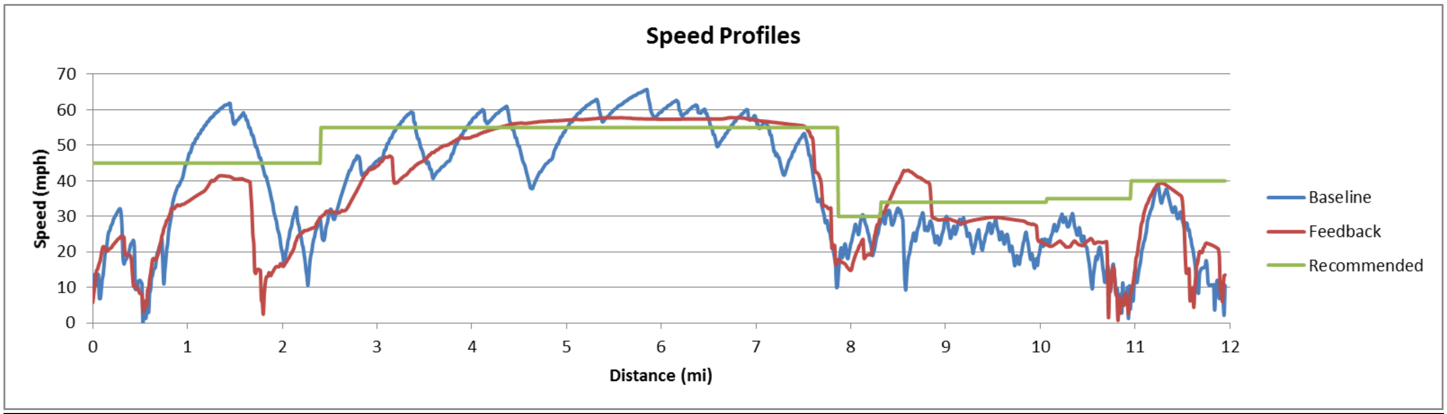

Acceleration (City)
Acceleration (mph/s)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

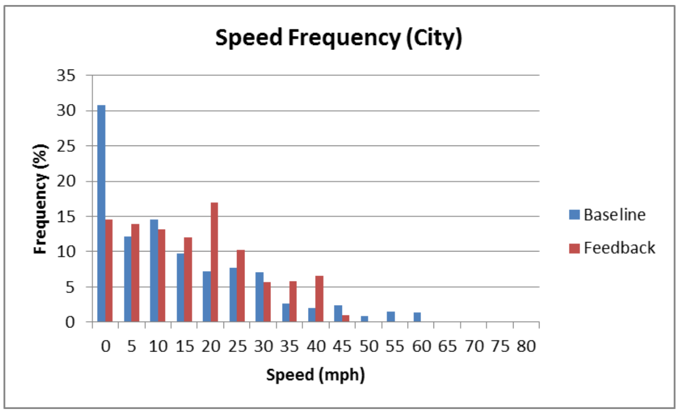

Acceleration (Highway)
Acceleration (mph/s)
0 0.1 0.2 0.3 0.4 0.5 0.6
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

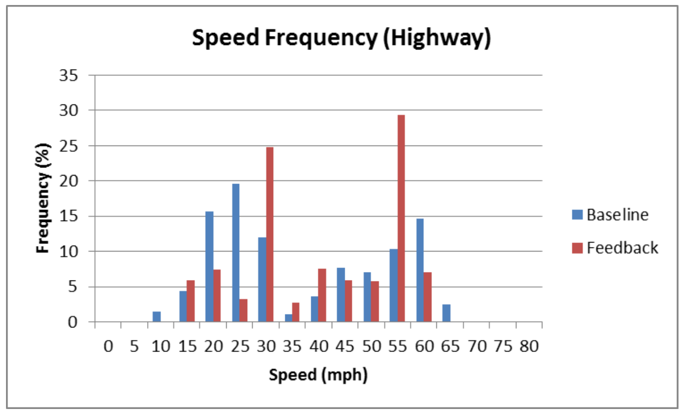

Deceleration (City)
Deceleration (mph/s)
0 -0.2 -0.4 -0.6 -0.8 -1 -1.2 -1.4
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

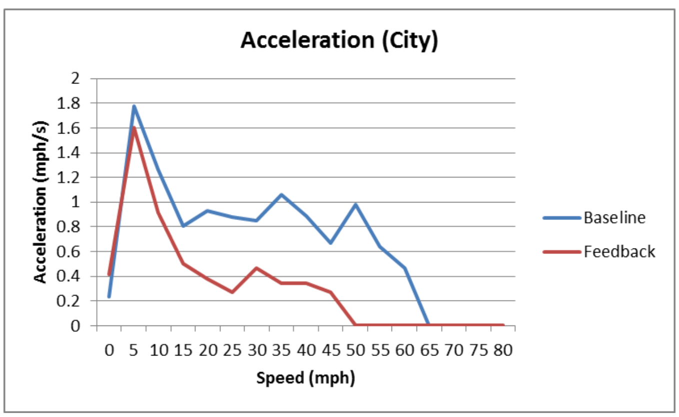

Deceleration (Highway)
Deceleration (mph/s)
0 -0.2 -0.4 -0.6 -0.8 -1 -1.2
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

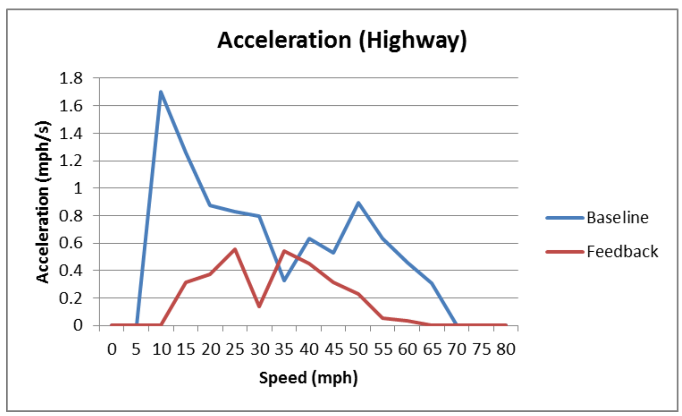
Driver #05

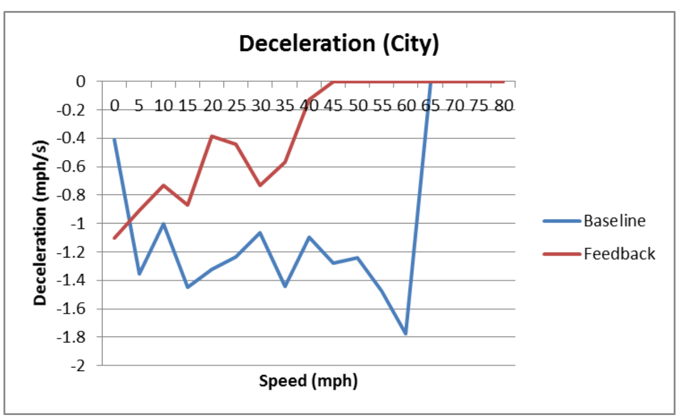

Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended

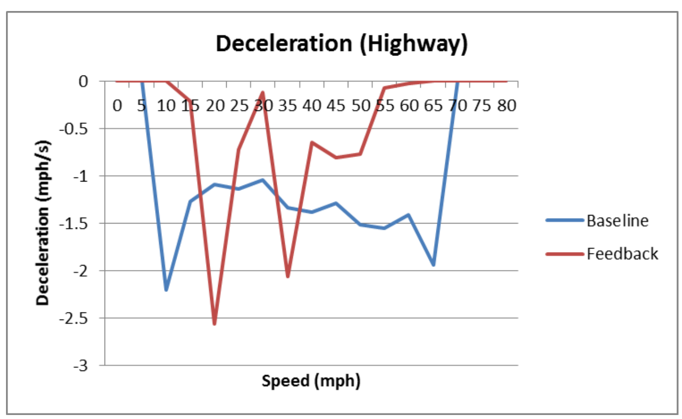

Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback


Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

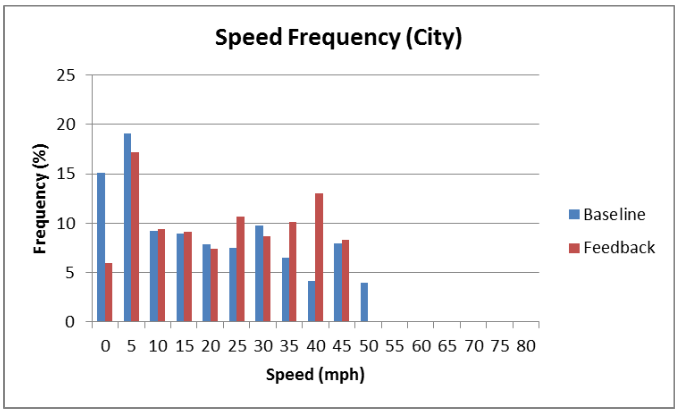

Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback


Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

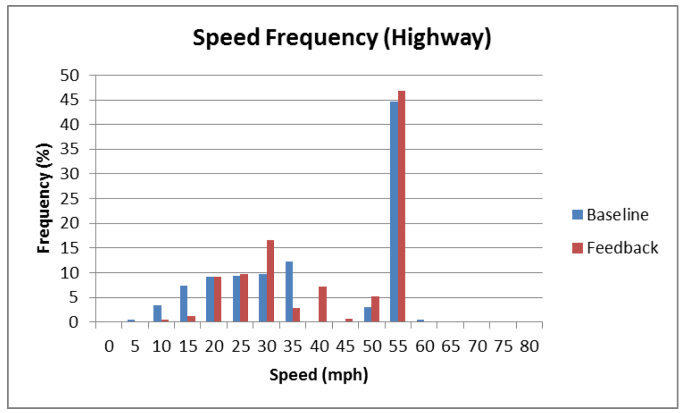

Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

Driver #06

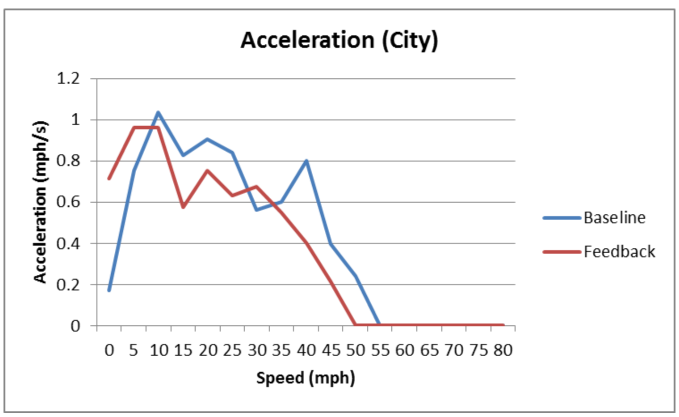
Speed Profiles
Speed (mph)
Distance (mi)
0
10
20
30
40
50
60
70
0
1
2
3
4
5
6
7
8
9
10
11
12
Baseline
Feedback
Recommended



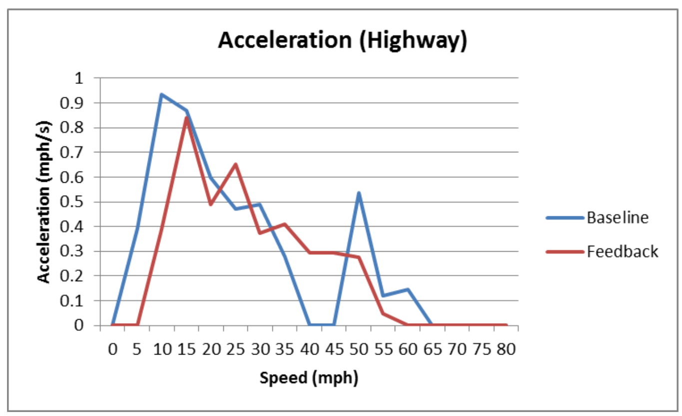
Speed Frequency (City)
Frequency (%)
0
5
10
15
20
25
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback



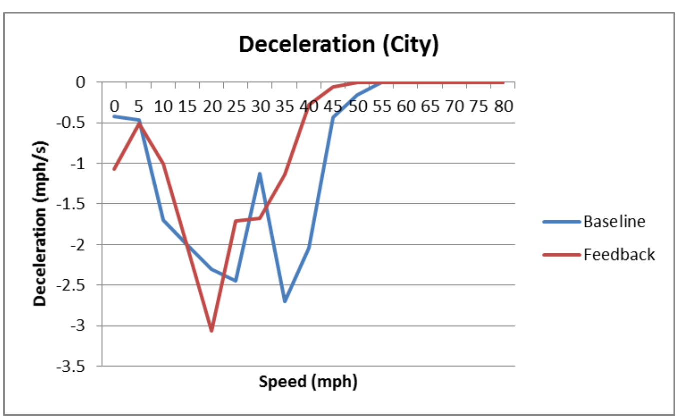
Speed Frequency (Highway)
Frequency (%)
0
5
10
15
20
25
30
35
40
45
50
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback



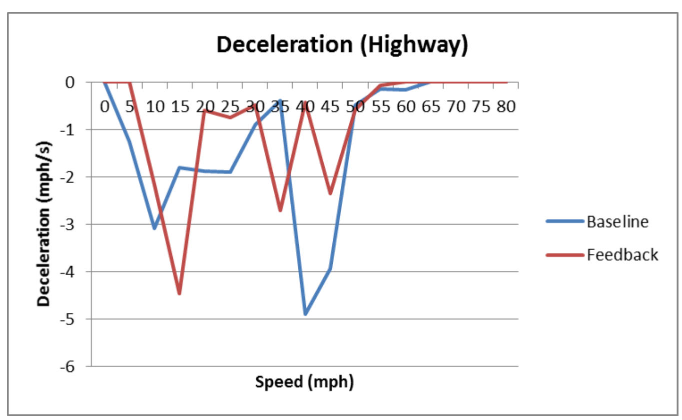
Acceleration (City)
Acceleration (mph/s)
0
0.2
0.4
0.6
0.8
1
1.2
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback



Acceleration (Highway)
Acceleration (mph/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback



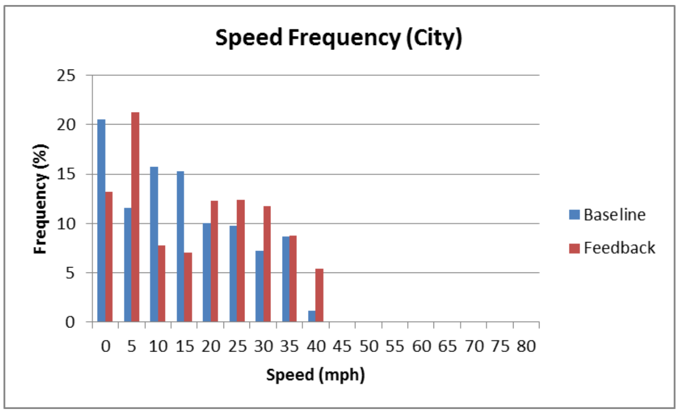
Deceleration (City)
Deceleration (mph/s)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

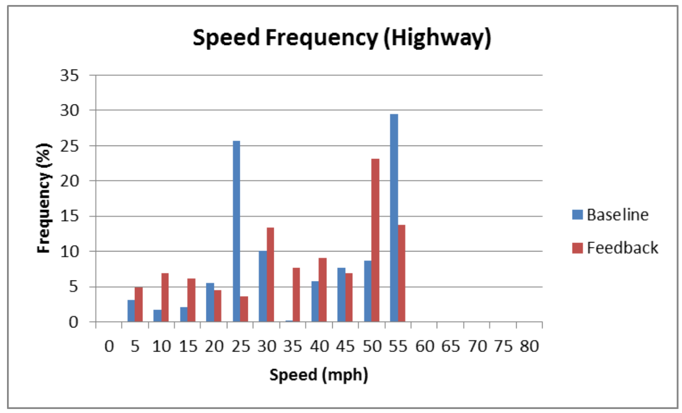


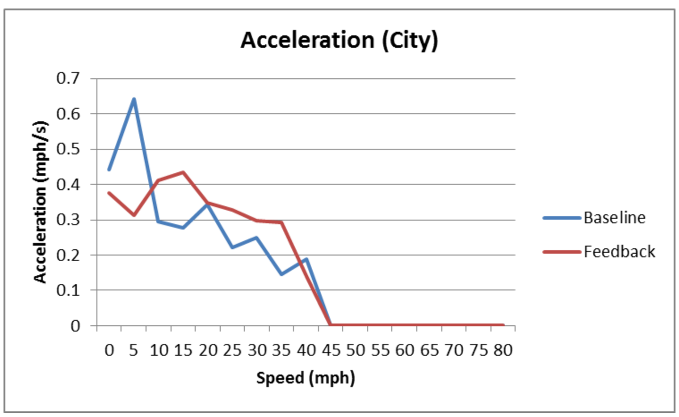
Deceleration (Highway)
Deceleration (mph/s)
0
-1
-2
-3
-4
-5
-6
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

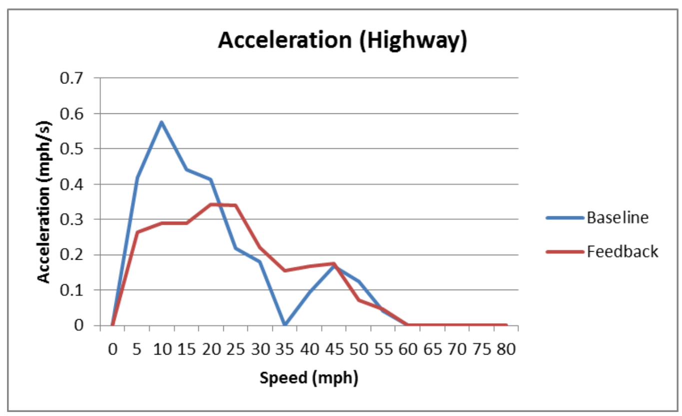
Driver #07

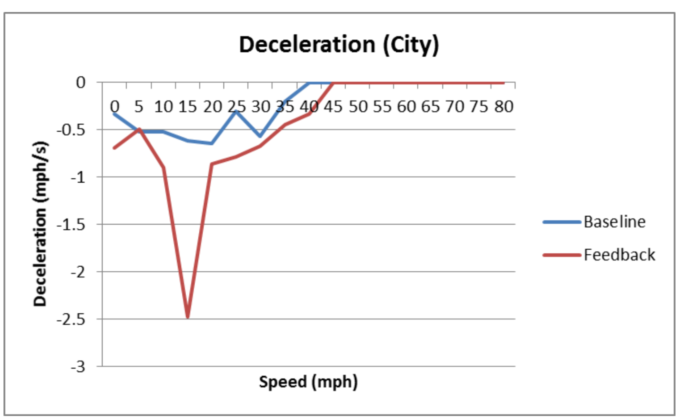

Speed Profiles
Speed (mph)
Distance (mi)
0 10 20 30 40 50 60 70
0 1 2 3 4 5 6 7 8 9 10 11 12
Baseline
Feedback
Recommended

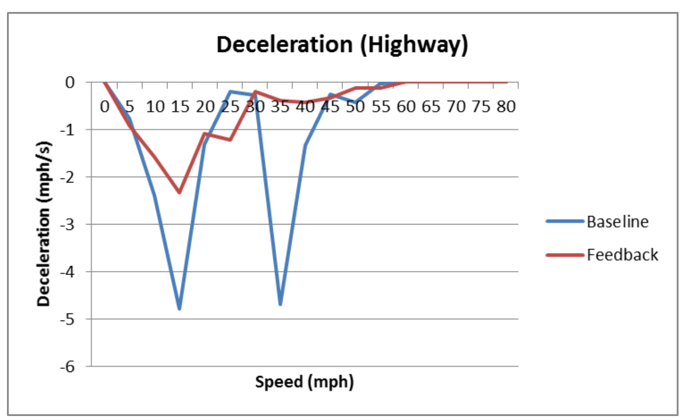

Speed Frequency (City)
Frequency (%)
Speed (mph)
0 5 10 15 20 25
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
Speed (mph)
0 5 10 15 20 25 30 35
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Baseline
Feedback


Acceleration (City)
Acceleration (mph/s)
Speed (mph)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Baseline
Feedback

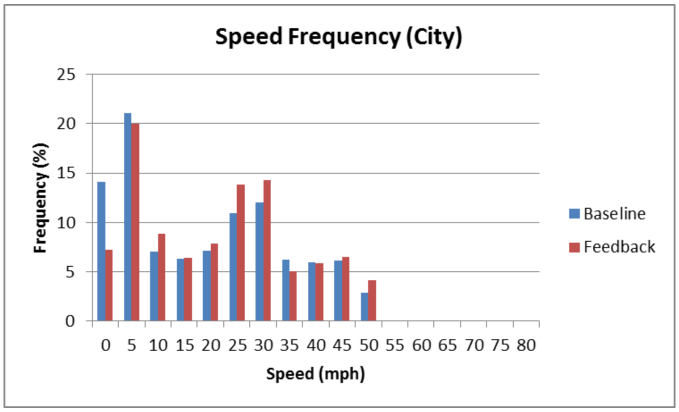

Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Baseline
Feedback


Deceleration (City)
Deceleration (mph/s)
Speed (mph)
0 -0.5 -1 -1.5 -2 -2.5 -3
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Baseline
Feedback

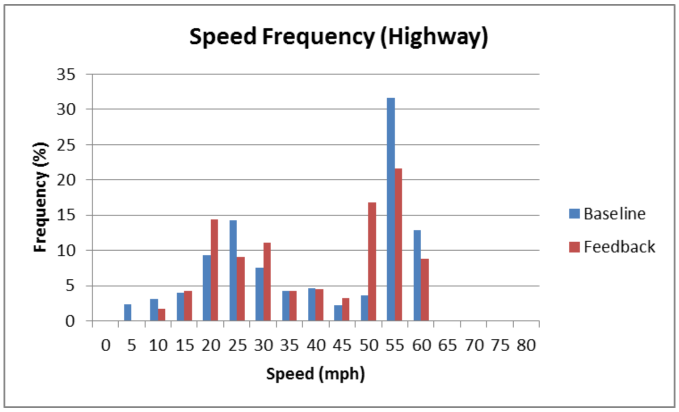

Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
0 -1 -2 -3 -4 -5 -6
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Baseline
Feedback

Driver #08

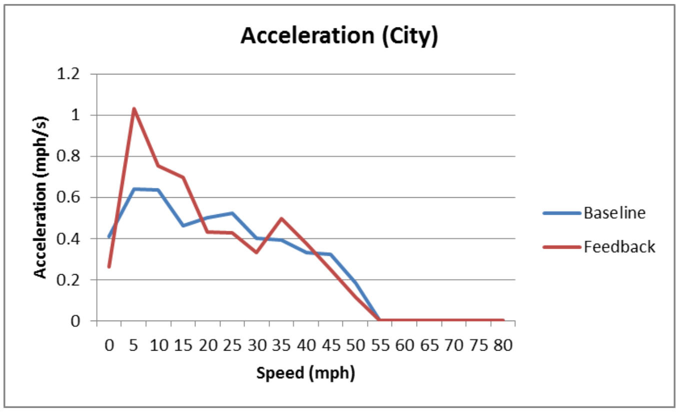
Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended



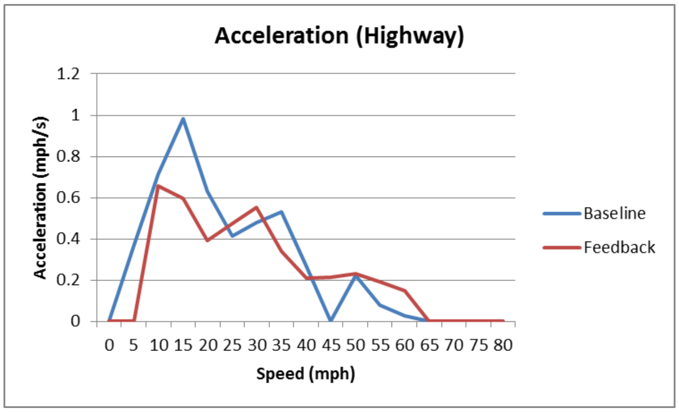
Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback



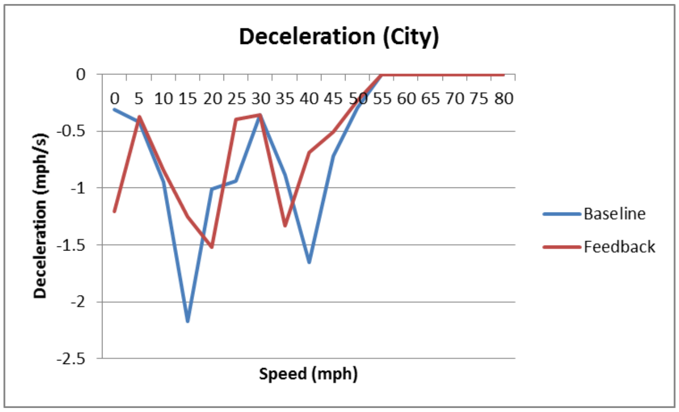
Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback



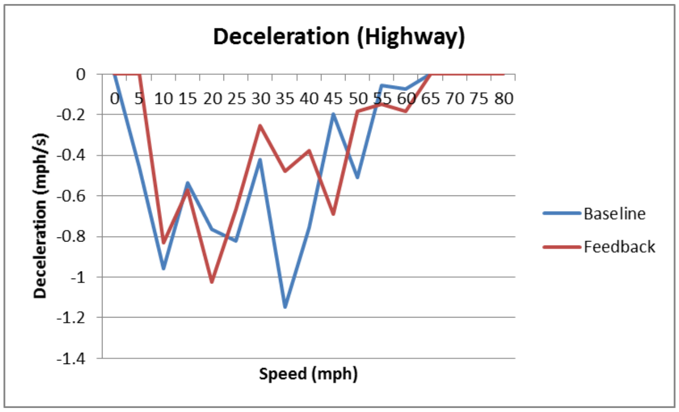
Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback



Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback



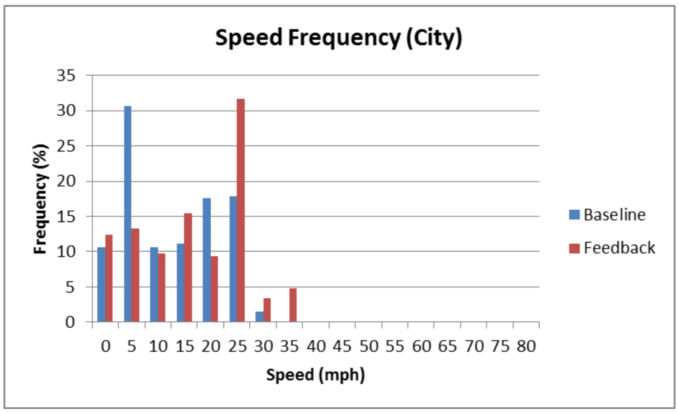
Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

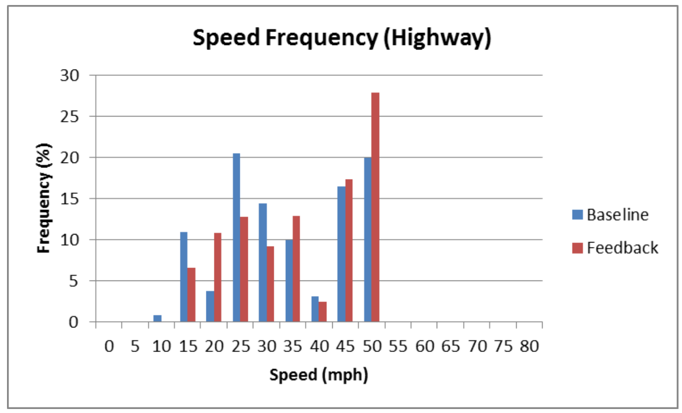


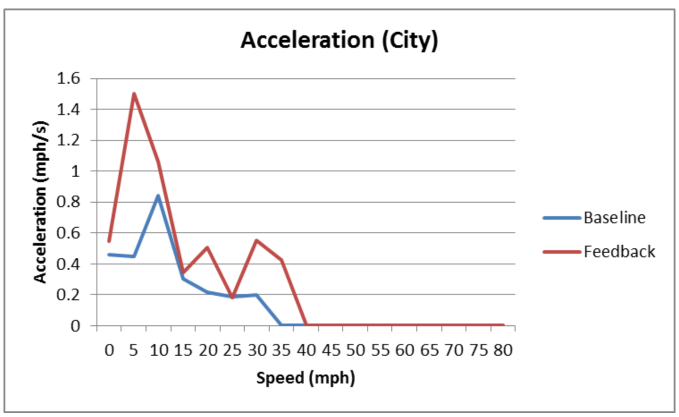
Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

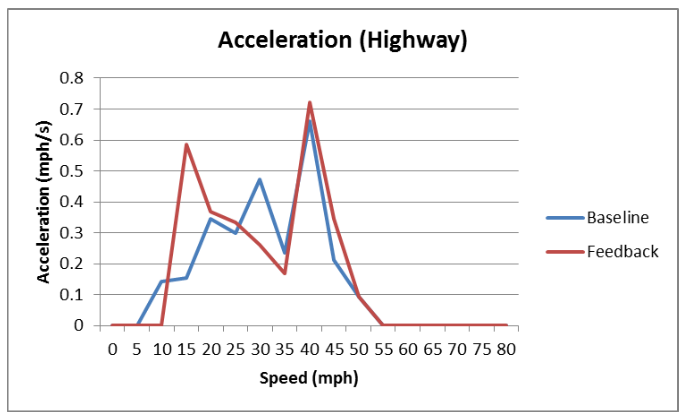
Driver #09

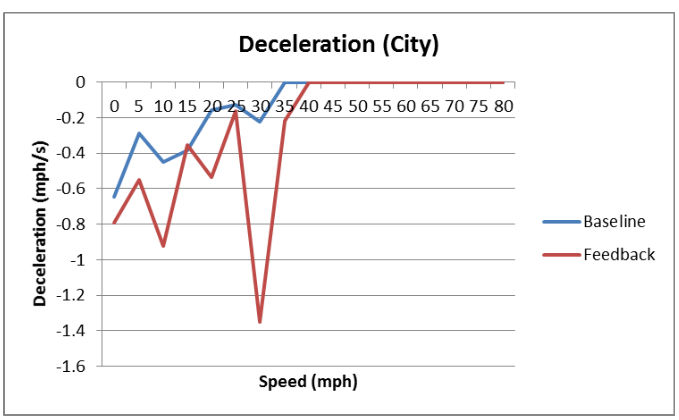

Speed Profiles
Speed (mph)
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11 12
Distance (mi)
Baseline
Feedback
Recommended

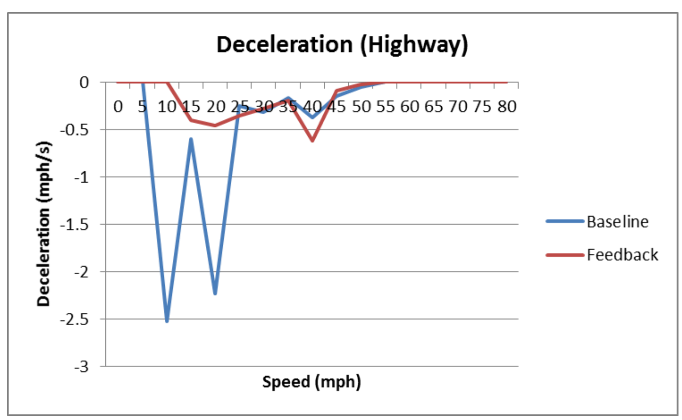

Speed Frequency (City)
Frequency (%)
35
30
25
20
15
10
5
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
30
25
20
15
10
5
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback


Acceleration (City)
Acceleration (mph/s)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

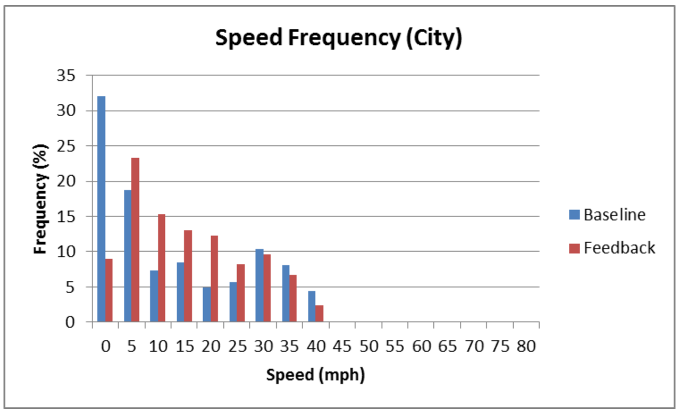

Acceleration (Highway)
Acceleration (mph/s)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

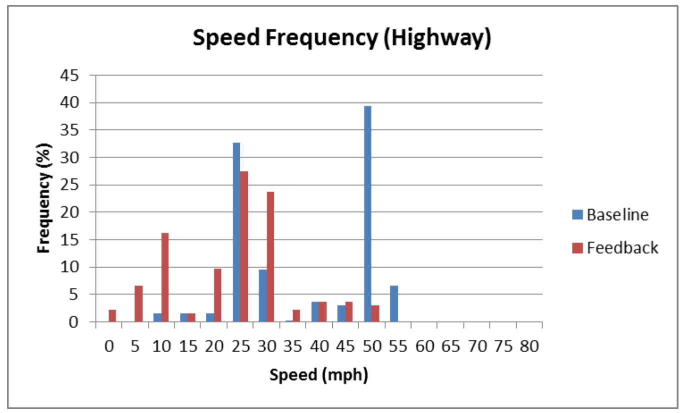

Deceleration (City)
Deceleration (mph/s)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

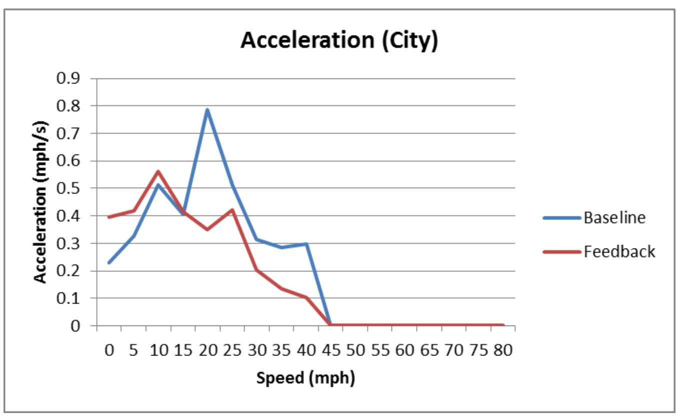

Deceleration (Highway)
Deceleration (mph/s)
0
-0.5
-1
-1.5
-2
-2.5
-3
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

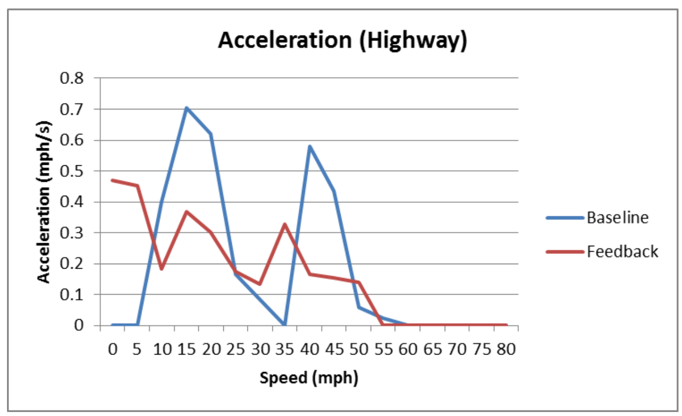
Driver #10

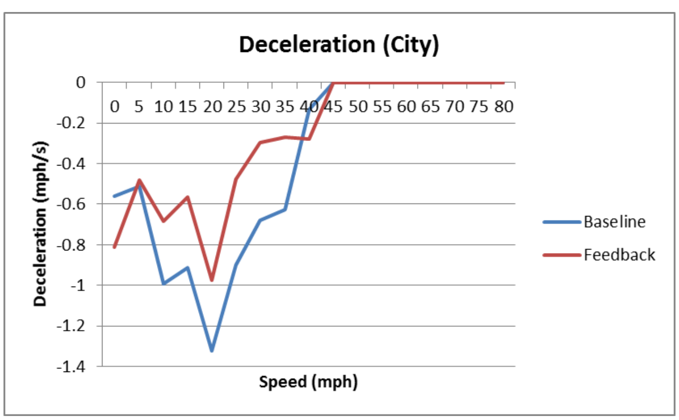

Speed Profiles
70
60
50
40
30
20
10
0
Speed (mph)
0 1 2 3 4 5 6 7 8 9 10 11 12
Distance (mi)
Baseline
Feedback
Recommended

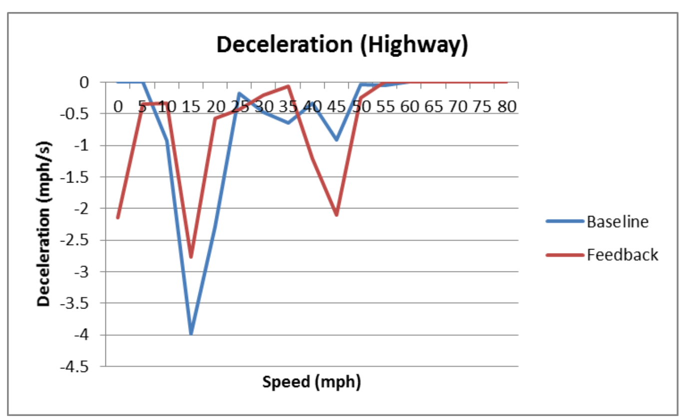

Speed Frequency (City)
35
30
25
20
15
10
5
0
Frequency (%)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
45
40
35
30
25
20
15
10
5
0
Frequency (%)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

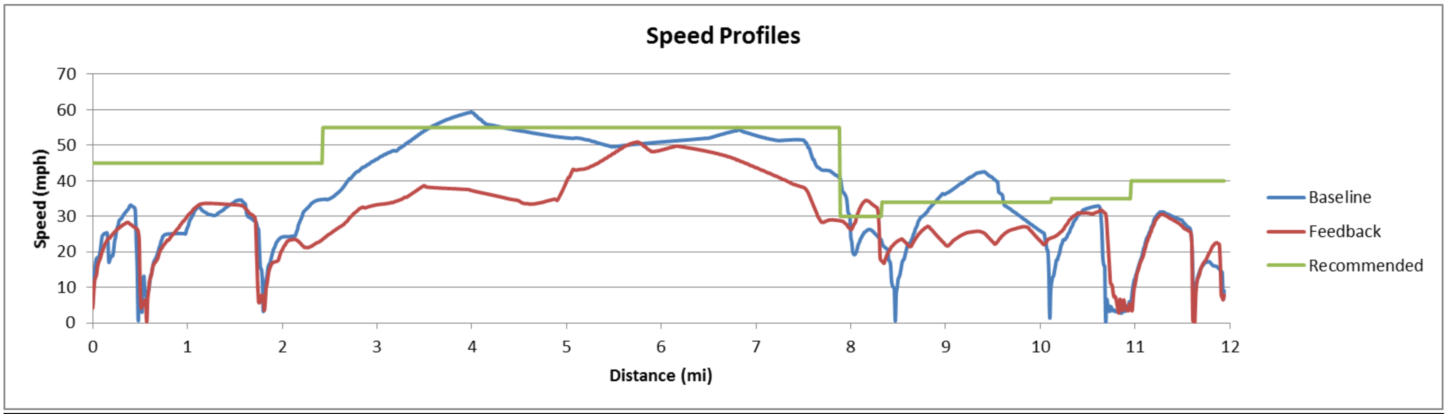

Acceleration (City)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Acceleration (mph/s)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback


Acceleration (Highway)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Acceleration (mph/s)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

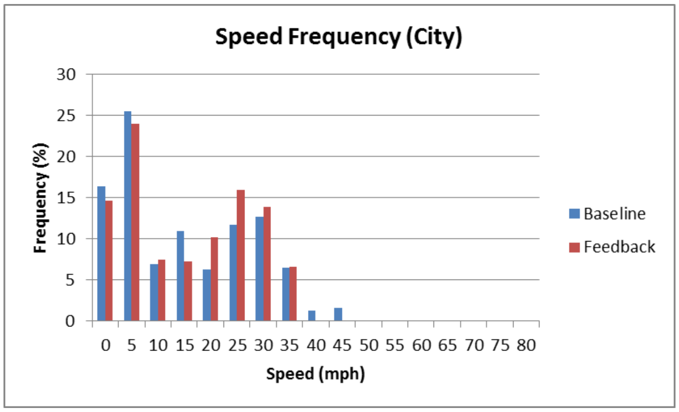

Deceleration (City)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback


Deceleration (Highway)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

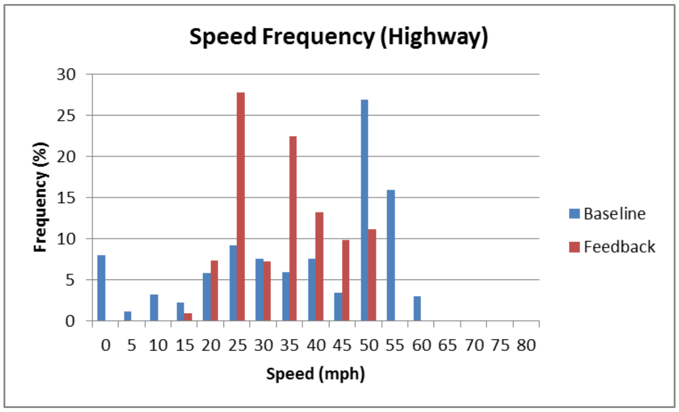
Driver #11



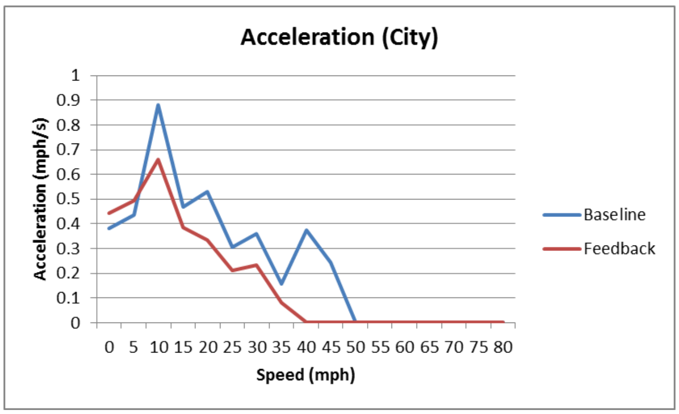
Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended



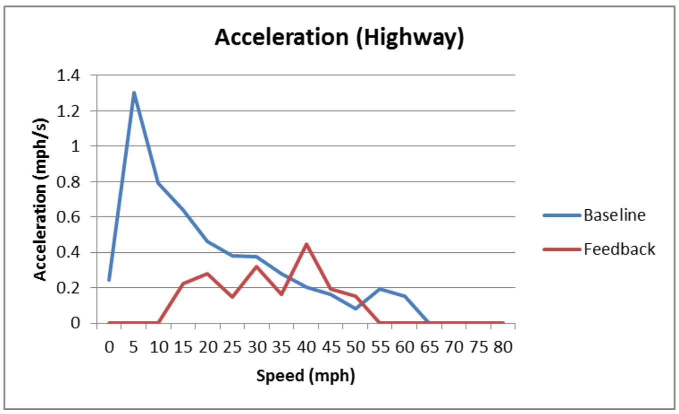
Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback



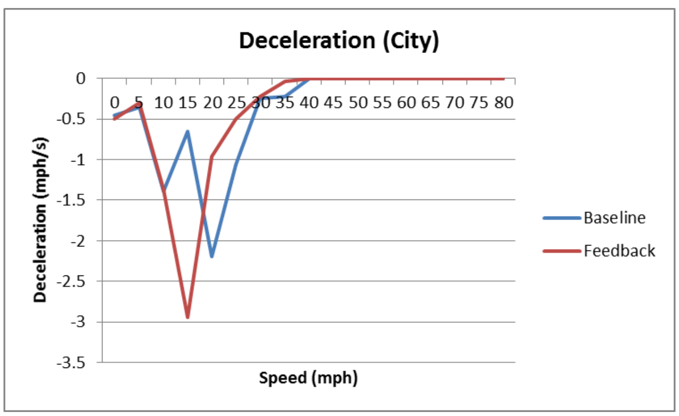
Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback



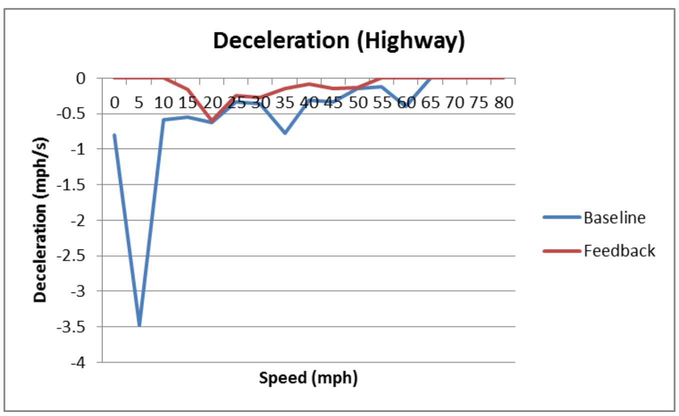
Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback



Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

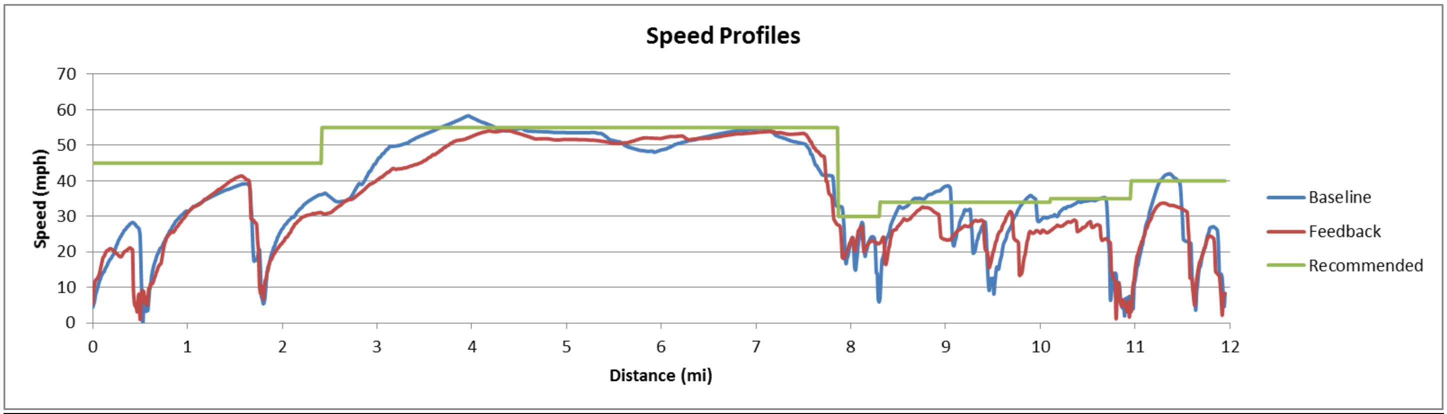


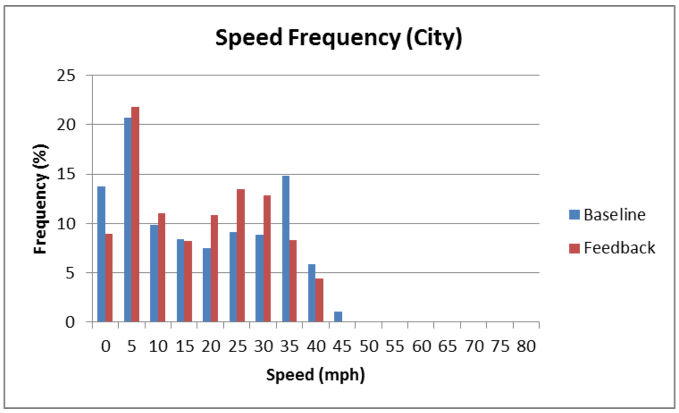
Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

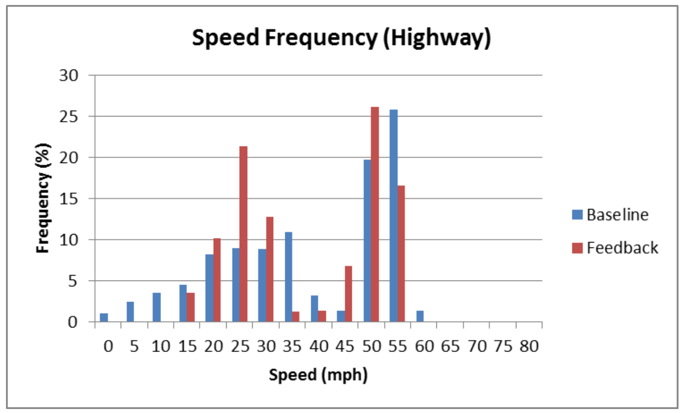


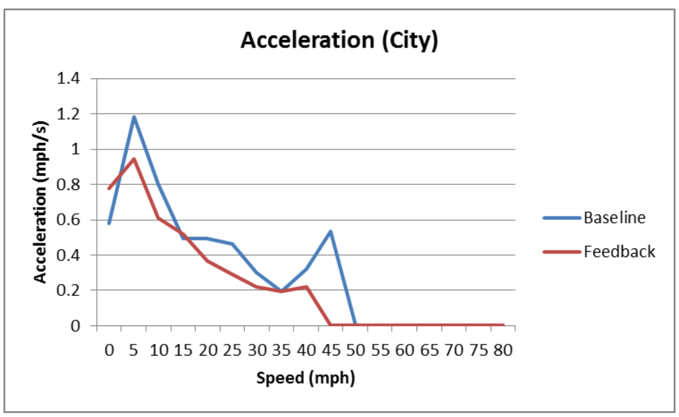
Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

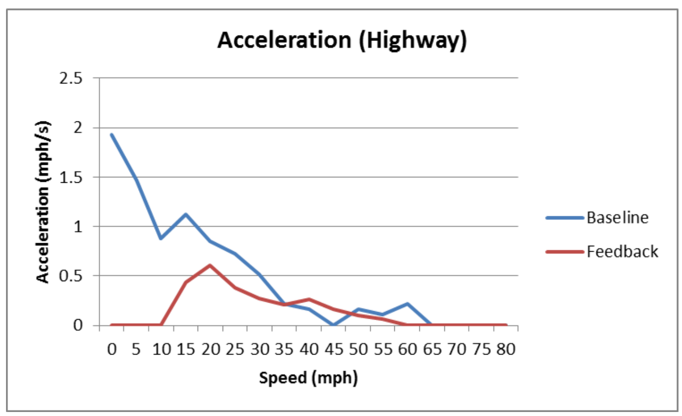
Driver #12

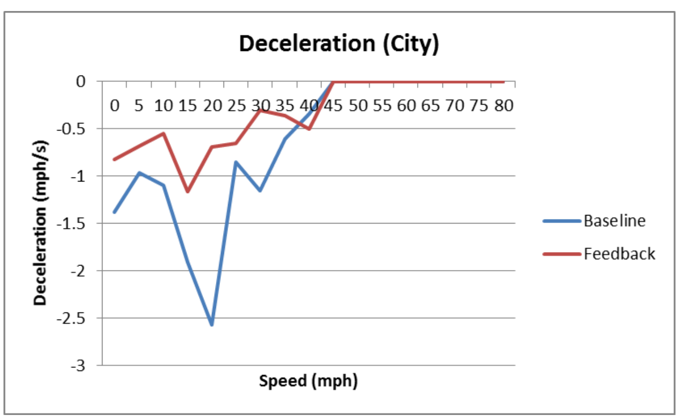

Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended

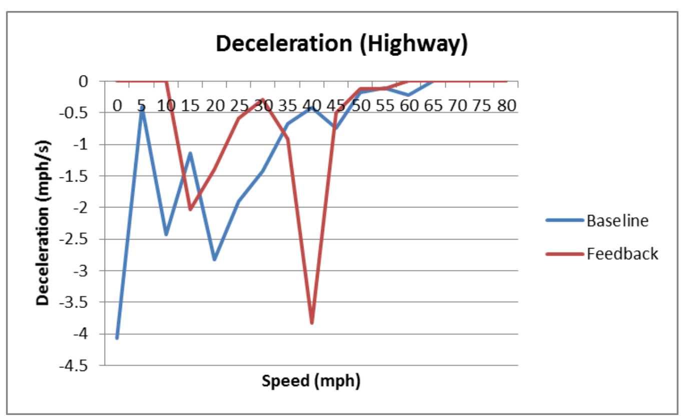

Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback


Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

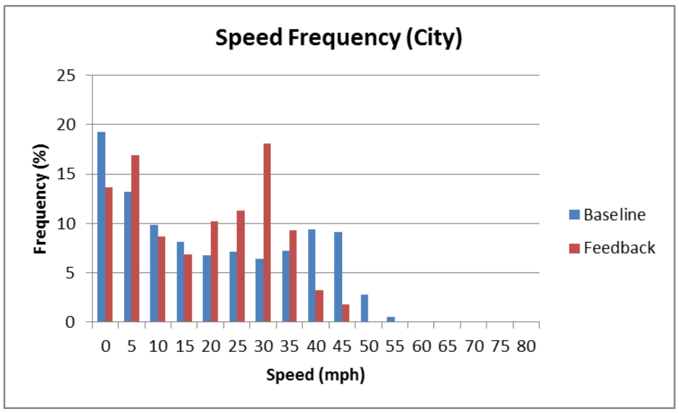

Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

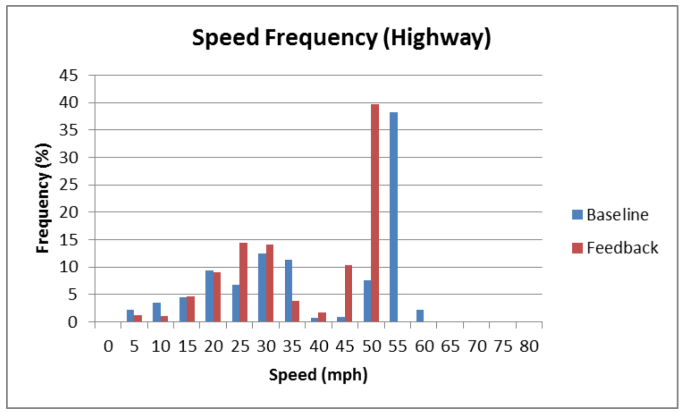

Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

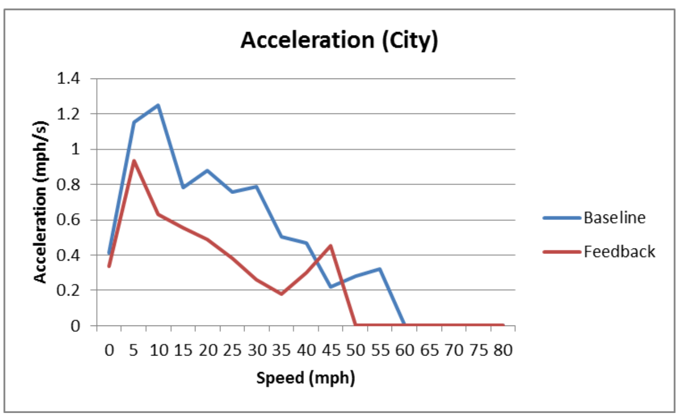

Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

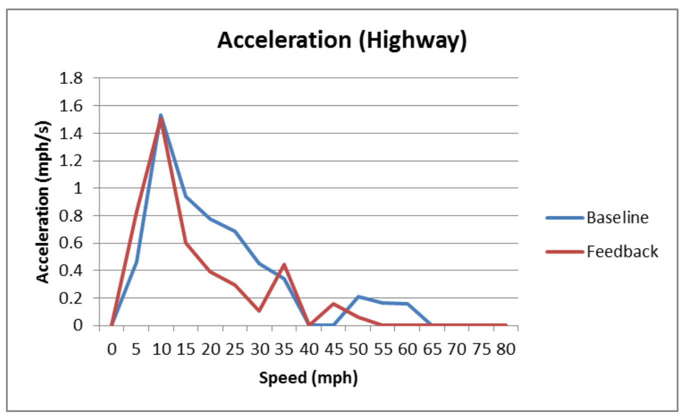
Driver #13

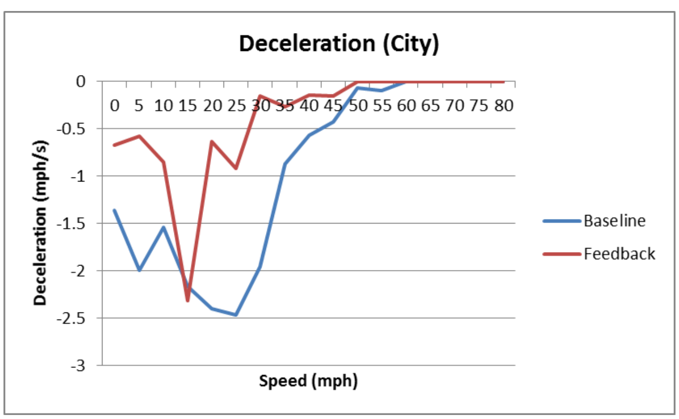

Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended

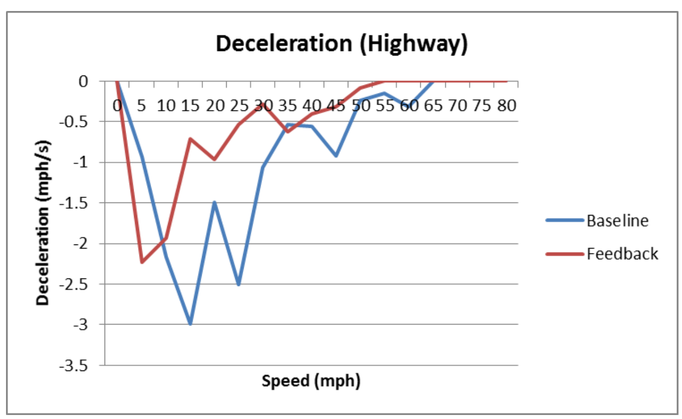

Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback


Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

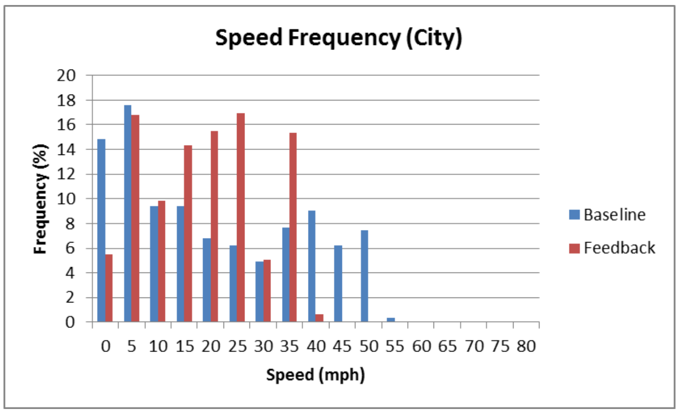

Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

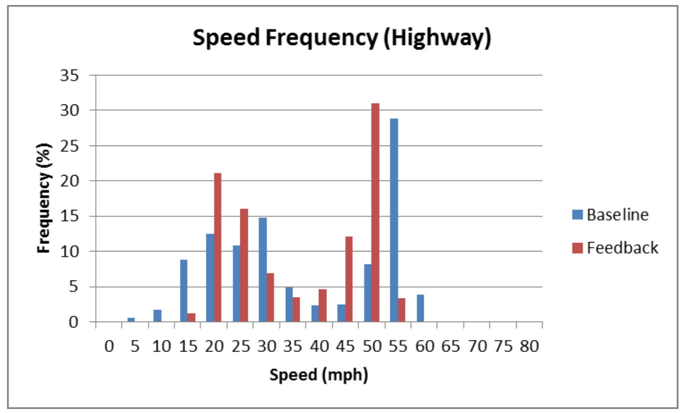

Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

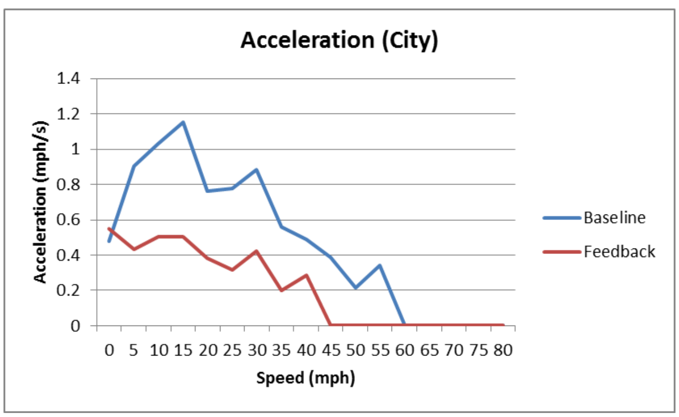

Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

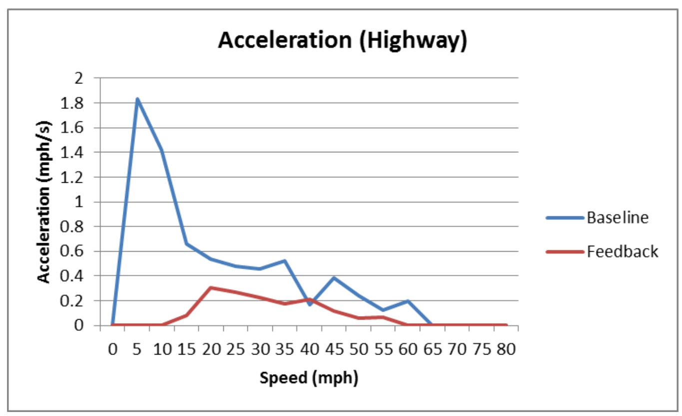
Driver #14

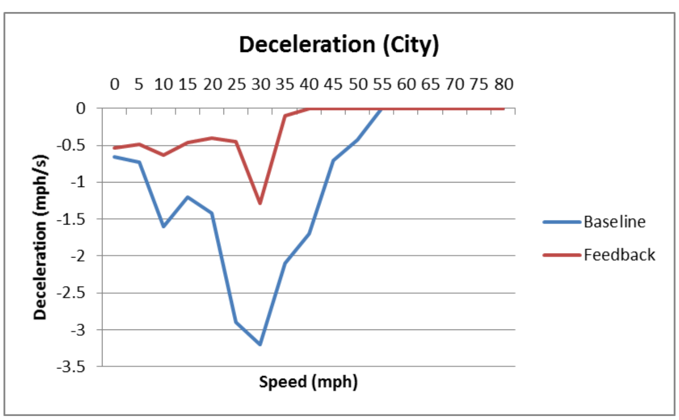

Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended

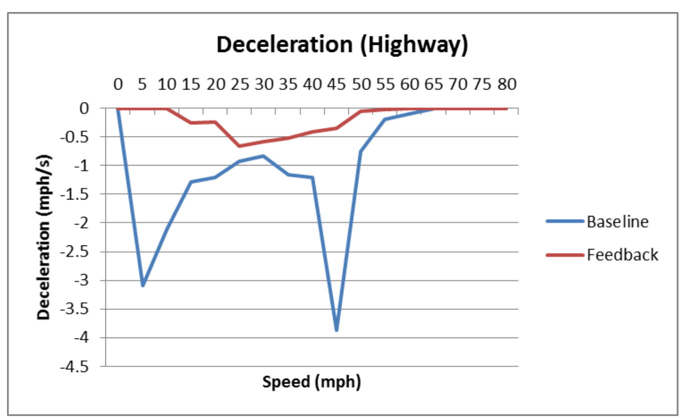

Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback


Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

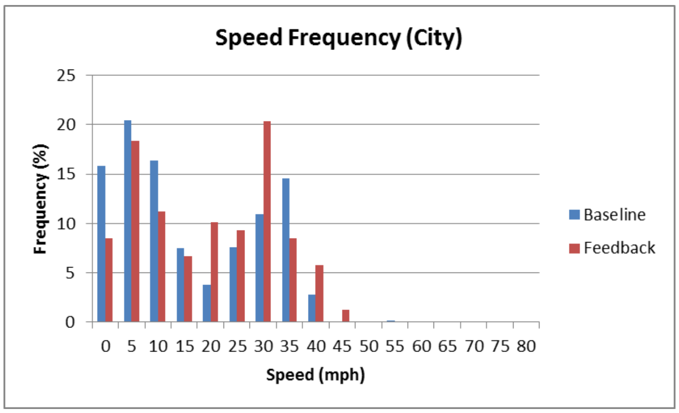

Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

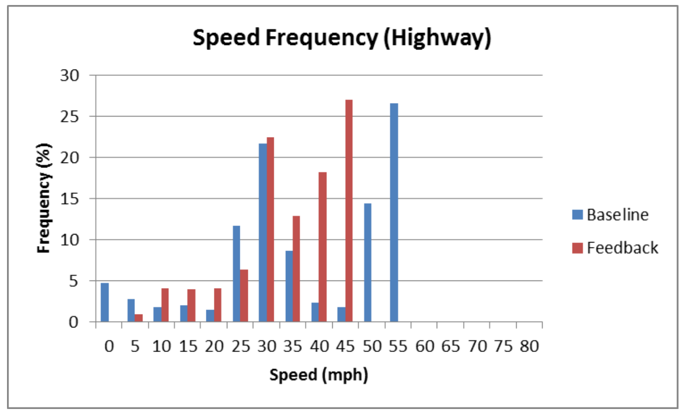

Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

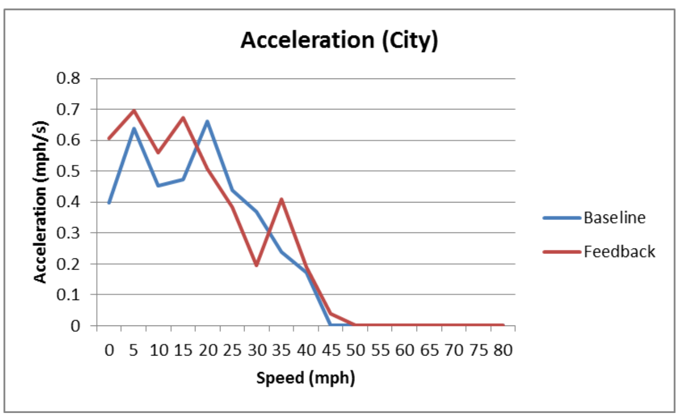

Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

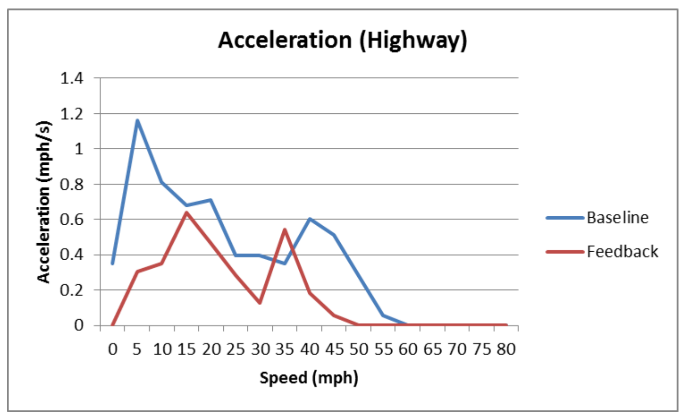
Driver #15

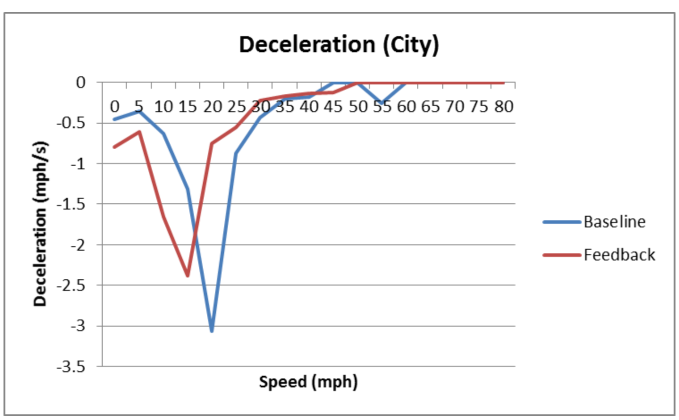

Speed Profiles
Speed (mph)
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11 12
Distance (mi)
Baseline
Feedback
Recommended

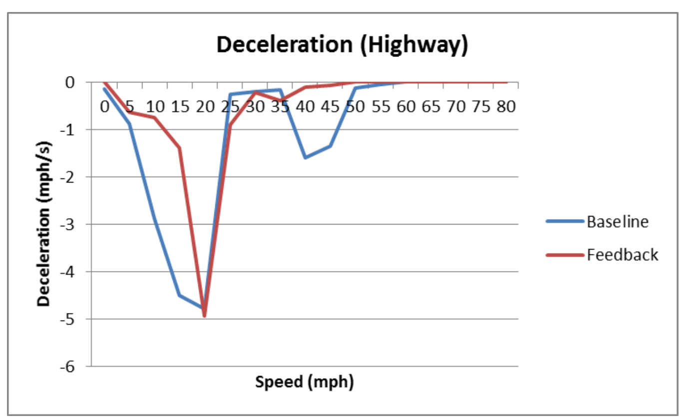

Speed Frequency (City)
Frequency (%)
25
20
15
10
5
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
30
25
20
15
10
5
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

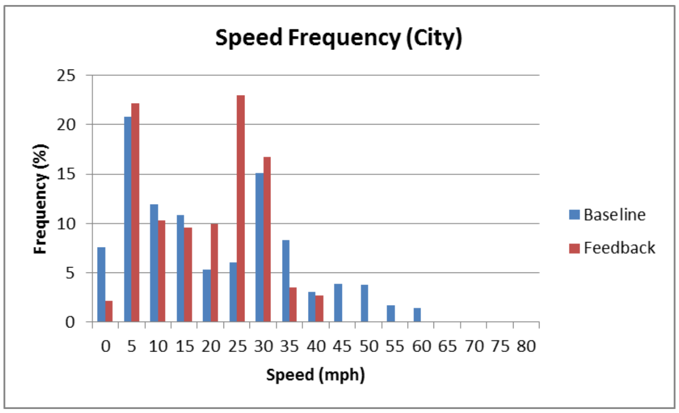

Acceleration (City)
Acceleration (mph/s)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

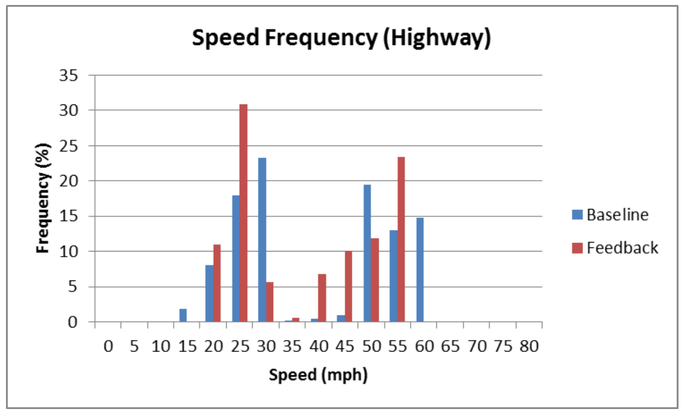

Acceleration (Highway)
Acceleration (mph/s)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

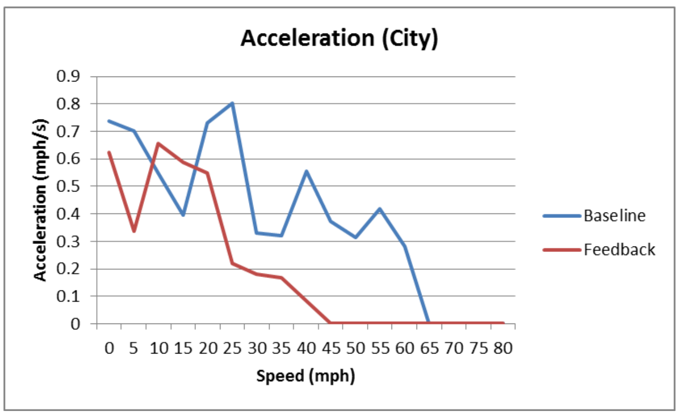

Deceleration (City)
Deceleration (mph/s)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

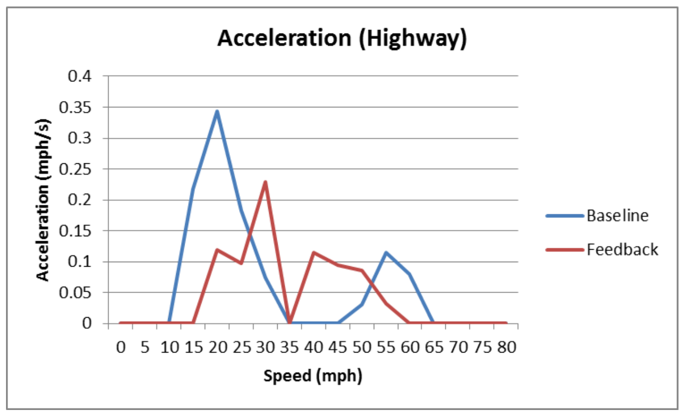

Deceleration (Highway)
Deceleration (mph/s)
0
-1
-2
-3
-4
-5
-6
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

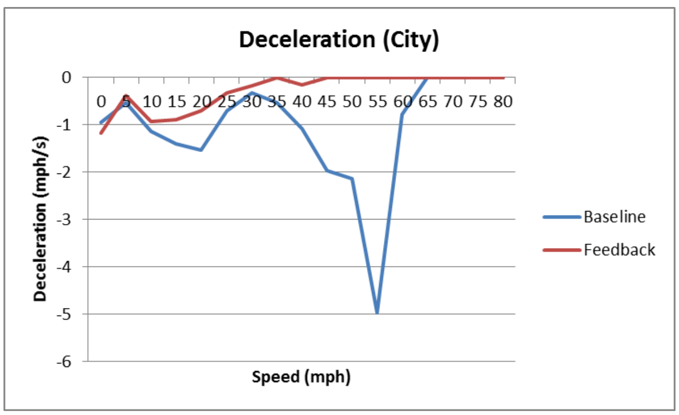
Driver #16

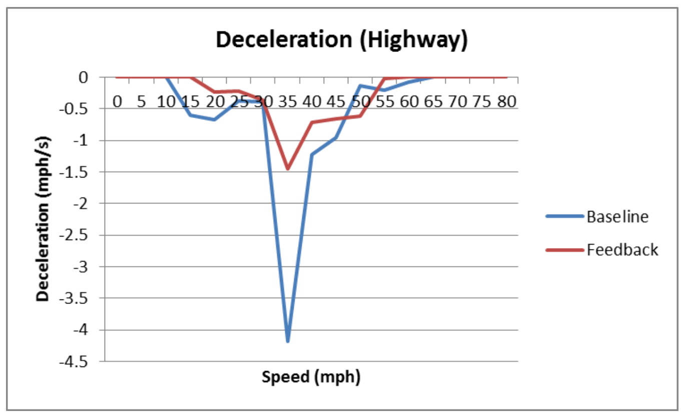






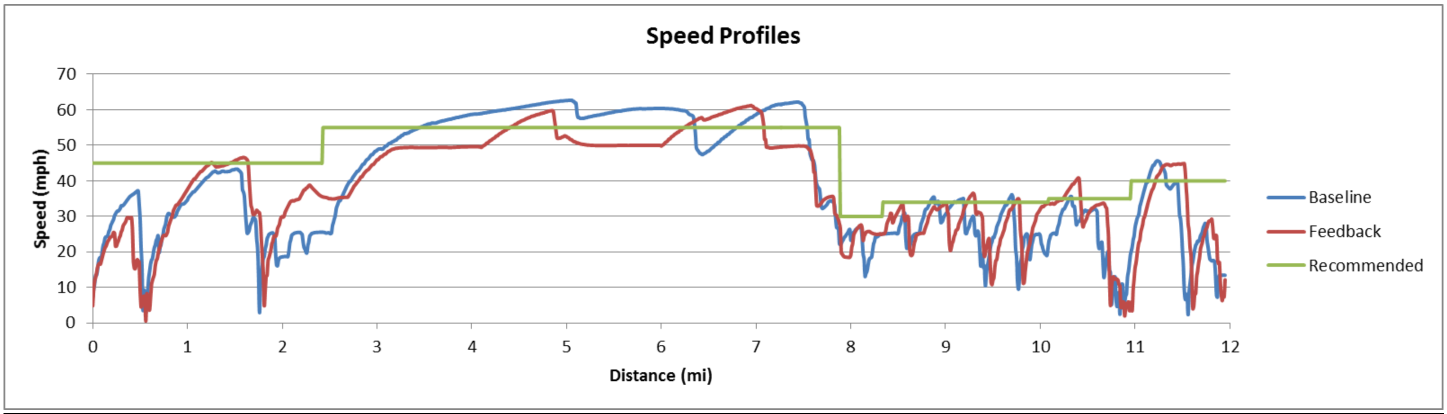


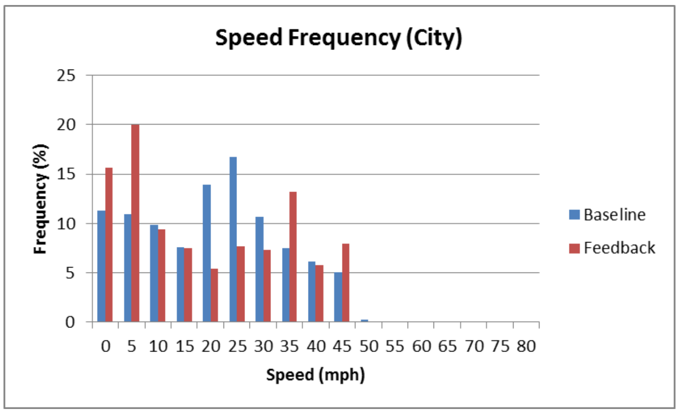


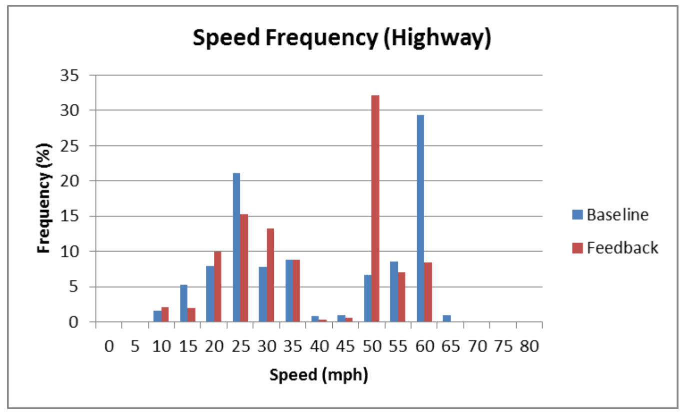


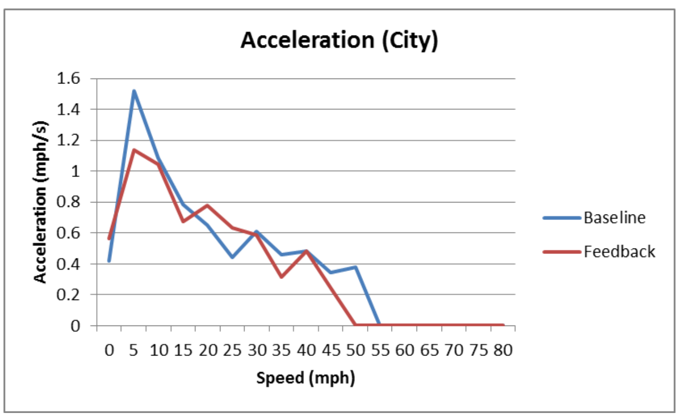
NCST

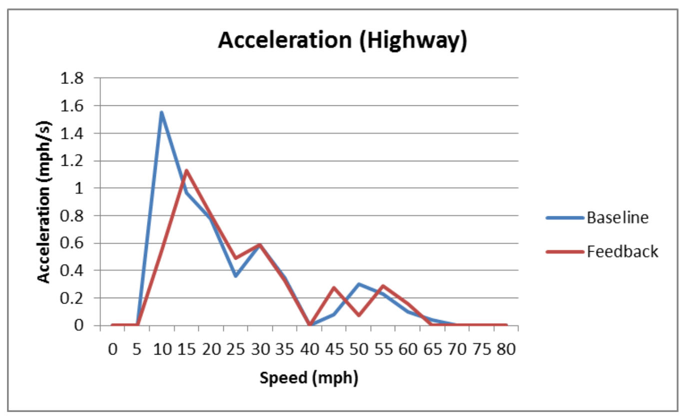
Driver #17

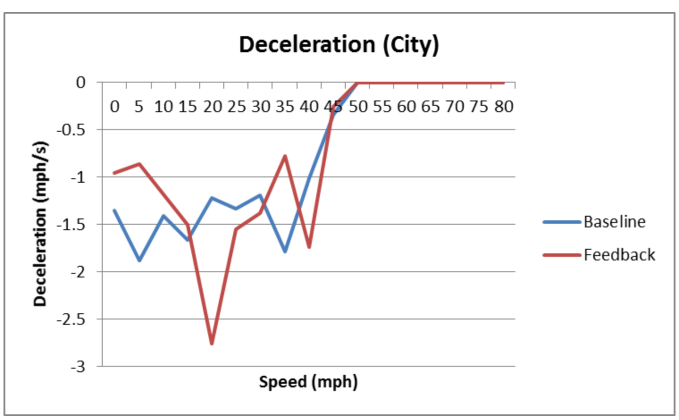

Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended

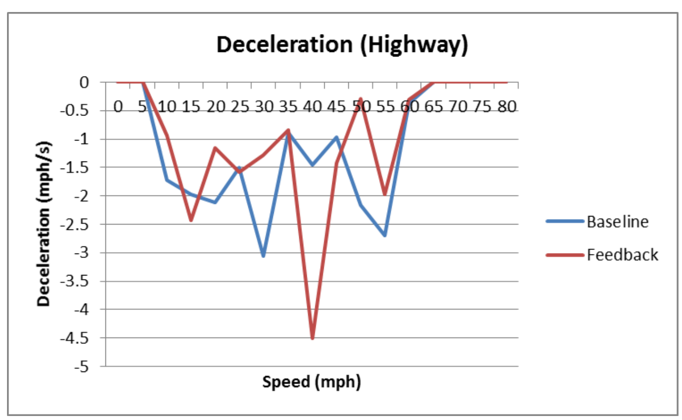

Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback

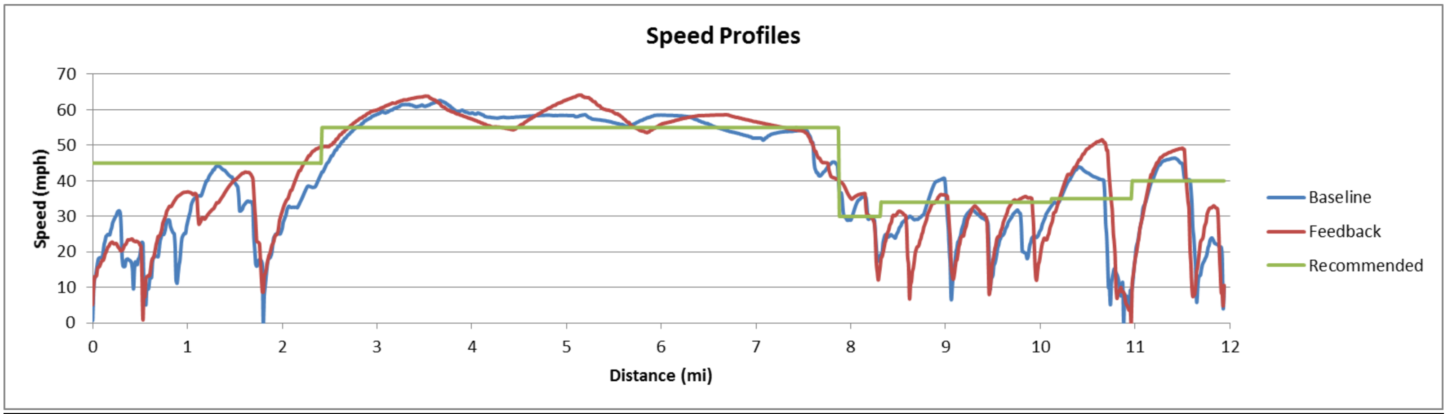

Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

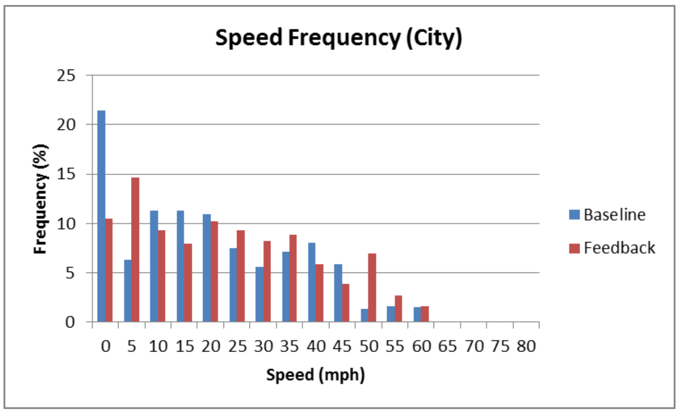

Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

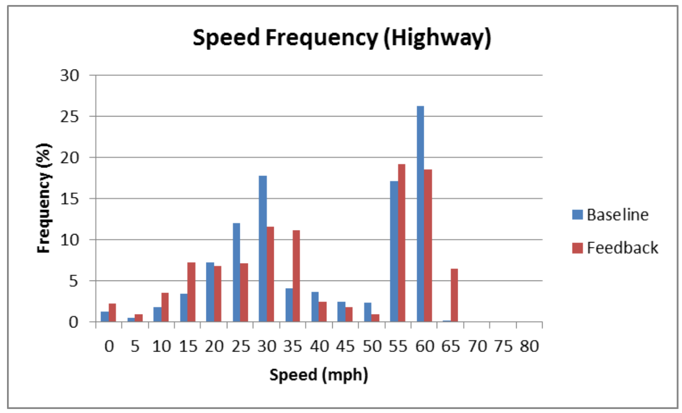

Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

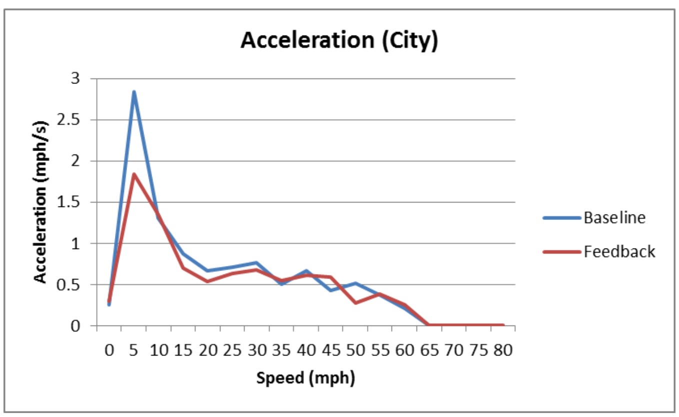

Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

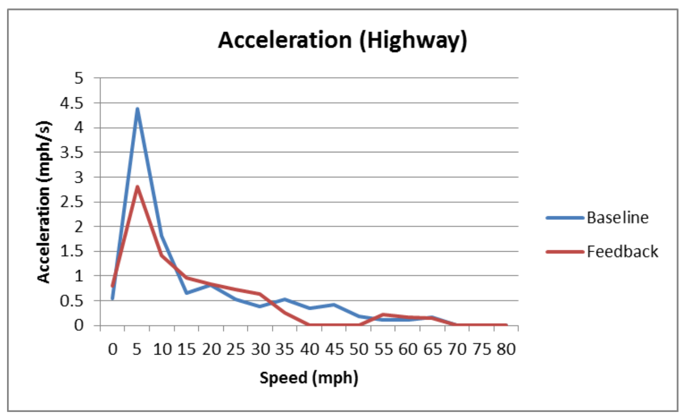
Driver #18

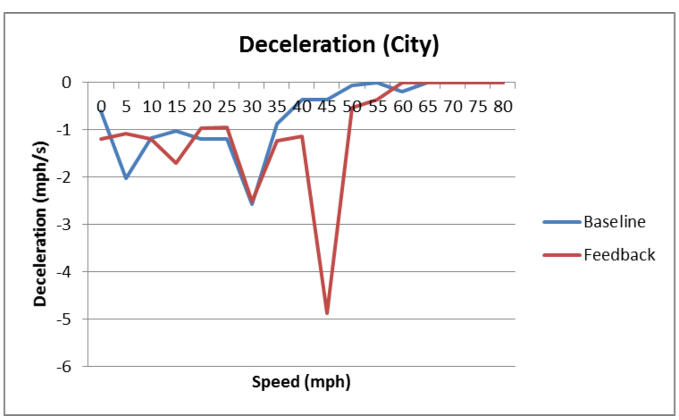

Speed Profiles
Speed (mph)
0 10 20 30 40 50 60 70
0 1 2 3 4 5 6 7 8 9 10 11 12
Distance (mi)
Baseline
Feedback
Recommended

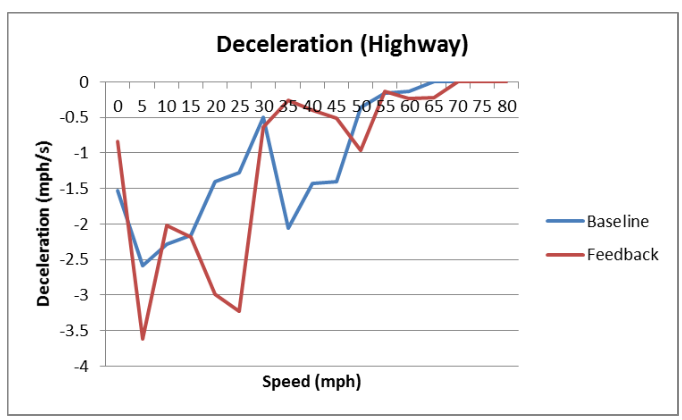

Speed Frequency (City)
Frequency (%)
0 5 10 15 20 25
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
0 5 10 15 20 25 30
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback


Acceleration (City)
Acceleration (mph/s)
0 0.5 1 1.5 2 2.5 3
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

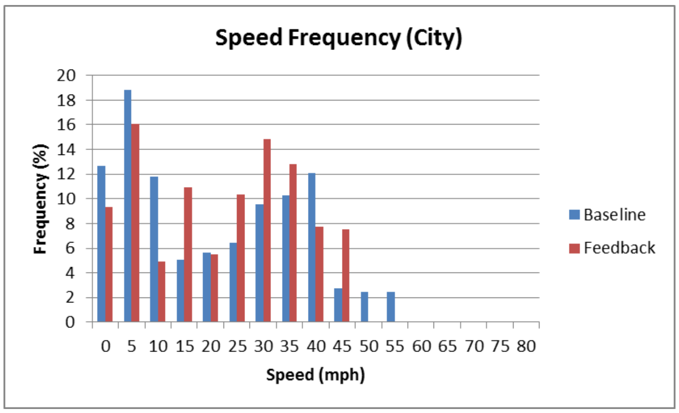

Acceleration (Highway)
Acceleration (mph/s)
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

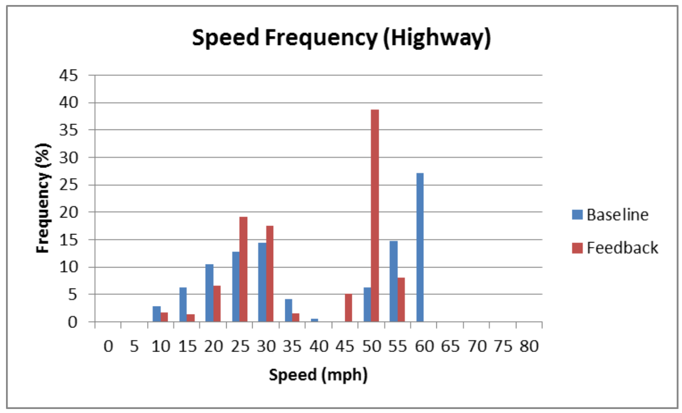

Deceleration (City)
Deceleration (mph/s)
0 -1 -2 -3 -4 -5 -6
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

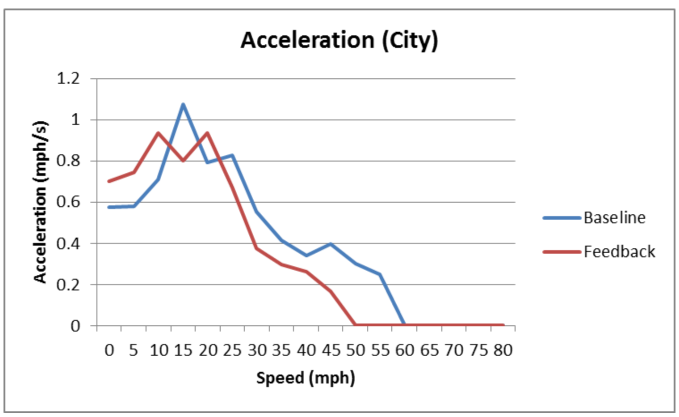

Deceleration (Highway)
Deceleration (mph/s)
0 -0.5 -1 -1.5 -2 -2.5 -3 -3.5 -4
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Speed (mph)
Baseline
Feedback

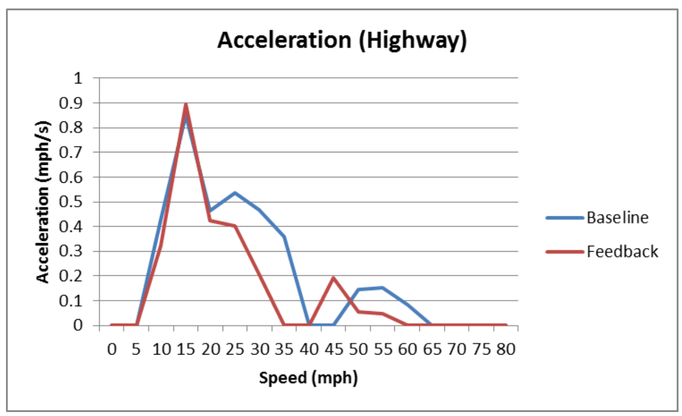
Driver #19

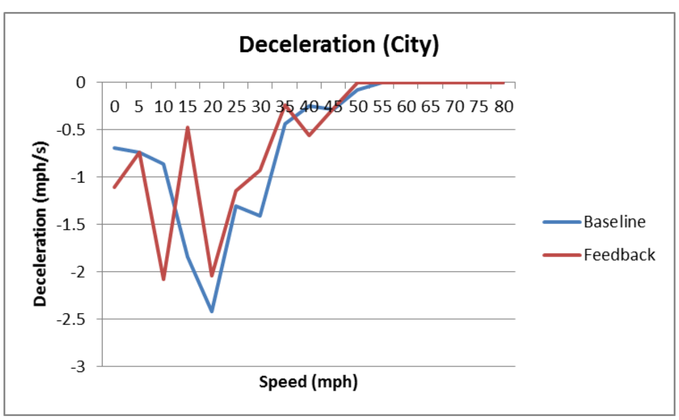

Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended

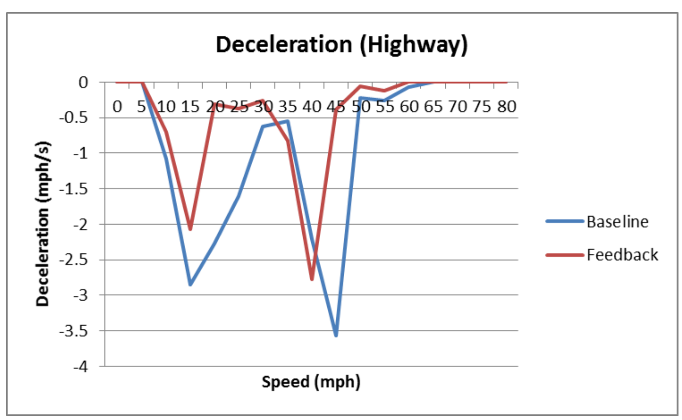

Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback


Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback

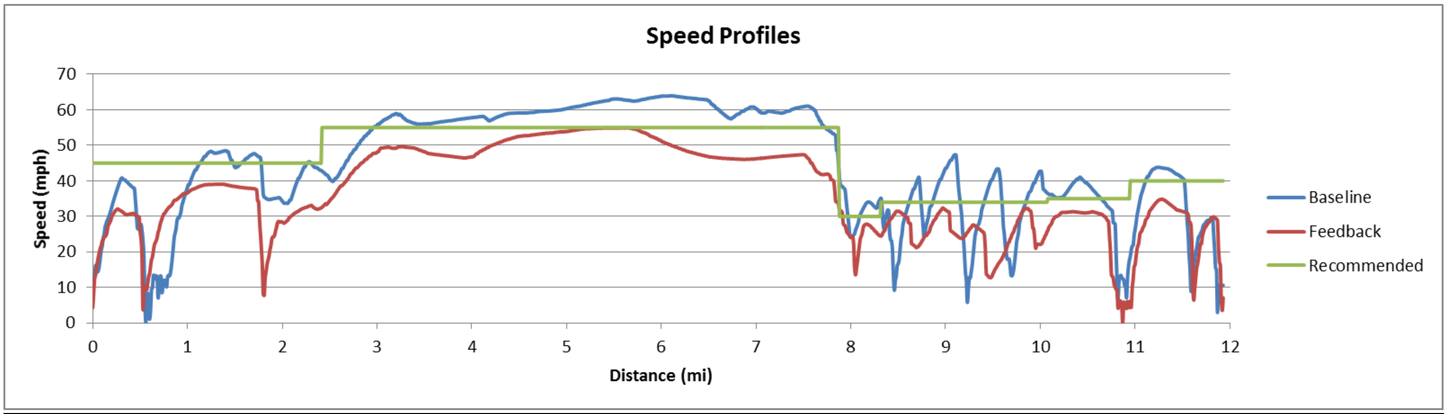

Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback


Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

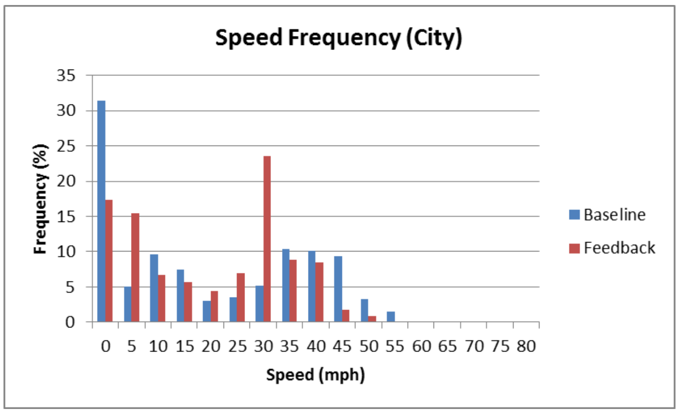

Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback


Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

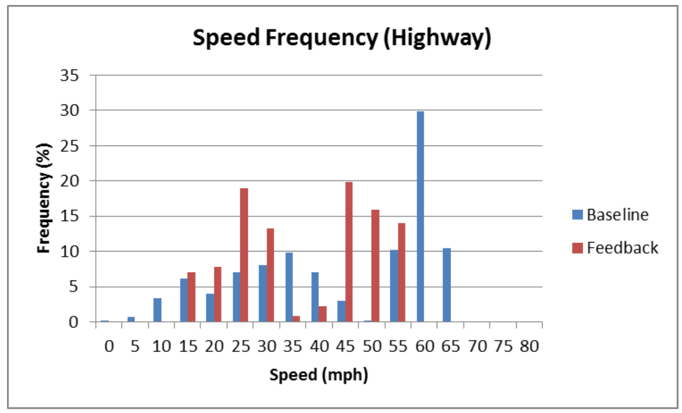
Driver #20



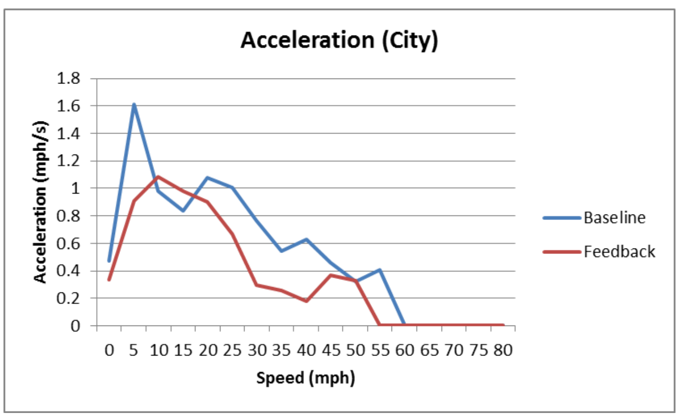
Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended



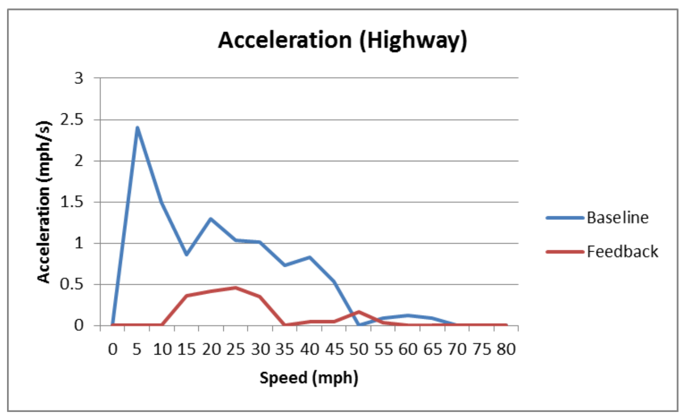
Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback



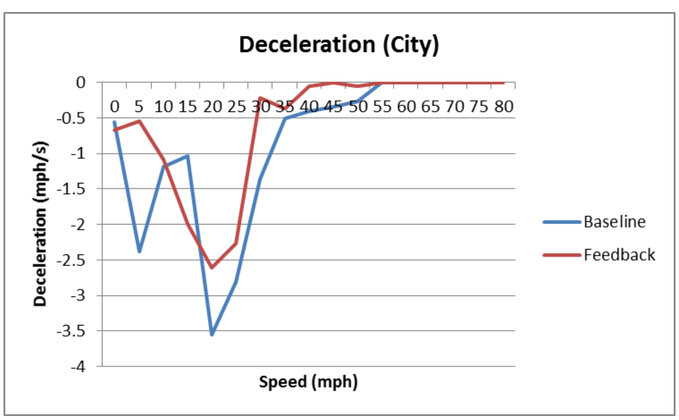
Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback



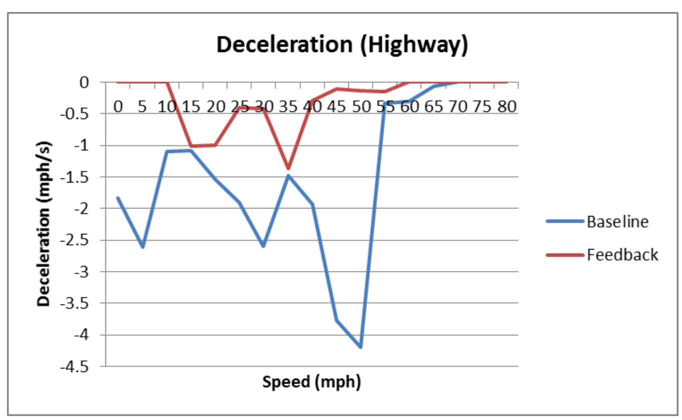
Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback



Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback

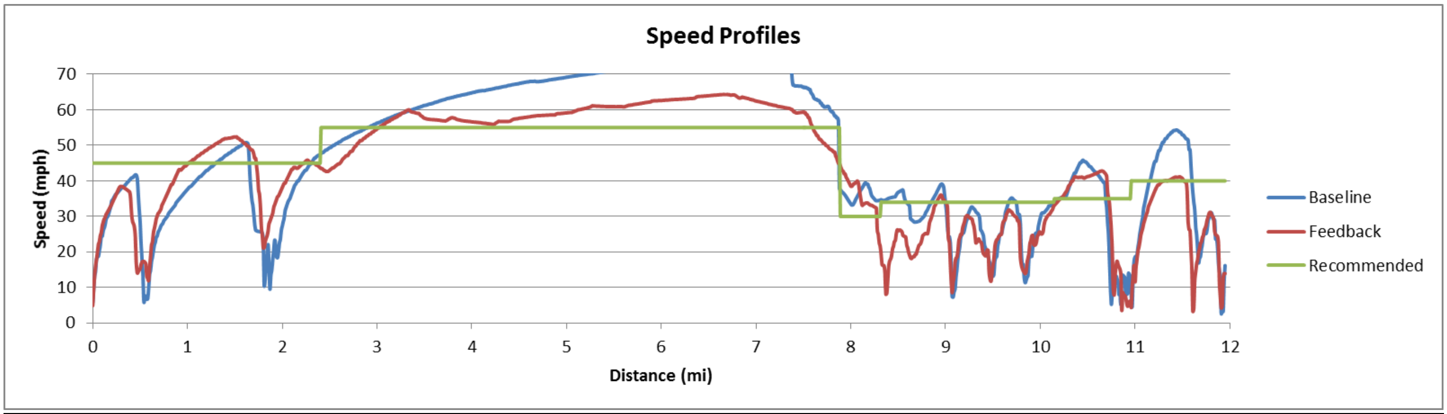


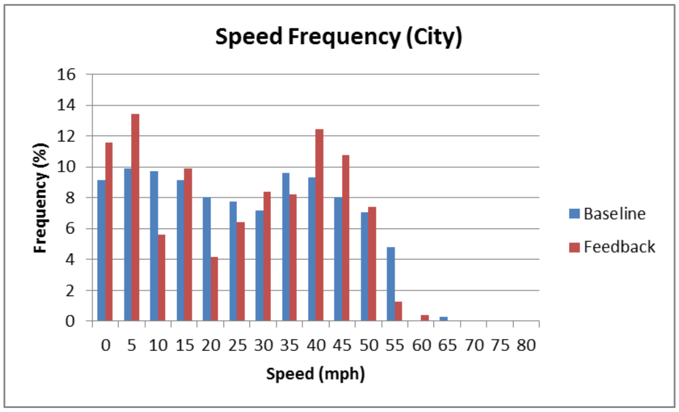
Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

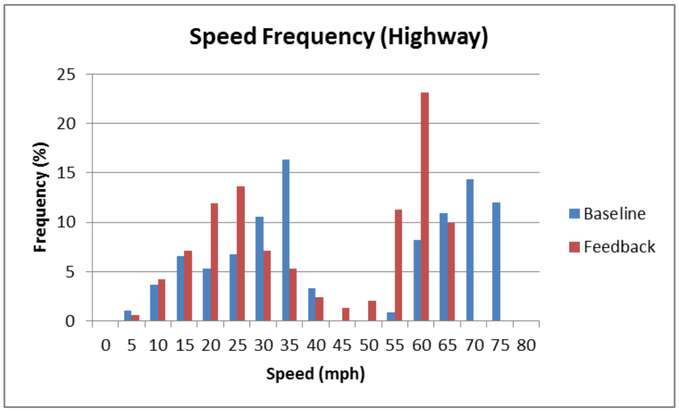


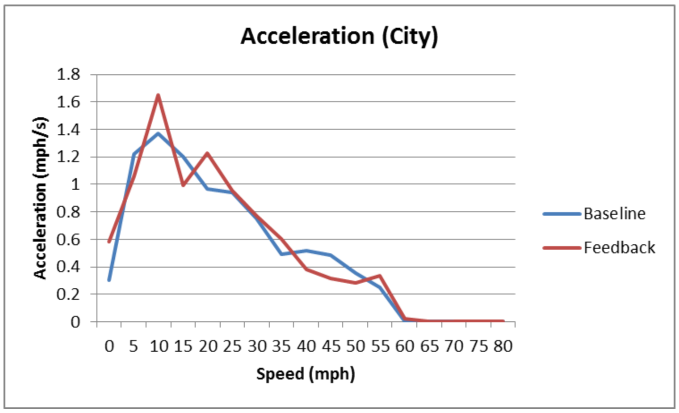
Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback

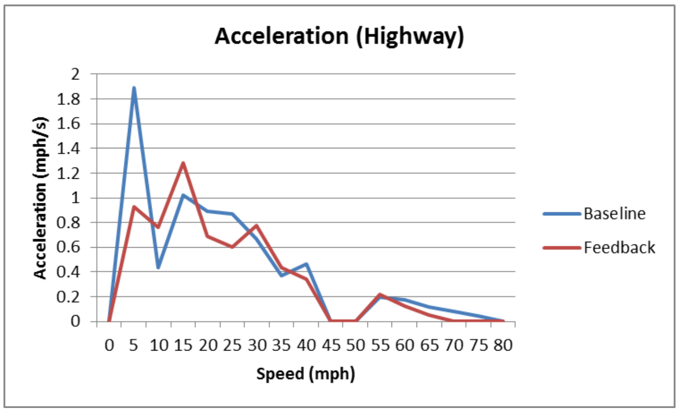
Driver #21

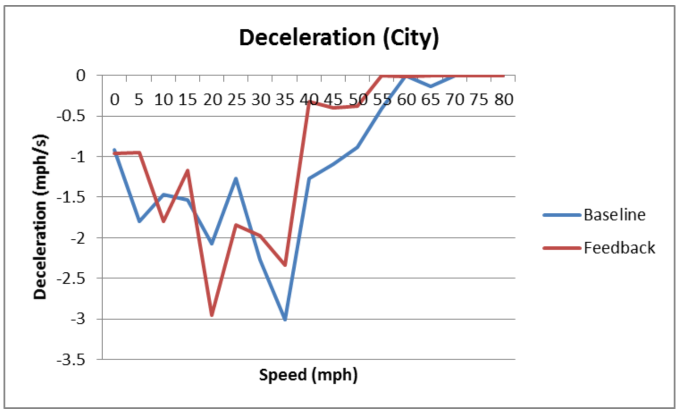


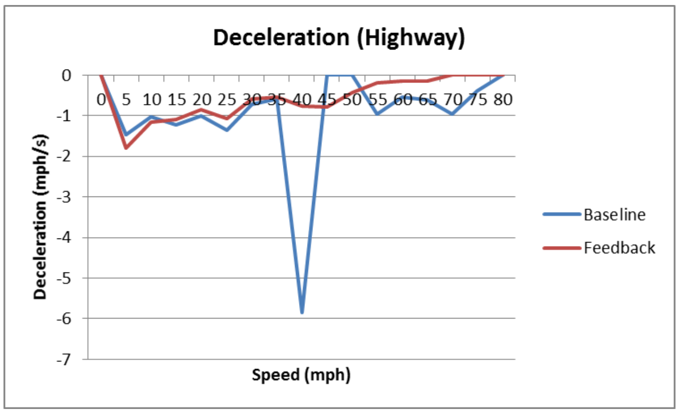






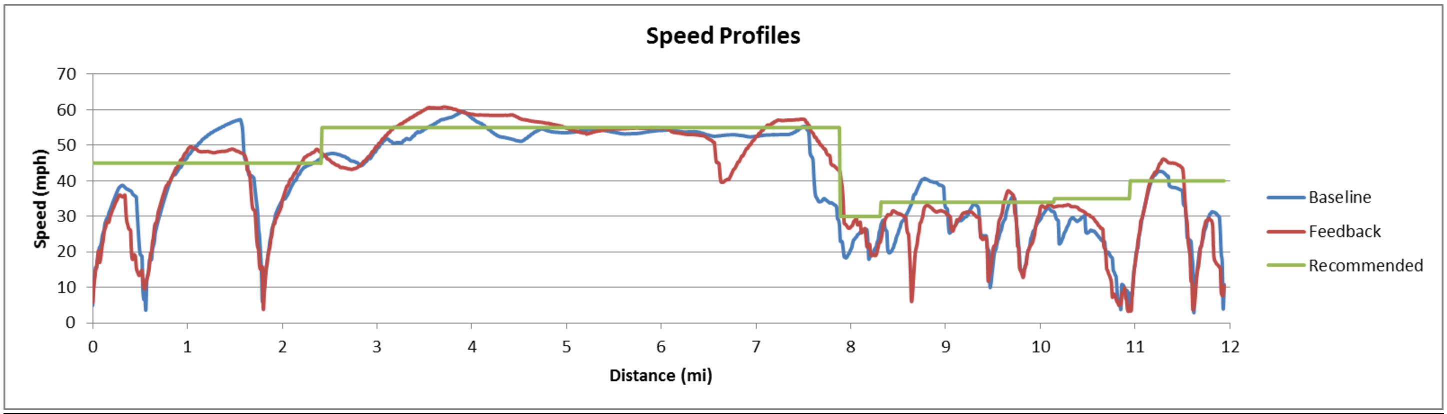




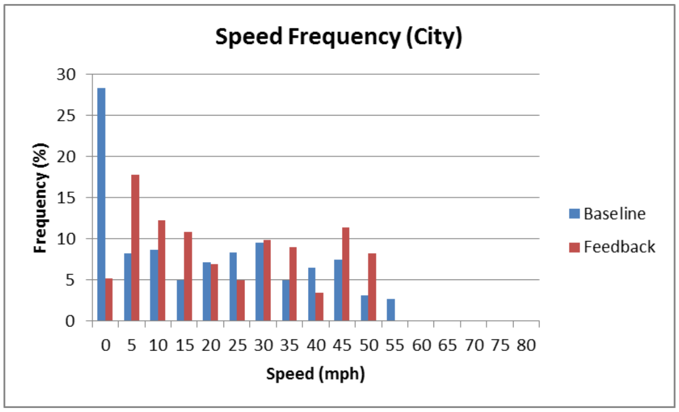


NCST

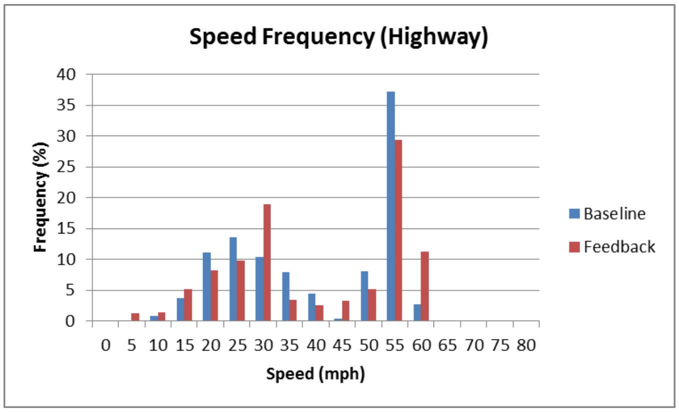
Driver #22



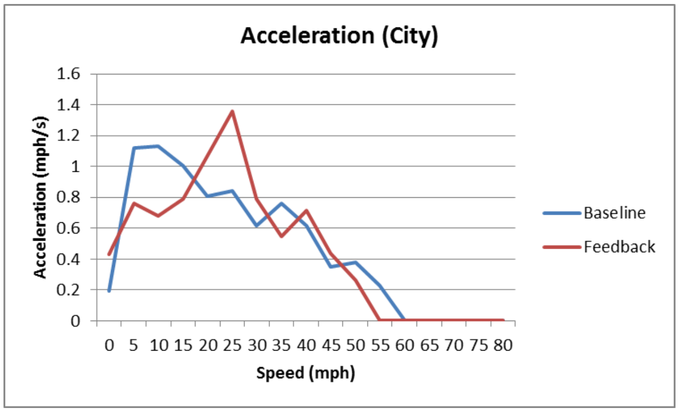
Speed Profiles
Speed (mph)
Distance (mi)
Baseline
Feedback
Recommended



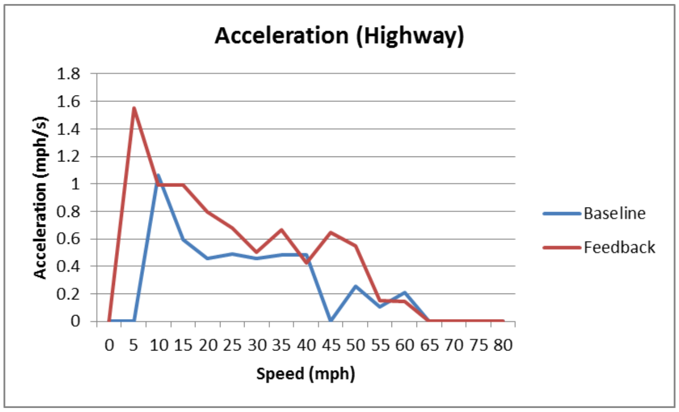
Speed Frequency (City)
Frequency (%)
Speed (mph)
Baseline
Feedback



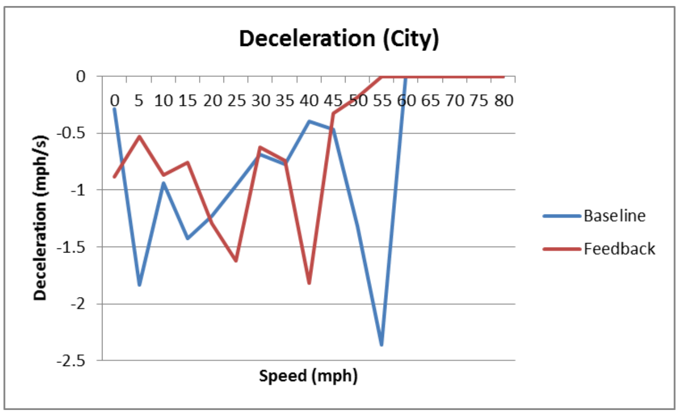
Speed Frequency (Highway)
Frequency (%)
Speed (mph)
Baseline
Feedback



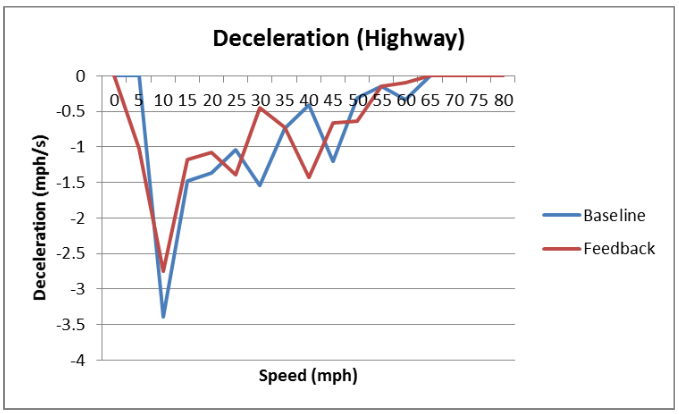
Acceleration (City)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback



Acceleration (Highway)
Acceleration (mph/s)
Speed (mph)
Baseline
Feedback



Deceleration (City)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback



Deceleration (Highway)
Deceleration (mph/s)
Speed (mph)
Baseline
Feedback