ECODRIVE I-80: A LARGE SAMPLE FUEL ECONOMY FEEDBACK FIELD TEST

FINAL REPORT

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Report: ITS-RR-13-15

Report Submitted in fulfillment of requirements of contract:
Oak Ridge National Laboratory: 4000102856

ABSTRACT

Energy feedback in the vehicle dashboard is one method to engage drivers in energy saving driving styles. In contrast to the occasional broadcasting of general driving tips, in-vehicle energy feedback gives drivers access to accurate information about their specific driving situation on an ongoing basis. The increasing prevalence of such feedback in new vehicles suggests a belief that the latter is effective. However, there is little reliable evidence of the effectiveness of energy feedback in real-word driving in passenger vehicles. This study begins to fill this gap. This report presents the results of a large sample eco-driving feedback study that includes 118 drivers (140 driver-vehicle combinations); the drivers reside in selected cities along the Interstate-80 corridor from San Francisco, CA to Reno and Sparks, NV. Participants are given a commercially available fuel consumption recording and display device to use in their personal vehicle for two months. The first month the display was left blank to record a baseline of driving and fuel consumption: the second month the display was switched on. The devices display one of three display designs spanning a variety of feedback modes; drivers are randomly assigned which design they will see. Using a mixed-effects linear model that controls for road grade and weather conditions, we find a statistically significant decrease of 2.7% in fuel consumption rate (grams of gasoline per meter) between the without and with-feedback months overall. We also find that drivers reduced their median trip speeds and mean acceleration rates in response to feedback. The three display designs ranged from 1.9% to 2.9% impact. Driver sex was an even greater determinant of savings with men averaging 1.9% and women 5% savings. Finally, the alignment of pre-feedback driver goals with certain designs resulted in one group achieving a 22% improvement, and we estimate that if each driver had received the optimal screen for his or her goal (rather than a random assignment) the group would have saved 9.2% overall. Analysis of households' exit interviews reveals that while many households claim that achieving good fuel economy is a goal of their driving, few can name more than three things they could do or actually do to increase fuel economy. Motivations for higher fuel economy span a range of cost savings, energy security, conservation, environmental protection, and climate change. A thematic analysis of the interview text produces a structure of four main themes, i.e., driving contexts, sense of personal control, learning, and durability over time of behaviors. Feedback can affect each of these themes and act as a bridge between them, e.g., increasing a sense of personal control over fuel economy can be accomplished by learning from feedback how personal actions affect fuel economy across driving contexts.

ACKNOWLEDGEMENTS

This research is funded by the U.S. Department of Energy through Oak Ridge National Laboratory. Our thanks to CSAA Insurance Group, a AAA Insurer for their assistance in recruiting participants. The University of California Sustainability Center provided additional funding. Our thanks to Lauryn Robinson for her assistance in summarizing and coding interview transcripts. The authors are solely responsible for the contents.

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INTRODUCTION

Past research indicates that real-world drivers of passenger vehicles will decrease fuel consumption by approximately 5% in the presence of fuel economy feedback, although some studies have shown higher impacts (Ando, Nishihori, & Ochi, 2010; Barkenbus, 2010; Greene, 1986). The suite of driving behaviors that result in this effect has come to be known as eco-driving. It includes moderating speeds and accelerations as well as increasing coasting (especially approaching stops). However, the potential improvements from an eco-driving style are mediated by roadway design, traffic, competing norms about driving styles, and drivers' own interest and knowledge regarding eco-driving compared to other goals they have for, and while, driving. To mention just one example, a goal such as saving time, whether it manifests as an attempt to make it through the next traffic signal before it changes or as high-speed freeway driving, would conflict with a goal to reduce fuel use. In this report, we focus on the impact of in-vehicle fuel economy feedback on on-road fuel consumption. Drivers' attitudes, interests, and knowledge are organized into a framework to help explain driver behaviors in response to fuel consumption feedback. Further, we organize the analysis into different types of trips to account for the mediating effects of speed, stops, and trip length. To expand the relevance of this study to the variety of feedback designs being deployed in new cars today, we test the effectiveness of three common graphical feedback designs. To expand the relevance of the study to a variety of land uses, traffic, and trip patterns, we deploy the study in three distinct urban areas. The next section reviews prior research, in part to put into context the research design deployed in this field test. The present research design is described in the next chapter. Following that is a description of the data and analysis. Then, four chapters present the results, followed by the concluding chapter.

Background

Review of Driver Feedback Studies

A meta-analysis of 15 prior studies in the scholarly and popular literature over the past 30 years indicates that feedback and driver training can lead to fuel consumption reductions (Ando et al., 2010; Boriboonsomsin, Vu, & Barth, 2010*; Driving Change: City of Denver Case Stud*y, 2009; Greene, 1986; Larsson & Ericsson, 2009; Lee, Lee, & Lim, 2010; Satou, Shitamatsu, Sugimoto, & Kamata, 2010; Syed & Filev, 2008; van der Voort, 2001; Wahlberg, 2007) (Table 1). However, few of the studies were completed in a naturalistic driving setting and only one (Wahlberg, 2007) presented statistically significant results. The majority of studies were based on feedback that consisted of a real-time numeric or graphical gauge display of fuel economy, i.e., miles-per-gallon (MPG). The apparent drop-off in effect observed between short term (one trip or a single day of driving) vs. long term (greater than two weeks) studies may be due to short term studies being more likely to include a positive performance bias, e.g., asking individuals to drive carefully to perform well in the experiment. In long-term studies, it is unlikely that an individual would continue to display such behavior for the benefit of the test, as over time the experiment will recede in importance as general life habits and goals re-assert themselves. One experiment found that in the short term, individuals who were simply asked to drive more carefully (with no additional training or feedback) increased their fuel economy by 10% (Greene, 1986). The suggestion is that in the short term, an experimental effect unrelated to the goals of the study may be responsible for a large amount of the effect being attributed to feedback designs.

Table 1: Driver feedback literature review

Source [internal reference]	Period of Measure (days)*	Effect (fuel use reduction)	Sample (n)	Stat. sig.†	Design	Real-world‡
(Lee et al., 2010)	1	0%	14	no	3 icon color display showing poor, neutral, and eco indicators	no
(Larsson & Ericsson, 2009)	42	0%	20	no	Haptic feedback	yes
(*Driving Change: City of Denver Case Study*, 2009)	~	0%	214	~	Web only feedback	yes
(Greene, 1986) [Bendix, 1981]	~	2.2%	1	~	Vacuum-based mpg meter	no
(Greene, 1986) [Banowetz and Bintz, 1977 (US DOT)]	1	3.0%	140	no	Vacuum-based mpg meter	no
(Boriboonsomsin et al., 2010)	14	3.8%	20	no	Real time mpg + throttle + lb. Co2/mile. Trip summary.	yes
(Wahlberg, 2007)	365	4.0%	350	yes	Real-time and average consumption (km/l) text display	yes
(Ando et al., 2010)	126	4.3%	50	~	Complex web and mobile phone feedback comprising scores and logs.	yes
(Greene, 1986) [Chang et al. 1976]	1	5.4%	1	~	Vacuum-based mpg meter	no
(van der Voort, 2001)	2.5	6.0%	12	~	Not described	no
(Greene, 1986)	~	8.8%	1	~	Vacuum-based mpg meter	no
(Syed & Filev, 2008)	1	10%	1	no	Accelerator pedal position advisory	no
(van der Voort, 2001)	2.5	11%	12	~	Driver advice based on vehicle operations	no
(Satou et al., 2010)	180	18%	150	no	Complex onboard + web. Realtime feedback + Fuel used by distance metric and rankings.	yes

*Short-term tests such as a circuit-driving course of undetermined length are listed as 1 day.
†Includes any report of statistically significant findings at an alpha level of 0.025 or below.
‡Real-world refers to drivers in everyday life. Non-real-world includes simulators, circuits, or other experimental setups.
~ Indicates unreported values.

The research design deployed here attempts to improve on past studies in three ways. First, it includes a larger sample, detailed sub-second data, and a long enough data collection period to allow more sensitive analysis to reach statistical significance. Second, it includes a long enough duration to likely suppress the effects of a short-term positive performance bias. Third, it tests multiple feedback designs in one experiment in coordination with surveys and interviews of driver attitudes, knowledge, and goals to better understand how and why drivers and their fuel use change between experimental phases. Regarding the third, the theory of planned behavior (TPB) forms the core behavioral framework for this study (Ajzen, 1980). The TPB is one of a number of rational behavior models that include decision-making pre-cursors such as attitudes about the behavior, perceptions of applicable social norms, or perceptions of behavioral control. The TPB behavioral model has generated a large literature including such applications as recycling (Tonglet, Phillips, & Read, 2004) and drivers' propensity to speed (Paris & Broucke, 2008).

Recent studies indicate that additional factors not included in the TPB play critical roles in behavior change, notably goals, as described in the extended model of goal directed behavior (EMGDB) (Perugini & Conner, 2000), and personality (Jackson, 2005). The TPB was proposed as a model to explain behavioral intention and outcome behavior (once the context was taken into account) and was not originally meant as a methodology by which to modify behavior, although the popularity of the TPB is largely due to researchers interested in theory-based behavioral interventions, and the TPB is seen as a model for studying intervention efficacy (Ajzen, 2002). TPB, as we amend it with other behavioral precursors, helps us understand why drivers may or may not find feedback motivating and engaging. A general hypothesis from the TPB would be that an individual's sense they have control over fuel consumption would lead to greater savings (if savings are possible in that specific context).

DESCRIPTION OF THE I-80 ECO-DRIVE FIELD TEST

The description of prior studies of eco-driving motivates these three research questions for this field test:

1. Evidence of existence: can we detect an effect on real-world, on-road fuel economy attributable to fuel economy instrumentation?
2. If so, does this effect vary by feedback design and/or individual-specific factors?
3. How do people experience fuel economy?

We test three versions of fuel consumption feedback in a field test in which each driver completes a natural driving quasi-experiment. To enhance the generalizability of our estimate of the efficacy of the three tested screen designs, thirty to forty participants were enrolled in three distinct regions in two states. Addressing the questions requires that we collect data suitable both for a quantitative test of on-road fuel economy in response to three types of feedback and for a mixed quantitative/qualitative description of the drivers and their experience of the field test. The resulting data set includes: 140 driver-vehicle pairs including 118 individual drivers who in aggregate produced 235,000 vehicle-km of driving data.

Study Regions and Household Selection Process

To ensure that the estimates of fuel savings can be generalized across many driving situations, residents of distinct and varied metropolitan regions along the Interstate-80 corridor were selected for study. In California, these were San Francisco, Oakland, Berkeley, and Davis. In Nevada, these were the contiguous cities of Reno and Sparks. Table 2 summarizes total population and population density from the 2010 US Census for these cities. While together San Francisco, Oakland, and Berkeley represent a large (in area and population) metropolitan region, San Francisco stands apart as one of the most densely populated cities in the US. Traffic levels in the Bay Area are high, parking is limited, and all three cities in the Bay Area are hilly. Davis is a small city in California's largely agricultural Central Valley. Its topographical challenges are limited to a few overpasses. It has a distinct urban boundary; it is separated from its nearest neighboring cities and towns by miles of agricultural fields and wetlands preserves that take ten to twenty minutes travel time by automobile to traverse. Though their combined populations rival that of Oakland, Reno and Sparks are barely a third as densely populated as Davis. Located at the western edge of the sparsely populated Great Basin, both cities sprawl across a high desert plateau. The western suburbs of Reno in particular climb the base of the steep eastern face of the Sierra Nevada. The cities are separated by a thirty-minute drive from their nearest neighbors, the much smaller Carson City, NV and the mountain town of Truckee, CA.

To assess whether the three feedback designs (described in a subsequent section) have different effects on fuel economy, an *a priori* random assignment of each household to a single display type was made. Within each geographic region, an approximately equal number of households were assigned to each display type.

Table 2: City population and population density

City	Population	Density (population per square mile)	Sample Distribution (percent)
California: San Francisco	805,235	17,179	13
Oakland	390,719	7,004	20
Berkeley	112,583	10,752	11
Davis	65,622	6,637	29
Nevada: Reno/Sparks	225,986 / 90,264	2,186 / 2,524	27

Source: Population and density, 2010 US Census

Household recruitment criteria included the requisite vehicle insurance coverage, residence in the study area, and ownership of at least one non-hybrid, post-1996 model year vehicle. All respondents were insured by a single company (CSAA Insurance Group, a AAA Insurer) who agreed to insure the households' under their existing policies and provided the initial recruiting contact through letters mailed to potential participants. The data display and recording device used in the field test plugs into the Onboard Diagnostic Port (OBD-II) required on motor vehicles in the U.S. since 1996.

The recruiting letter described the general outline of the study and included a link to an on-line recruiting survey. Following this link was the hand-off from the insurer to researchers at UC Davis. Participants were enrolled in the study from the pool of respondents to the online survey. A researcher visited each household at the start of their field test to formally enroll the participating drivers in the study and install the device in the participating vehicles. To enable proper estimation of the effect of the interface in vehicles with multiple drivers, the display was programmed to allow each driver to enter a unique identification, allowing up to three drivers per vehicle to be recorded. It was explained to drivers that for the first month the display would be blank—except to log-in who was driving—but would be recording data. It was further explained that after one month a researcher would return to the household to reprogram the device to enable the fuel economy feedback. The household would then drive for a final month with the display enabled. Lastly, they were told a researcher would return a final time to interview the participants about their experience and retrieve the device.

Sample Description

The sample of participating households is described and compared to data on other populations. The comparisons put the participants into context and, while neither confirming nor refuting the generalizability of their specific results, do confirm the plausibility that the effects reported here would manifest in other samples of drivers. This comparison will reveal some differences in the descriptions of the I-80 Eco-drive field test households and their vehicles from other samples—some of these differences may prompt questions about whether the participants in this study are more or less interested in fuel economy. However, we close this section with a comparison of the distribution of trip distances from this study to that from the 2009 NHTS: whatever their differences from other samples of drivers, the I-80 Eco-drive field test participants produce a trip distance distribution that looks like the distribution from the much larger, national NHTS sample. Further, the differences in trip distance distributions that do exist would tend to produce a conservative estimate of the effect of energy feedback to drivers on their vehicles' on-road fuel economy, as will be discussed in the results section.

The comparative data sources include the 2010 US Census, the 2009 Nationwide Household Travel Survey (NHTS), and a sample from late 2007 of households that buy new cars (Axsen & Kurani, 2008). The 2007 sample can be weighted to be representative both nationally and of the northern California region along Interstate 80. The latter is closest to that of the present study, excluding the cities of Reno and Sparks, NV. These data will be identified as "AK2007" in the figures. In general, comparative data from the NHTS 2009 sample used here excludes households who own zero vehicles, as the I-80 Eco-Drive field test households must own at least one vehicle.

Household Size and Composition

Participating households contained between one and five members. In general, household member 1 and 2 identified in Table 3 were household heads; other household members tended to be their children. Of the household members, most were employed but the sample also contains several retired persons and students. (There are large universities in all the regions.)

Table 3: Household descriptions

Household Member	Employed	Family Care Giver	Un-employed	Retired	Student	No Response
1	48	3	1	20	4	1
2	39	2	2	15	2	2
3	5	1	1	2	13	2
4	0	1	0	0	11	1
5	0	1	0	0	3	0
Total Count	92	8	4	37	33	6
Percentage	51%	4%	2%	21%	18%	3%

The proportion of women and men is nearly even: 48/52. Taking the age of the household member who responded to the invitation and comparing it to the AK2007 study and the NHTS 2009, respondents in this study are more likely to be older. The age distribution shown in Figure 1 is skewed toward older drivers compared to both the sample of new car buyers collected in northern California in 2007 (AK2007) and the national sample of households in the NHTS. Note this is true even though the NHTS data plotted in Figure 1 has been truncated to exclude people younger than age 18 because both the I-80 and AK2007 samples had an 18 year minimum age requirement to participate in the studies.

As shown in Figure 2, the distribution of the number of people per household in the I-80 Eco-drive field test is similar in overall shape of that of the total population of the US and that of the new car buying households in northern California in late 2007. Still, the I-80 Eco-drive field test has proportionally too many two-person households and too few with either fewer or more people.

Figure 1: Respondent age, years

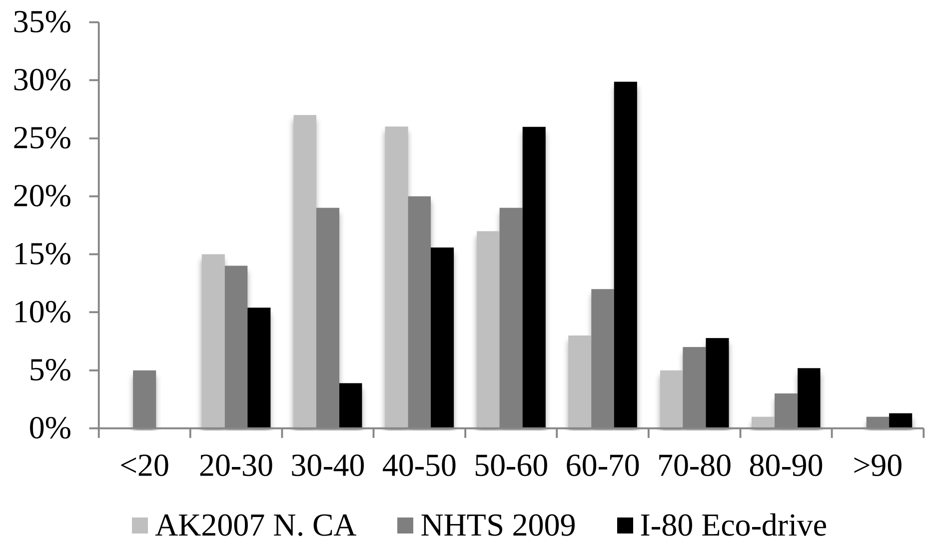
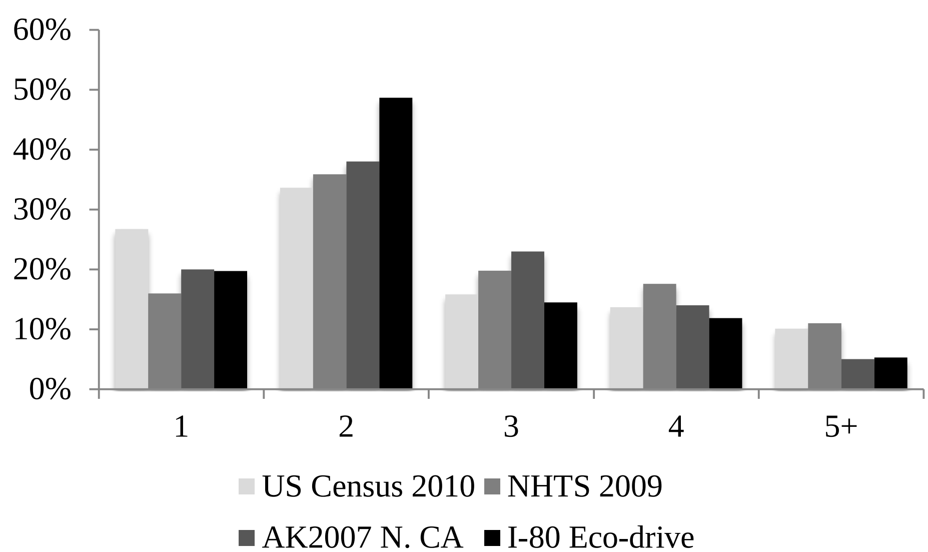
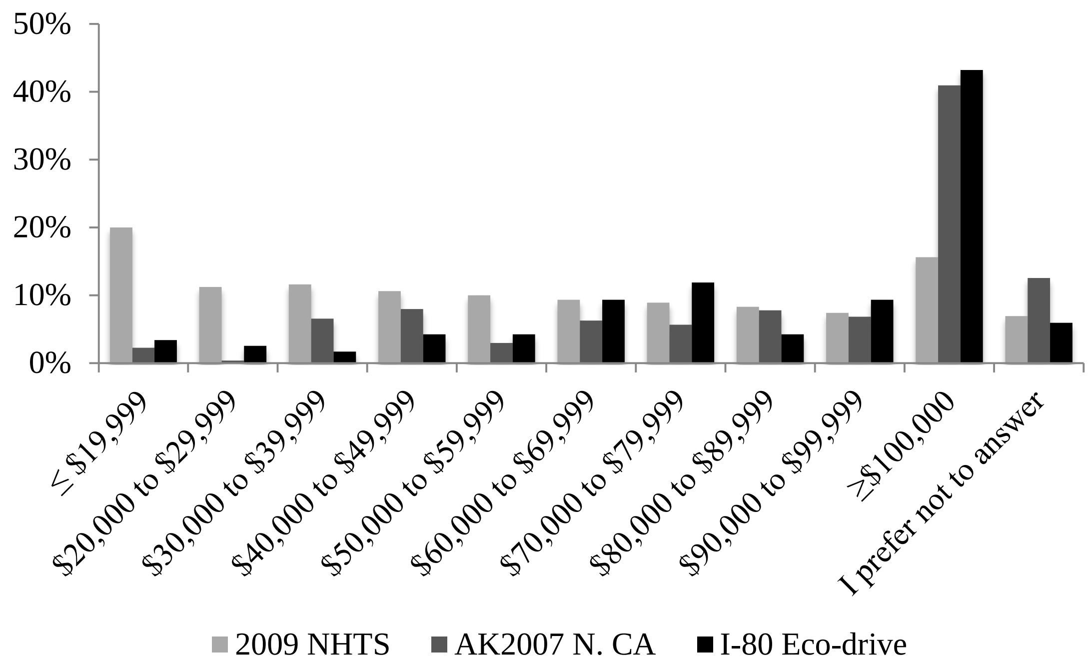


Figure 2: People per household



The data plotted in Figure 3 show the I-80 field test sample contains more high income households compared to the 2009 NHTS but is more similar to a northern California sample of new car buying households. This is not entirely unexpected given information from our insurance company partner regarding how their population of insured drivers differs from all insured drivers: older, higher household income, and owns more and newer vehicles.

Figure 3: Household income, self-reported



The distribution of the number of vehicles owned by the households in the field test differs from the prior AK2007 sample of new car buyers in northern California and the 2009 NHTS. (The latter data are truncated to omit households that own no vehicles.) As seen in Figure 4, the I-80 Eco-drive field test sample is much more likely to own one vehicle. Still, the samples have in common that they are all more likely than not to own two or more vehicles.

The distributions of our calculation of vehicle ages for up to three vehicles in the field test households and all vehicles in the NHTS 2009 sample are shown in Figure 5. Age is calculated as the model year minus one. In general, the shapes of the two distributions are similar: a broad maximum from six to eight years old. Truncating the long tail of the distribution for the oldest vehicles in the NHTS at 18 years emphasizes it by creating the spike at "≥18". We would also expect a longer tail of older vehicles if we had queried the I-80 sample for the age of all their vehicles.

Figure 4: Number of vehicles per household

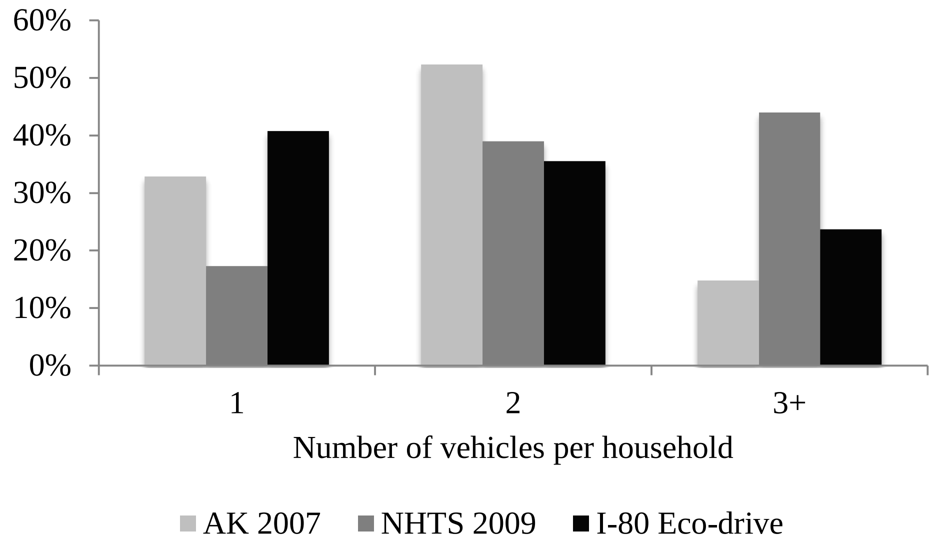


Figure 5: Age distribution of vehicles in the I-80 Eco-drive households, includes non-participating vehicles

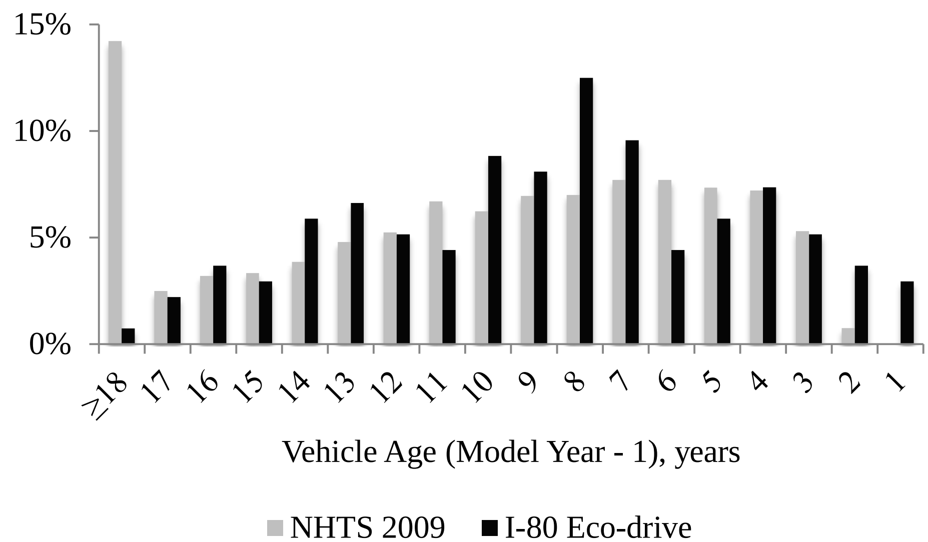
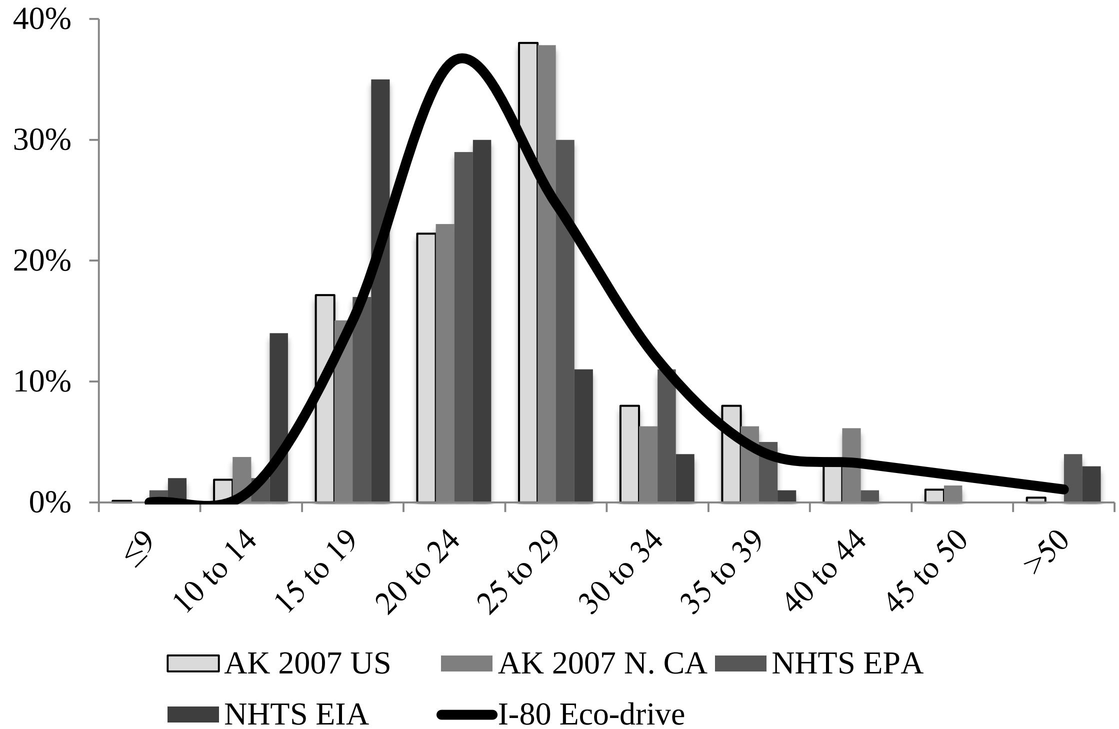


Figure 6 shows a comparison of the fuel economy of the vehicles owned by I-80 Eco-drive households to a previous sample of new car-buying households and to two different measures from the 2009 NHTS. The I-80 Eco-drive and AK2007 data are self-reported values, so ostensibly are subject to similar self-reporting biases (see Turrentine and Kurani, 2007 for a discussion of whether and how households can report the fuel economy of their vehicles). The "US" and "Northern CA" data are a bit older (circa 2007), but are from households that are new car buyers. Whatever the differences, it appears that the modal value of the distribution is the category "20 to 24" MPG for the I-80 Eco-drive sample and "25 to 29" MPG for the comparative samples. The NHTS EPA data are the (45/55 weighted) city/highway EPA values; the NHTS EIA data are estimates made by the Energy Information Administration to adjust the EPA values for on-road conditions and household travel.

Figure 6: Household vehicles' fuel economy



The I-80 Eco-drive sample is also more likely than the 2007 sample of new car buyers in northern California to have an instantaneous or average fuel economy display already incorporated into their vehicle's driver display (Figure 7). The presence or absence of such information was ascertained for only one household vehicle (the most recently purchased) in the AK2007 data; it was ascertained for up to three vehicles in the I-80 data. While less than half the AK2007 sample reported having instantaneous or average MPG data displayed in their (one) vehicle, a bit more than half did so in one vehicle in the I-80 sample. Allowing for responses for up to three vehicles, nearly two-thirds of the I-80 sample reports have a fuel economy display in at least one of their vehicles.

Annual driving distances for the vehicles owned by participating households—including vehicles not driven as part of the field test—are shown in Figure 8. The NHTS data are the BESTMILE variable from the VEHV2PUB data set. The overall patterns of the cumulative percent of total miles per household that are driven in vehicles are similar across the two data sets.

Figure 7: Household vehicles, self-reported presence of fuel economy feedback

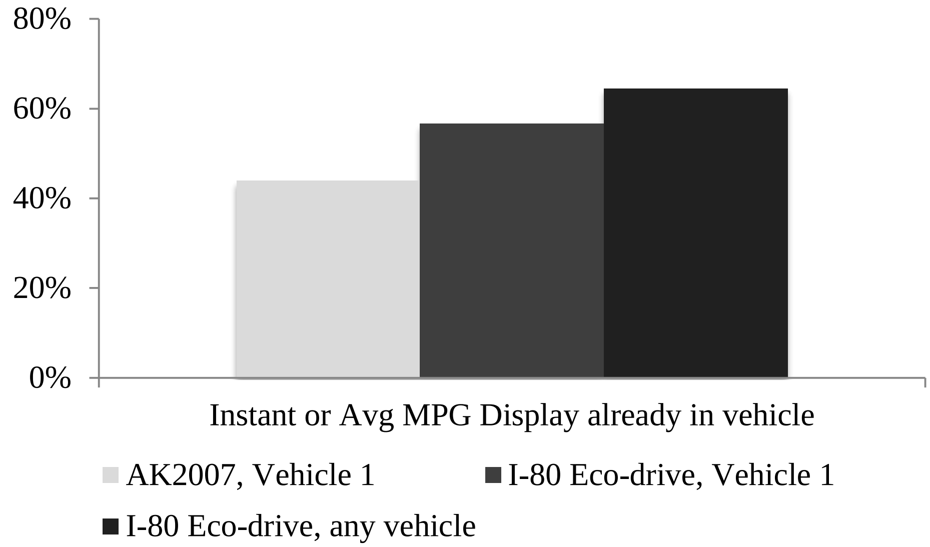
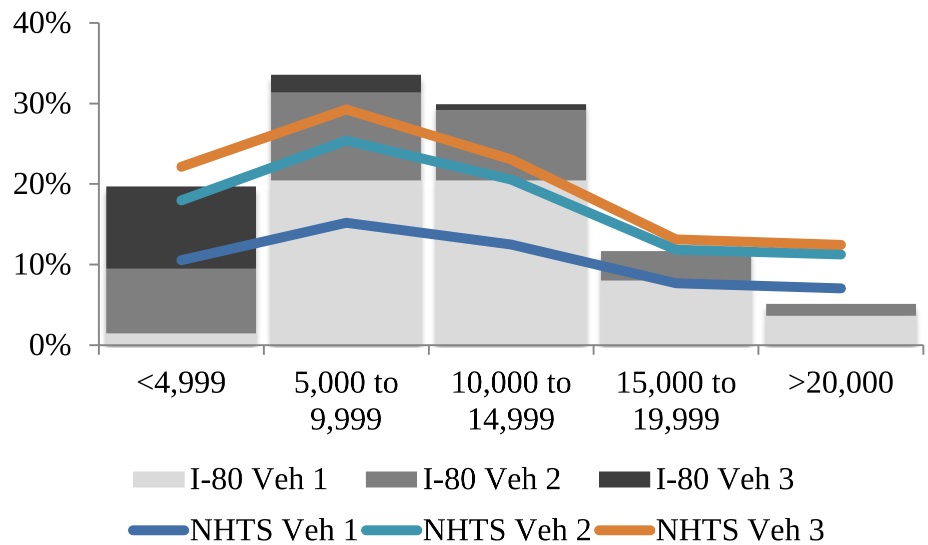
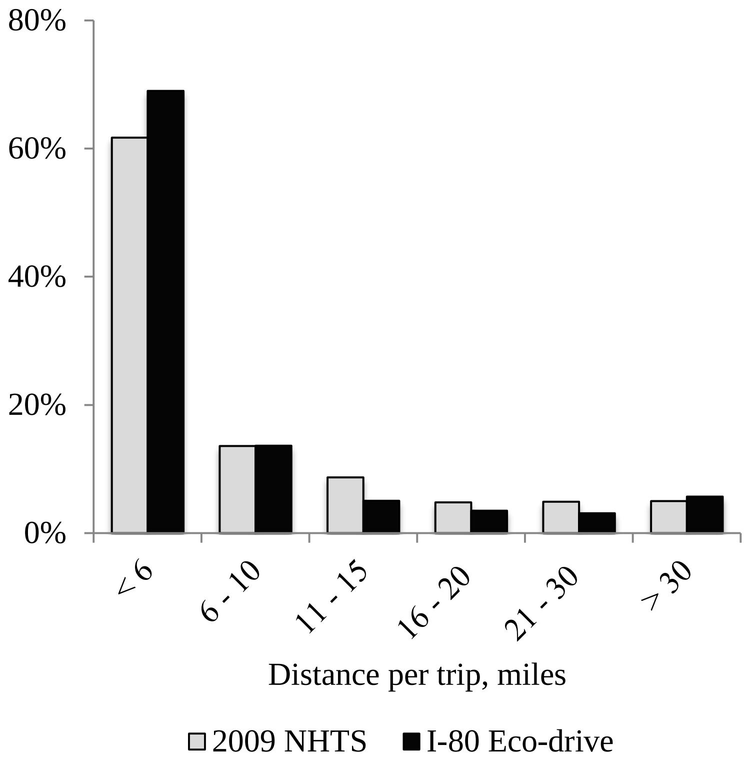


Figure 8: Annual driving distance for all vehicles in the I-80 Eco-drive households, cumulative percent



The trip data collected during the I-80 Eco-drive field test produced aggregate trip distributions that closely match the national trip distance distribution in the 2009 NHTS (Figure 9). While the two distributions are similar in shape, the over-representation of the shortest trips in the field test would tend to suppress the size of the fuel economy effect. As will be shown in the results, feedback appears to have the least effect during the shortest (as well as slowest and most stop-and-start) trips. A finer distinction in trip distances between the without feedback (phase 0) and with feedback (phase 1) data of the field test is discussed in the Results.

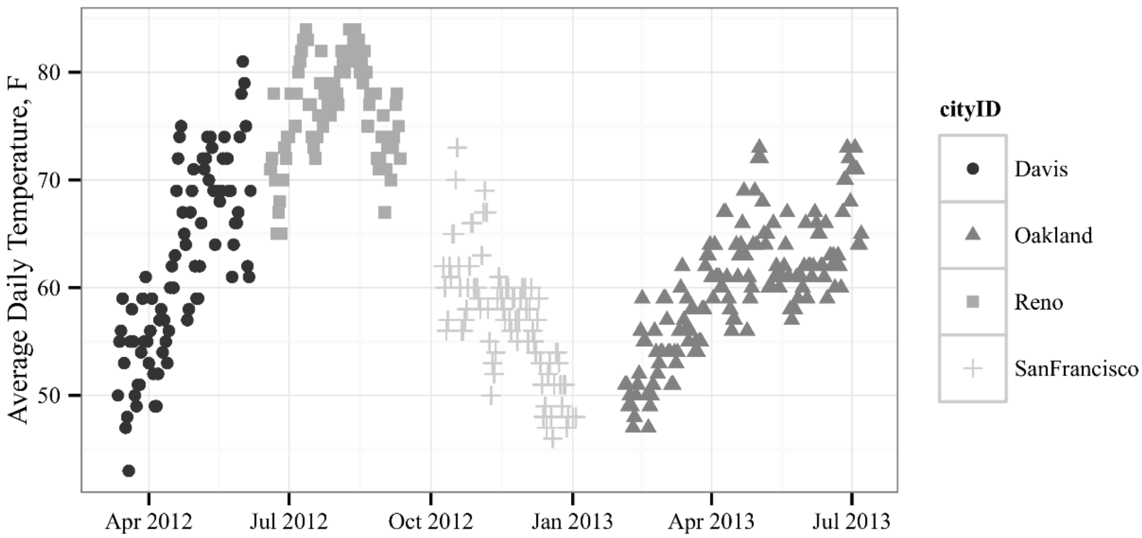
Figure 9: Comparison of trip length distribution, 2009 NHTS vs. I-80 Eco-drive Field Test



Driving context: Temperature

In addition to the land use, traffic, and travel distances we expected to encounter across the different cities chosen for the field test are other environmental factors. In addition to the very different climates of the San Francisco Bay Area, California's Central Valley and the high desert of Reno and Sparks, because the study was conducted city-by-city, there were also seasonal components to these differences in climates. One way we control for the effects of these differences on our calculations of fuel economy is to include daily temperature. The differences throughout the study period are illustrated in Figure 10.

Figure 10: Seasonal temperature fluctuations during the study



Flow of the Field Test from a Household Perspective

From the perspective an individual household, their encounter with the field test lasted for a period of a few months from initial invitation to final interview. A household would first receive a letter from their automotive insurer, CSAA Insurance Group, a AAA Insurer. The letter directed the household to a weblink to a recruiting questionnaire hosted on a UC Davis computer server. The web site provided a bit more information about the study and the on-line questionnaire ascertained information about the number, age, and type of households the vehicle owned, the number of drives, some basic socio-demographic and economic information about the household, and asked them to provide us with contact their information if they were willing to proceed. Based on these questionnaires, selected households were contacted and the first household visit scheduled.

The first household meeting involves the (repeated) explanation to the household of the entire research process and the responsibilities of the households and the researchers, formal enrollment of the household into the study, and the installation of the data recording and display device. After approximately one month, a researcher returns to the household to switch on the display. At this time the household is told how the display works and what values are being shown graphically. In addition each household is provided with an email attachment figure that explains the basic functions of their display, but no additional explanation or coaching of what they are to do in response to the screen is provided. Again after approximately one month, the final visit is made to the household. They are encouraged to complete their last on-line questionnaire if they have not already done so, the exit interview is conducted, the equipment collected from their vehicle(s), and they are provided with their incentive payment.

Three Feedback Screens

Three feedback screen designs were selected that span the range of designs tested for user comprehension and satisfaction in the 2010 NHTSA Fuel Economy Driver Interface Report (Jenness, Singer, Walrath, & Lubar, 2009). The selection of three screens from the NHTSA report's seven representative screens was based on three factors: reducing cognitive load by reducing the number of different information types shown to drivers (measured by user response time), improving comprehension (measured by a user task with a binary correct/incorrect result), and increasing user satisfaction (measured by user self-reports). The three screens were implemented in this study nearly as shown in the NHTSA report, although higher-contrast colors are used to increase visibility in the vehicle (Figure 11, a-c). The assignment of households to screen types resulted in 33% of households seeing Display 1: Numbers, 31% Display 2: Accelerator, and 36% Display 3: Shrubbery.

Figure 11a: Display 1, "numbers" feedback design (NHTSA design CS06)

Real-time MPG (1), trip average MPG (2), current value shown by a green bar chart. (A) The mean value is set to the EPA combined cycle fuel economy rating for that vehicle. (B) The current value is also shown in numeric form (C).

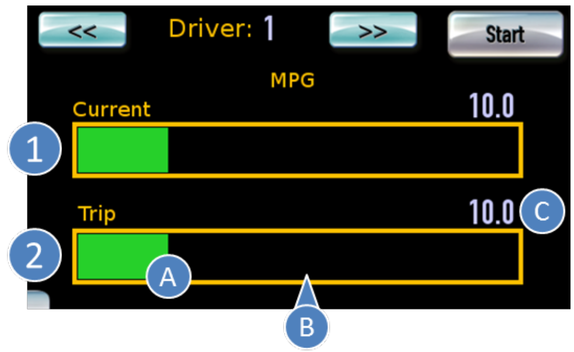


Figure 11b: Display 2, "accelerator" feedback design (NHTSA design CSO2)

Trip-level leaf representation of fuel economy (1) where the center point (A) represents the EPA combined cycle Fuel Economy Rating. Instantaneous acceleration bar (2); rightward shows acceleration and leftward shows deceleration. The acceleration bar is truncated to 0.25G in each direction.

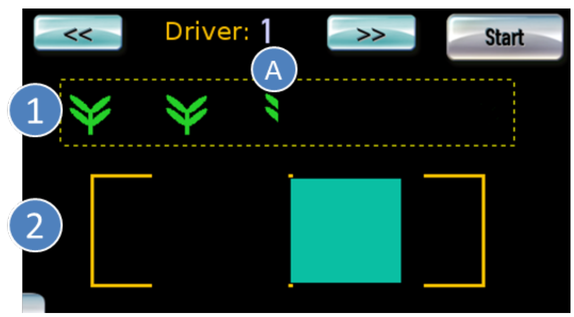
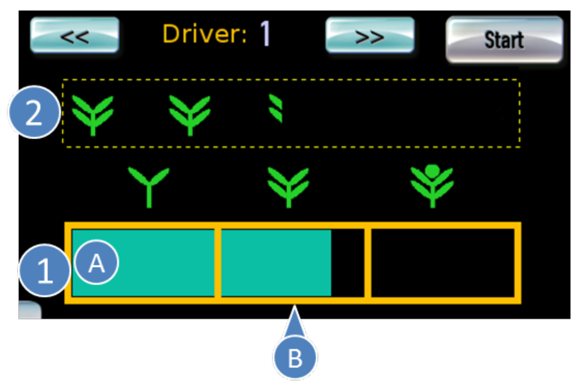


Figure 11c: Display 3, "shrubbery" feedback design (NHTSA design CSO3)

Real-time (1A) and trip-level (2) leaf representations of fuel economy. The mean value of the bars is set to the EPA combined cycle fuel economy rating for that vehicle (B).



DATA TREATMENT AND ANALYSIS

Vehicle Data for Fuel Economy Calculations

Each trip was recorded as a distinct comma separated value (CSV) file on a 4GB memory card in the DashDaq. Typically, each driver generated 500MB to 1GB of data during the 2 months of the field test; it was apparent at the visit between the without and with feedback phases that a few drivers would generate more than 4GB of data. For these drivers, their first month of data was transferred from the memory card before the start of their second month. During the initial analysis each trip file was loaded into the statistical package R to generate summary trip statistics including the vehicle and driver identification, distance, fuel consumed, ambient temperature, elevation changes, and speed statistics including mean, maximum, and variance.

A mixed effects linear regression model was fit to the data to best adjust for changing drivers, vehicles, weather, road grade, and driving patterns. The regression model includes a random-effects fuel consumption model for each driver-vehicle to account for the different intrinsic efficiency of different vehicle-driver pairs. Then the effects of temperature, wind-speed, road grade, and other basic non-behavioral factors are included as model fixed-effects along with the experimental dummy variable ("phase" 0 = without feedback, 1 = with) interacted with trip distance to provide a direct estimate of the additional gram-per-meter effect of feedback. Multiple such models are fit to the data. The first tests the average effect of feedback on fuel consumption for the entire sample. Then the same model is run on a subsample including only data from each of the three feedback designs to measure any differential efficacy related to the feedback design.

In addition to the overall and screen specific models, trips were clustered into five distinct types as described in the Trip Type section below to test for differences in effectiveness of the feedback based on the driving pattern. Finally, additional models are created to test the effectiveness of the display on both goal and demographic subgroups.

Trip Contextual vs. Behavioral Factors

The agency of drivers, i.e., their freedom to act, exists within multiple layers of structure that both facilitate and constrain their agency. The extent of fuel consumption improvements that a driver can possibly achieve through even the most willful attention to changes in driving style are shaped by driving context, especially for a given trip and vehicle. Contextual factors that structure the limits of the effects of feedback (and eco-driving more generally) include road width and number of lanes, frequency of stops, speed limits, traffic speeds, traffic levels, and other network, regulatory, enforcement, and land-use details. To determine what changes in observed on-road energy use are due to driver behavior, it is essential to use a model of fuel consumption that separates contextual structure from driver agency. As this study focuses specifically on driver behavior in the act of driving the vehicle, e.g. eco-driving, other factors such as ambient temperature and the trip drive-cycle are contextual factors exogenous to eco-driving and are therefore included as explanatory model terms to reduce unexplained variance in the dependent variable and increase the precision of the behavior change estimate.

Trip types

The K-means methodology was used to cluster trips according to drive-cycle characteristics. The four dimensions used for clustering are the trip distance, mean speed, maximum speed, and stops per kilometer. Seven trip-types were identified using K-means, although two of the groups were too small to include in the analysis and were merged with their most similar neighbors, leaving five final trip types. Table 4 shows the cluster means, totals, and trip fuel economy (not used for clustering). Trip types are illustrated in Figure 12 and cumulative trip totals in Figure 13.

Table 4: Trip type cluster centroids and group totals

	cluster means				totals			
trip-type	speed (kph)	speed (max kph)	stops per km	distance (km)	trip count	distance (km)	fuel consumed (grams)	economy (gp100m)*
1	7	14	2.3	2	6,313	14,792	1,822,524	12.3
2	12	22	0.9	7	6,251	40,795	3,817,146	9.4
3	10	22	1.6	14	1,170	16,210	1,594,624	9.8
4	17	31	0.4	18	2,783	48,846	3,814,824	7.8
5	24	34	0.1	63	1,833	115,065	8,682,897	7.5

Figure 12: Trip type cluster descriptions

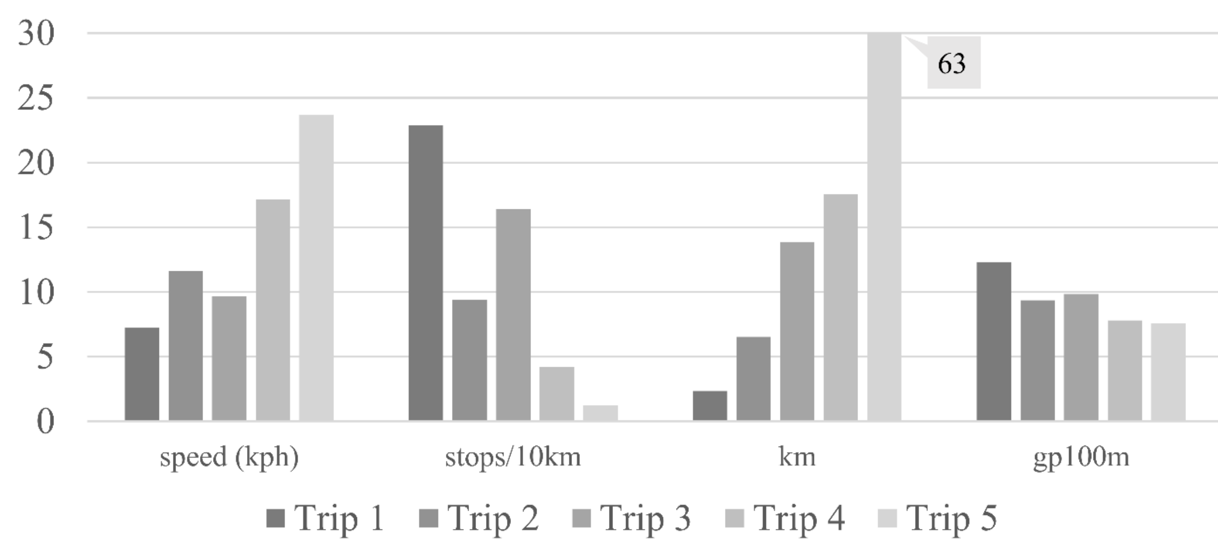
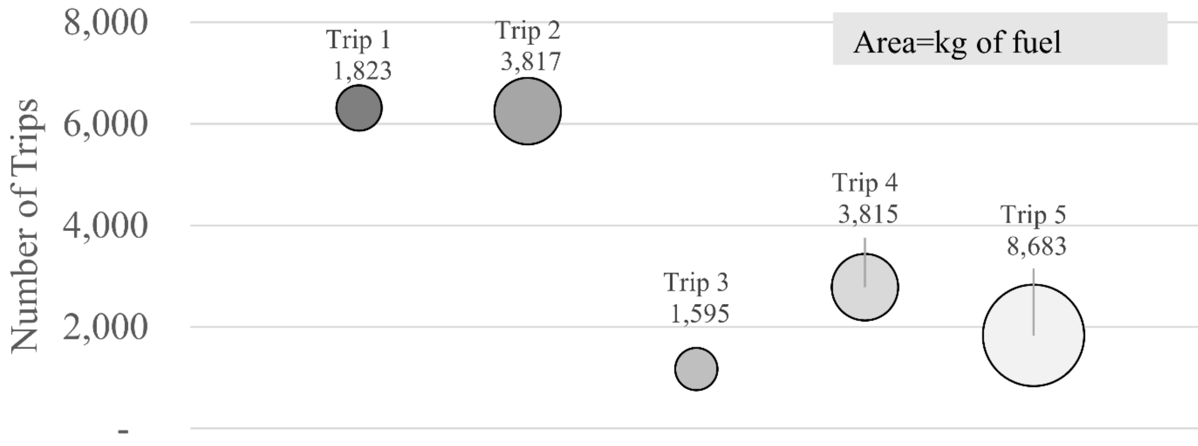


Figure 13: Cumulative miles driven and fuel consumed in each trip cluster



Analysis Methodology

Explanatory variables include daily positive and negative temperature difference from 65°F (to account for heating and cooling effects individually), trip average road grade, local wind speed, and local precipitation from NOAA historical daily weather tables, and distance traveled in the trip. A random-effects model with the same explanatory variables for each driver-vehicle pair accounts for pair-specific differences from the grand mean. This model formulation allows one model to measure the group mean change in fuel consumption from a variety of vehicles with different individual model efficiencies. To estimate the change between the pre-feedback and post-feedback periods a feedback dummy variable is interacted with distance and a variable of interest in the fixed effects portion of the model. The interaction coefficient is the group mean change in fuel consumption per meter, and can be compared directly with the group mean fuel consumption per meter.

Driver Data: Questionnaires and Interviews

Data on drivers was collected in the on-line pre-screening questionnaire used for recruiting, on-line questionnaires during their field test months, and the final exit interview. Data recorded in on-line surveys is immediately written to a database suitable for export to spreadsheet programs to manage recruiting and databases for statistical analysis.

The final interviews give households their opportunity to describe the field test from their perspective: the first prompt was, “Tell us about your experience in the study.” While the in-vehicle data is used to calculate on-road fuel economy, the interviews provide examples of their reactions to the display including both their behaviors and emotions, as well as detailed descriptions of roadways, intersections, traffic conditions, and other driving contexts. This provides an alternative perspective on who was affected by which displays and the possible durability of any fuel economy changes beyond the experimental period.

The final exit interviews were conducted entirely as open-ended discussions. These discussions were semi-structured: an outline of specific topics guided the discussion and some key prompts were provided for the researcher, but the participants were expected and encouraged to reply in their own words and at length if they chose to do so. There were no closed-form questions with pre-determined possible answers.

Interview Summaries

The vehicle data consists of second-by-second data for tens of thousands of miles of driving that are analyzed as thousands of trip segments. In short, we have a statistically precise measure of the differences in on-road fuel economy between the without-feedback and with-feedback periods for the participating households. For the interview data, we have only as many distinct data points for any question as we have respondents, thus the precision of any statistical tests of the distributions of their responses will be lower than for the on-road fuel economy estimates. Even if effects measured at the driver level are large in size (as well as statistically significant), they are best interpreted as descriptive of the sample. The value of interviewing households and analyzing those interviews is in the opportunity to more fully describe the participants and allowing them to give voice to their experience—to understand how they experience, or not, fuel economy.

The participants were interviewed during the final visit by researchers. A summary sheet for the interview was designed based on the original interview protocol and an initial reading of a subset of the interview transcripts. The summary sheet consists of closed-ended questions and text boxes or quotes from the transcript. It should be understood the researchers completed the summary sheets, not the households. In most instances any closed-ended question on the summary sheet had a corresponding open-ended question in the original interview protocol. Thus the summary data presented here are an additional interpretive product of the research, not “raw” data. To link the summaries to the drivers’, quotes from transcripts are used to elaborate the discussion here.

Interview Thematic Analysis

Additionally, the interview transcripts are analyzed through a process of defining themes, i.e., substantive topics of conversation across interviews. The researchers created the themes in several steps. The first step was the design of the research project and the definition of the research questions. The second follows from the first in the design of the interview protocol. The decisions about when within the flow of the field test to hold these conversations with households and the questions included in the protocol shaped the themes that could possibly be created. The third step was to conduct the interviews. The fourth was the researchers’ iterative reading of the interview transcripts.

From a first reading of a subset of the transcripts, an initial list of themes was produced by each of four researchers; these four were reconciled into a new list. In some instances similar sounding ideas are distinguished as separate themes. For example, while either of the themes of *personal control over fuel economy* and *situations in which it is good or bad to use fuel economy feedback* could contain the theme *affect of traffic pressure*, the three are distinguished by these three ideas: personal control is a statement about the participant themselves, situations describe driving contexts, and traffic pressure is an elaboration of specific driving contexts that limit control a driver can exert over on-road fuel economy. Within a theme more specific meanings were specified. For example, within the theme of personal control over on-road fuel economy, some respondents believe they do have control, some believe they don't. Within each of these, there may be more specific reasons why a person believes they can or cannot exert control.

RESULTS: ESTIMATION OF ON-ROAD FUEL ECONOMY

The quantitative analyses are broadly categorized at three analytical scales. This section will start with the broadest, most aggregate outcomes, move toward more specific trip-based models and outcome driving behaviors, and finally present driver-oriented models of goals and demographic factors.

In the simplest sense, less total fuel was used and less total distance was driven in the feedback phase than in the baseline (without feedback) phase (Table 5), but this is due primarily to there being fewer total subject-days in the feedback phase period. There was a slight increase in driving intensity (km per day) but an overall slight decrease in consumption intensity (fuel consumed per day) due to an increase in efficiency between the two periods.

These simple measures of fuel use and miles aren't an answer to our first question: can we detect evidence for an effect on real-world, on-road fuel economy attributable to fuel economy instrumentation? This is because of changing road conditions, changes in the mix of miles by driver, and changes in the patter of trips taken over time. To answer that first question we move toward more specific, individual-level analysis. The total effects in Table 5 were tested using a paired t-test of person-level aggregates (using a sum or mean per experimental phase per person). The average trip length increased, but changes in other summary factors shown in Table 5 were not statistically significant different on the individual level between experimental phases.

Table 5: Study driving summary

Experimental Phase	Total km Driven	Gas Consumed (grams)	gp100m (grams per 100-meters)	Average Trip Distance (km)	Study Days	km/day	grams/day
Baseline	121,719	10,377,762	8.5	12.2	2,401	51	4322
Feedback on	113,990	9,354,253	8.2	13.5	2,187	52	4277

Table 6: Display-specific driving summaries

Display Group	Experimental Phase	Total km Driven	Gas Consumed (grams)	gp100m (grams per 100-meters)	Average Trip Distance (km)	Study Days	km/day	grams/day
g1	Baseline	46,674	4,066,198	8.7	13.1	951	49	4,276
g1	Feedback on	43,084	3,795,504	8.8	15.2	806	53	4,709
g2	Baseline	42,286	3,875,035	9.2	12.6	789	54	4,911
g2	Feedback on	31,975	2,678,016	8.4	11.4	733	44	3,654
g3	Baseline	33,807	2,514,820	7.4	10.9	711	48	3,537
g3	Feedback on	43,565	3,170,962	7.3	14.0	701	62	4,523

As for on-road fuel consumption based on an analysis of all trips, the overall (full sample) model results shown in Table 7 finds a statistically significant ($p < 0.0001$) decrease in fuel consumption (grams per meter) after the introduction of feedback. This is our first evidence of existence—both for overall effects and for difference in effects between different feedback designs, i.e., our second research question. The overall and design specific results shown in Table 7 indicate that there was a statistically significant ($p < 0.05$) reduction of 2.7% in fuel consumption over all drivers when controlling for road grade and weather effects. All three feedback displays also are associated with statistically significant reductions. Though the difference between feedback types appears dramatic, e.g., Group 3 who saw the "shrubbery" display (Figure 11c) averaged nearly twice the improvement of Group 2 who saw the "accelerator" display (Figure 11b), the confidence intervals of the groups overlap, so no firm conclusions about differential efficacy should be drawn.

Table 7: Basic display efficacy results

	grams/meter (phase 0)	delta grams/meter	delta grams/meter	95% confidence interval high	95% confidence interval low
overall	0.06698	-0.00181	**-2.7%***	-3.4%	-2.0%
g1	0.0694	-0.00187	**-2.7%**	-4.1%	-1.3%
g2	0.06904	-0.00113	**-1.6%**	-2.8%	-0.5%
g3	0.06364	-0.00186	**-2.9%**	-3.8%	-2.1%

Note: g1 = Numbers display; g2 = Accelerator; g3 = Shrubbery
*Negative values indicate that fuel was saved in the feedback period, i.e. the feedback was successful.
Italics indicate confidence at the $p < 0.1$ level, and **bold** indicates $p < 0.05$.

One additional adjustment to understand the impact of feedback on driving behavior specifically (as opposed to fuel consumption) is required. As seen in Figure 16, the quantities of driving varied markedly by experimental phase. This is potentially important because the efficacy of feedback varies by trip type, as shown in Table 8 and Figure 17. The table shows that only in the longest, freeway trips (trip type 5) were the three feedback displays similarly effective. In other trip types the results were specific to each display, with particularly dramatic improvements for group 1 in trip type 3, and as equally dramatic *reduction* in efficiency for group 2 (the accelerator display) in trip type 1 (the shortest, slowest trips with the most stops).

Thus, the trip type distributions changed between both phases and feedback groups. To control for these changes and make an apples-to-apples estimation of feedback efficacy for on-road efficiency, each group's overall impacts are estimated by creating a weighted average of trip-type impacts using the overall population average trip distribution as the weighting factor. This methodology normalizes all impacts to replicate a scenario in which each driver completed an identical proportion of trips in each type in both phases. As shown in the estimated impact row of Table 8 the re-weighting has two effects. The first is that the estimate of overall efficacy is reduced from 2.7% to 2.2%, indicating that part of the prior estimate was due to a shift in trip types. The second effect is that the differential efficacy of each display is accentuated, with the numbers screen (group 1) mean effect now estimated to be 3.5%, the shrubbery screen (group 3) 2%, and the accelerator screen (group 2) at a nearly null 0.3%.

Figure 16: Comparison of trip length distribution, before and after the feedback was introduced

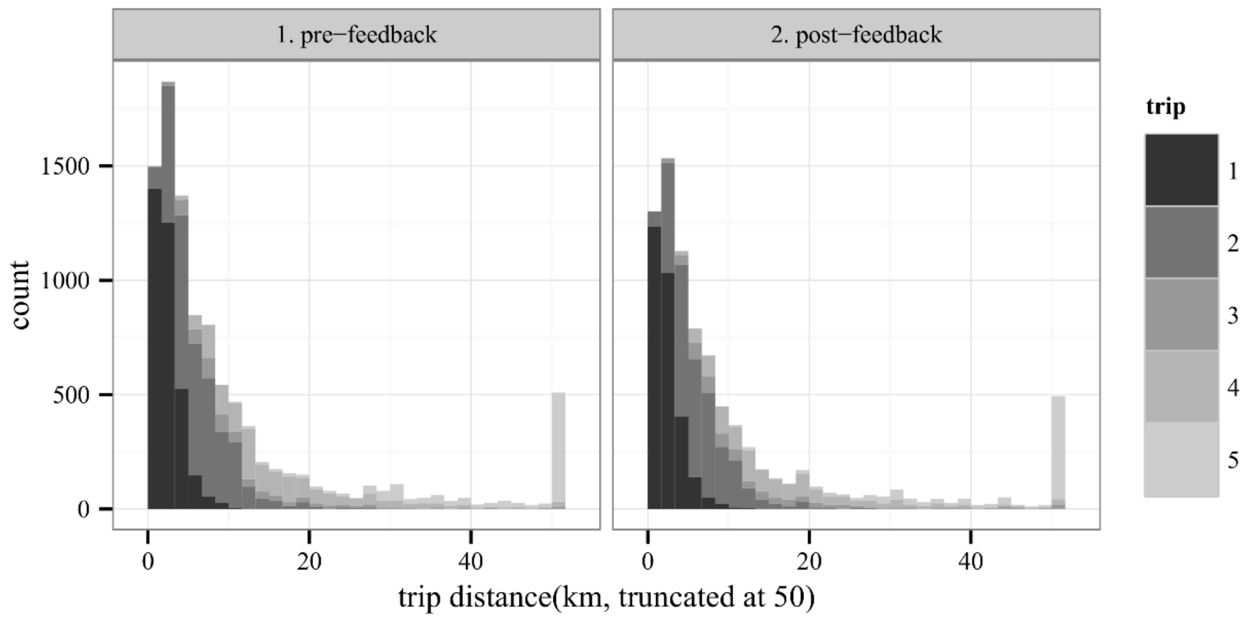
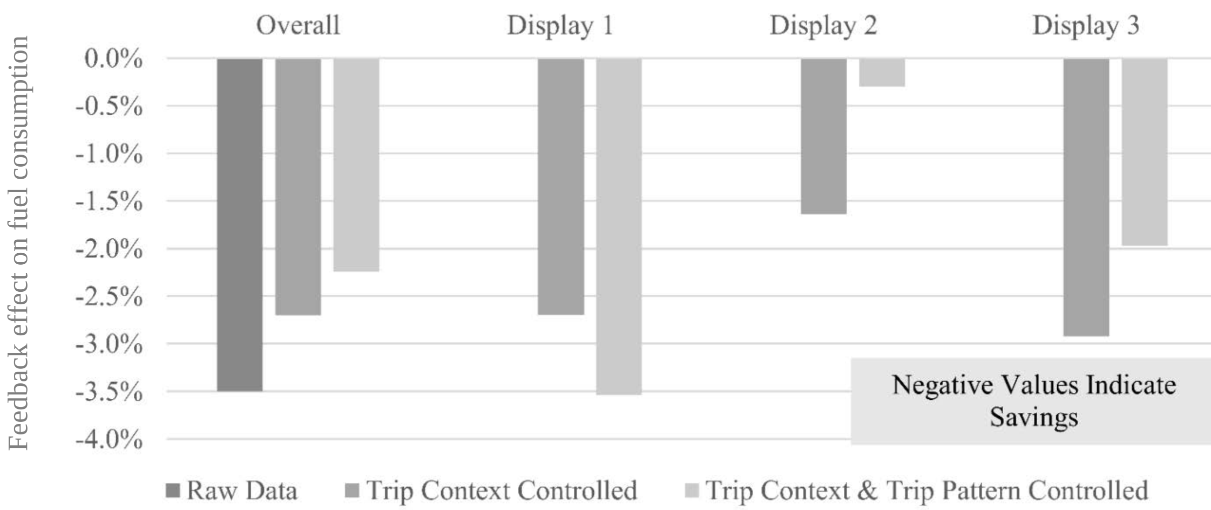


Table 8: Results by trip-type and constant-trip pattern estimate

	Overall	g1 (Numbers)	g2 (Accelerator)	g3 (Shrubbery)
Trip 1	0%	-11%	**10%**	0%
Trip 2	1%	1%	2%	0%
Trip 3	**-9%**	**-18%**	1%	-2%
Trip 4	-1%	**-3%**	0%	1%
Trip 5	**-3%**	**-2%**	**-3%**	**-4%**
Estimated impact	**-2.2%**	**-3.5%**	**-0.3%**	**-2.0%**

Note: *italics* indicate confidence at the p < 0.1 level, and **bold** indicates p < 0.05. Negative values indicate savings.

Figure 17: Results summary including both trip context and trip pattern controls



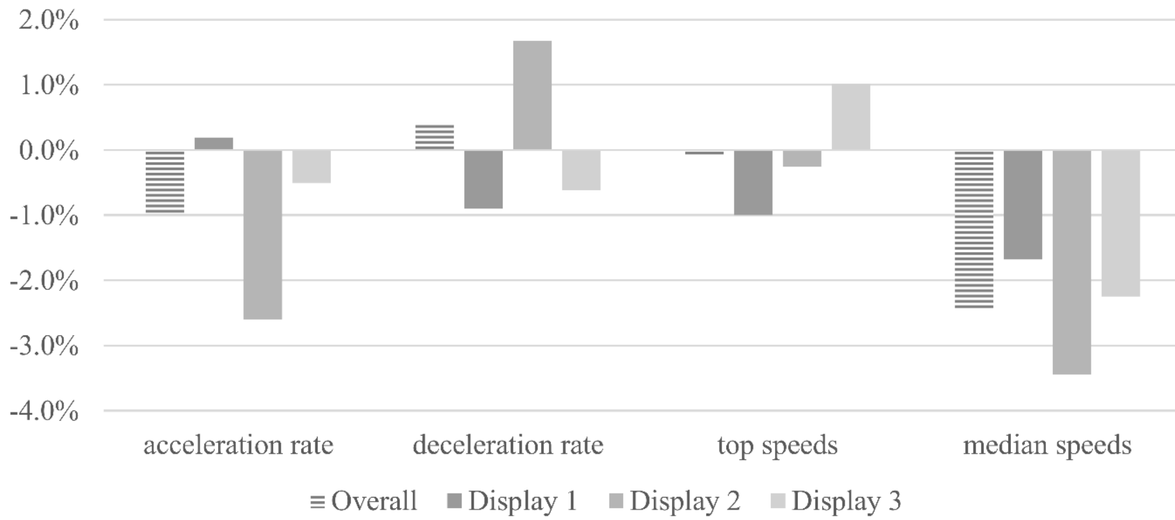
The causal factors that underlie these display-group specific results are summarized in Table 9. In this analysis a new series of regression models were built to test the hypothesis that driver behaviors that affect trip-level average acceleration rate, deceleration rate, top speed, or median speeds may have changed between the without and with feedback phases. In each model the behavior is the outcome variable and a dummy variable for experimental phase indicates the magnitude and statistical significance of the effect. As shown in Table 9 and Figure 18 the only consistent behavior change across feedback designs, i.e., groups, was a reduction in median speed. The shrubbery group (3) showed a decrease in deceleration rate, but the largest changes were in the accelerator group (2), which showed both a statistically significant decrease in acceleration rate and an *increase* in deceleration rate (harder braking).

Table 9: Behavioral impacts

	Overall	g1 (Numbers)	g2 (Accelerator)	g3 (Shrubbery)
Acceleration rate	**-1.0%**	0.2%	**-2.6%**	-0.5%
Deceleration rate	0.4%	-0.9%	**1.7%**	***-0.6%***
Top speeds	-0.1%	-1.0%	-0.3%	1.0%
Median speeds	**-2.4%**	-1.7%	**-3.4%**	**-2.2%**

Note: *italics* indicate confidence at the p < 0.1 level, and **bold** indicates p < 0.05. Negative values indicate savings.

Figure 18: Behavioral impacts of the three displays



RESULTS: THE INFLUENCE OF ATTITUDES AND DEMOGRAPHIC FACTORS

Thus far the analysis has focused on the full sample results broken into display groups. However, there may be important differences between drivers that make them more or less motivated or capable to make driving behavior changes in response to feedback. In this section both differences in drivers' goals as well as demographic descriptors are investigated as additional sources of variation in response.

To assess drivers' relevant attitudes each participant was asked to choose and rate up to three goals in declining order of importance. The ratings of each driver's first selected goals are shown in Figure 19. The question was asked after enrollment in the study but before the driver saw any fuel economy feedback. The goal options included: No Response, Drive Less Overall, Drive More Safely, Reduce CO_2, Get Around Faster, Save Gas, and Save Money. As shown in Figure 19 the most frequent responses were Get Around Faster and Save Money, but there was a broad distribution of responses with no response receiving less than 10% or more than 25%.

Figure 19: Participant driving goals stated before viewing feedback

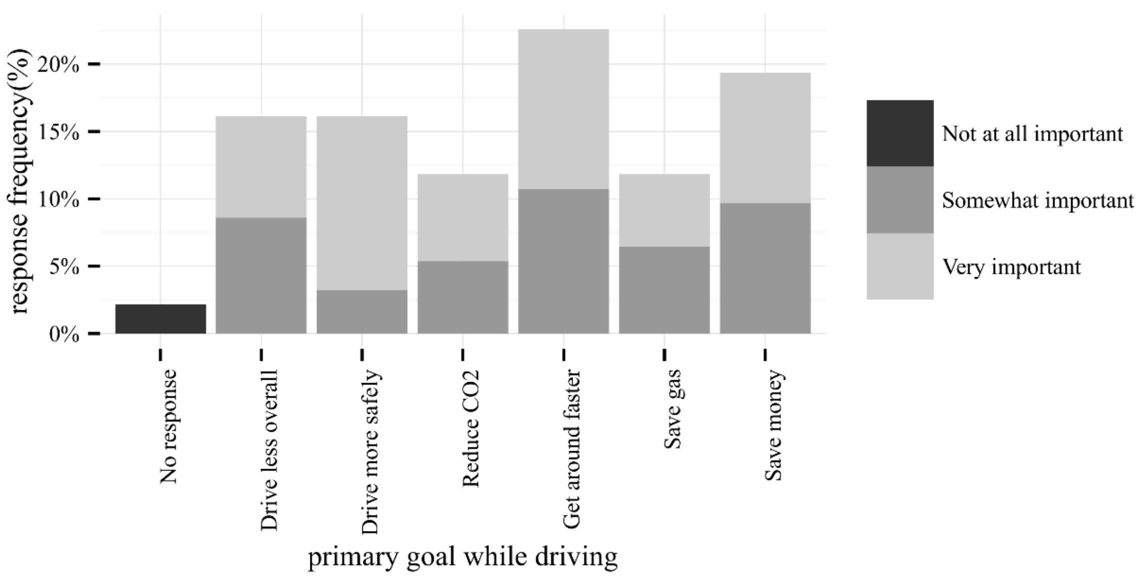
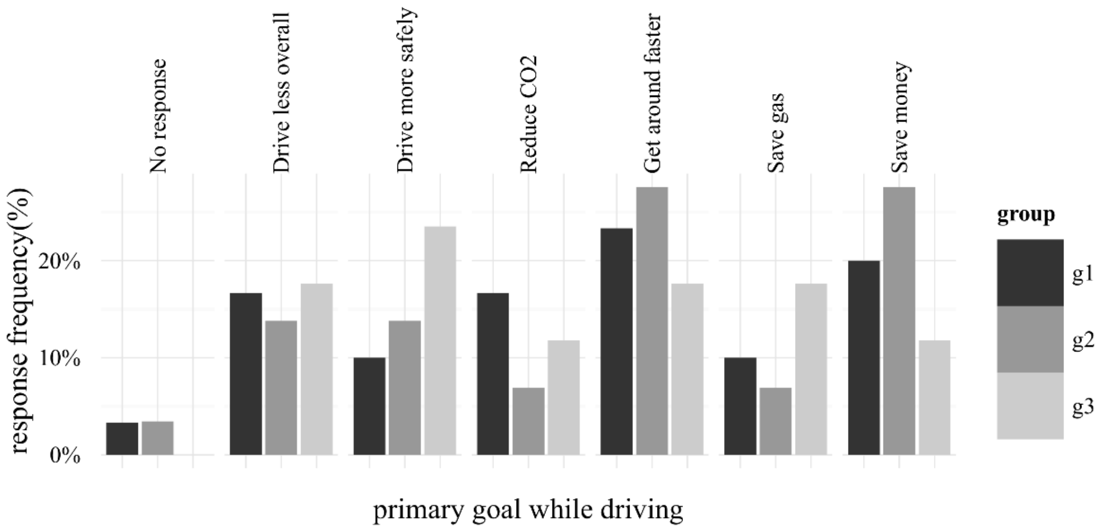


Figure 20 shows the response distribution broken out by display group, showing some differences in the goals of the groups, which could explain some of the variation in display efficacy. However, a Pearson's Chi-Squared test of the responses shown in Figure 20 indicates that, as expected due to the randomized nature of the group assignment, the observed differences in the response distributions between display groups are not statistically significant (p=0.29).

Figure 20: Participant driving goals by display type



The behavioral models discussed in the introduction suggest that when information is aligned with attitudes and goals, behavior change potential is increased. This suggests that people with different goals are likely to respond differently to different information content (such as display 2) or abstract, symbolic values (such as display 3). To test for these differences the sample was split into goal-oriented groups and the effect in each display group was calculated using the same methodology used for the full-sample results presented above. The goal-specific results are presented in Table 10. In general, drivers with the goals to Travel Faster, Save Gas, and Save Money reduced their fuel consumption regardless of which display type they saw. Neither Display 1 (Numbers) nor 2 (Accelerator) produced fuel savings that can be concluded are different form zero for drivers whose goal was to Drive Less, Drive Safely, or Reduce CO2.

Table 10: Display efficacy by stated goal

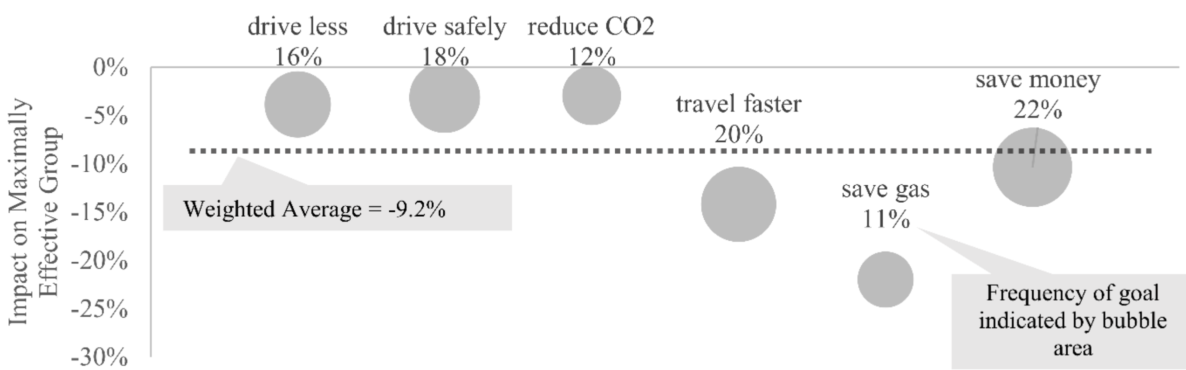
Primary Goal When Driving	Change in Fuel Consumption (%)			
	Overall	Display1	Display2	Display3
Drive less	-1.3%	0.7%	-2.9%	**-3.9%**
Drive safely	-1.1%	*-3.1%*	**8.9%**	**-2.7%**
Reduce CO2	-0.5%	0.9%	0.5%	**-3.0%**
Travel faster	**-3.6%**	**-14.2%**	**-3.4%**	**5.7%**
Save gas	**-9.3%**	*-3.5%*	**-22.0%**	**-6.0%**
Save money	**-3.6%**	**-10.4%**	**2.0%**	**-5.5%**

Note: *italics* indicate confidence at the p < 0.1 level, and **bold** indicates p < 0.05.
Negative values indicate savings.

The goal-specific results suggest two important outcomes. First, with the right motivation matched to the right feedback design drivers can save dramatically more fuel than suggested by the average results. On average, drivers with a goal to Save Gas achieved a 9% reduction in fuel consumption, regardless of display type. On average and controlling for changes in trip types, we estimated a 1% reduction in fuel consumption for Display 2, but cannot conclude that this effect is in fact zero. However, drivers whose goal was Save Gas who saw Display 2 achieved the largest reduction (22%). Conversely then, mismatches between driver goals and feedback design can produce much worse outcomes than average. Drivers with a goal to Drive Safely who saw Display 2 had 9% worse fuel consumption.

Second, different displays may be optimal for drivers with different goals, i.e., there may not be a single best feedback design, but different designs that are best for drivers with different driving goals. Taking this hypothesis further, we estimate the outcome of the field test *as if* each driver had seen the most effective feedback style for his or her goal. The best display for each goal is shown in Figure 21 along with the frequency that each goal was expressed in our sample. The efficacy estimate is therefore the weighted average of the most effective screen for each goal weighted by the size of the group. This efficacy estimate, as shown in Figure 21 is 9.2%.

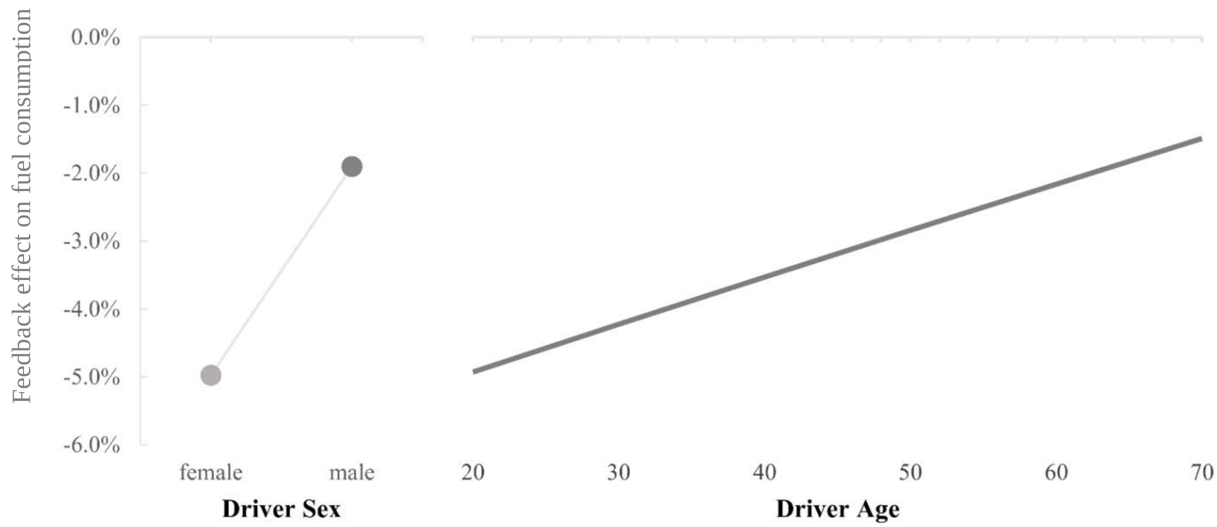
Figure 21: Hypothetical best improvement in the presence of specific goal-oriented feedback



Note: Negative values on the y-axis indicate savings

In addition to driver goals, more traditional demographic factors could play a role in driver response to feedback. We tested income, sex, and age in relation to the magnitude of behavior change after the introduction of feedback. We found that income had no statistically significant relationship to fuel consumption changes, but that both sex and age did ($p < 0.05$) as shown in Figure 22. Females averaged more than twice the efficiency improvement (5%) as males (1.9%). The effect of age varied over a very similar range as did the effect of sex. Older drivers reduced fuel consumption least; each decade less of driver age was associated with about 0.75 percentage point increased improvement.

Figure 22: Effect of sex and age on overall efficacy of the displays



Note: Negative values on the y-axis indicate savings

RESULTS: INTERVIEW SUMMARIES AND THEMATIC ANALYSIS

Finally, we take on our third research question: how do participants experience fuel economy, or more accurately, talk about the experience? We start by summarizing responses to more specific questions across the interviews. The interview summary presented here is organized to present a general temporal flow from before the participant was enrolled in the study, through their experience in the field test, and on to whether they have formed an opinion about fuel economy feedback for future vehicles.

Was achieving high fuel economy a goal of your driving prior to the study? Why?

Participants were asked about their driving prior to their participation in the study; one of the questions was whether achieving high fuel economy was already a goal for them. This is a leading question for volunteer participants in a study of fuel economy; the high percentage (81%) saying "yes" cannot be regarded as representative of all drivers or even otherwise similar drivers living in the study cities. Still, nearly one-in-five said high fuel economy was not a prior goal, assuring some variability within the sample. Further, even among those who say high fuel economy was a prior goal, their stated motivations are varied. As shown in Figure 23, a third of those who say high fuel economy was a goal for their driving don't articulate a specific reason why; a similar number says it is to save money. Environmental reasons are offered by 14%, but most of this is stated in general terms: only 4% claim that climate change specifically was their motivation. Similar numbers of participants state their motivations are energy security and conservation as state environmental motivations.

Do you already have a fuel economy (MPG) display in your car?

As illustrated in Figure 24, about one-fourth of the participants reported their car does not already have a fuel economy display. Another fourth report their car does have such a display, but they don't use it. The remaining half both has a fuel economy display and they use it.

A contingency analysis of whether participants already had an MPG display in their car by whether increasing their on-road fuel economy was already a goal suggests there may be a relationship between the two. The mosaic plot in Figure 25 shows that those who both already had an MPG display in their car and say they use it were much more likely to report that high fuel economy was already a goal for their driving. Those who report they already had a fuel economy display but did not use it, appear to be serious about not using it—they are the least likely to report that high fuel economy was already a goal for their driving. However, the apparent relationship must be regarded as suggestive, not conclusive. We don't report the statistical tests of the relationship because too many sparse cells in the cross-classification may be the cause of the large chi-square values, i.e., an apparently statistically significant difference between the two groups.

Figure 23: Motivation for achieving high fuel economy, percent of those who say high fuel economy was a prior goal of their driving

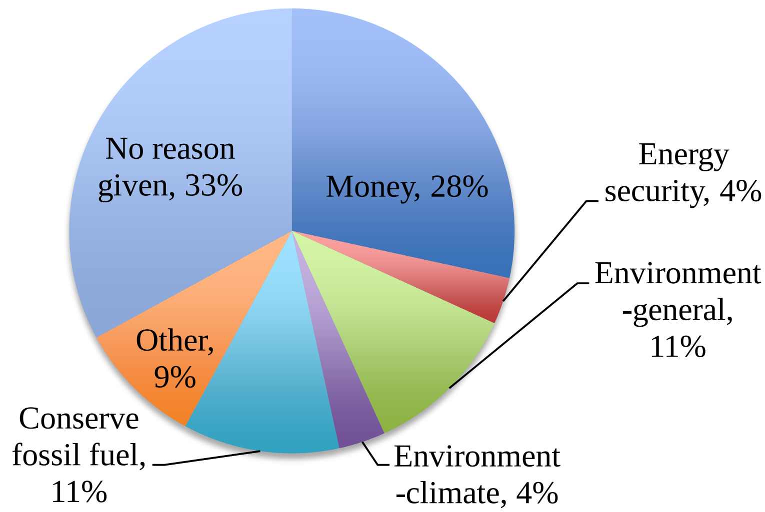


Figure 24: Fuel economy displays already in their car, percent

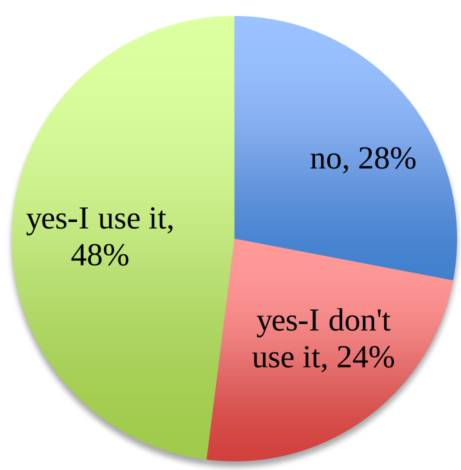
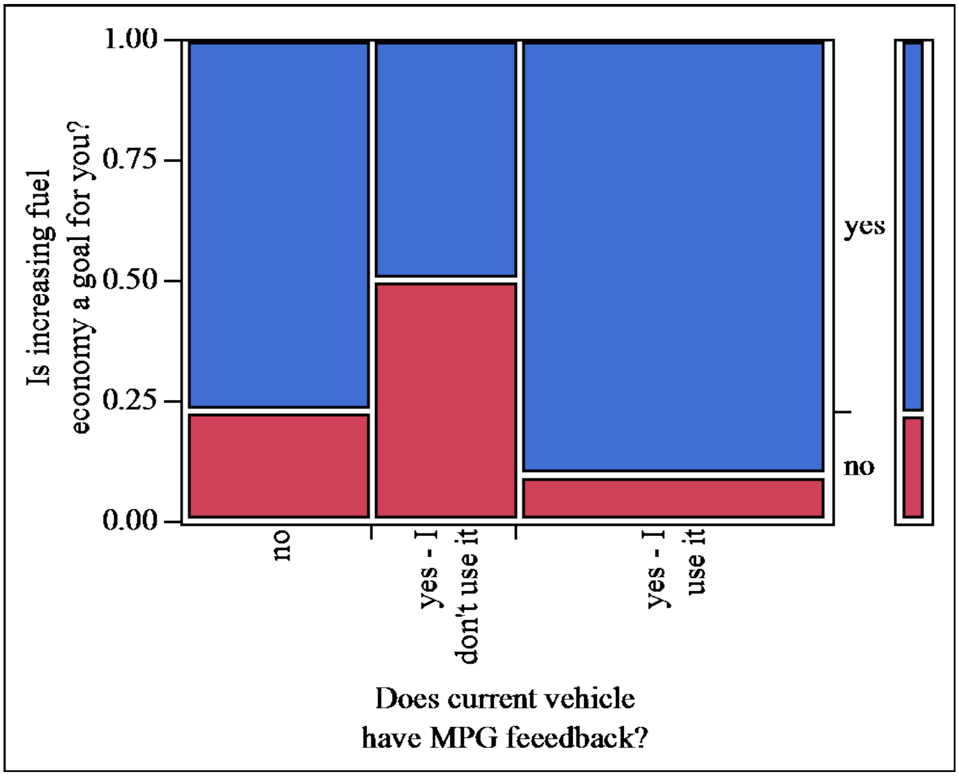


Figure 25: Mosaic plot of prior goal of high fuel economy by prior presence of fuel economy display in their vehicle



What can any driver do to increase fuel economy? What did this driver do prior to field test? What do they do now?

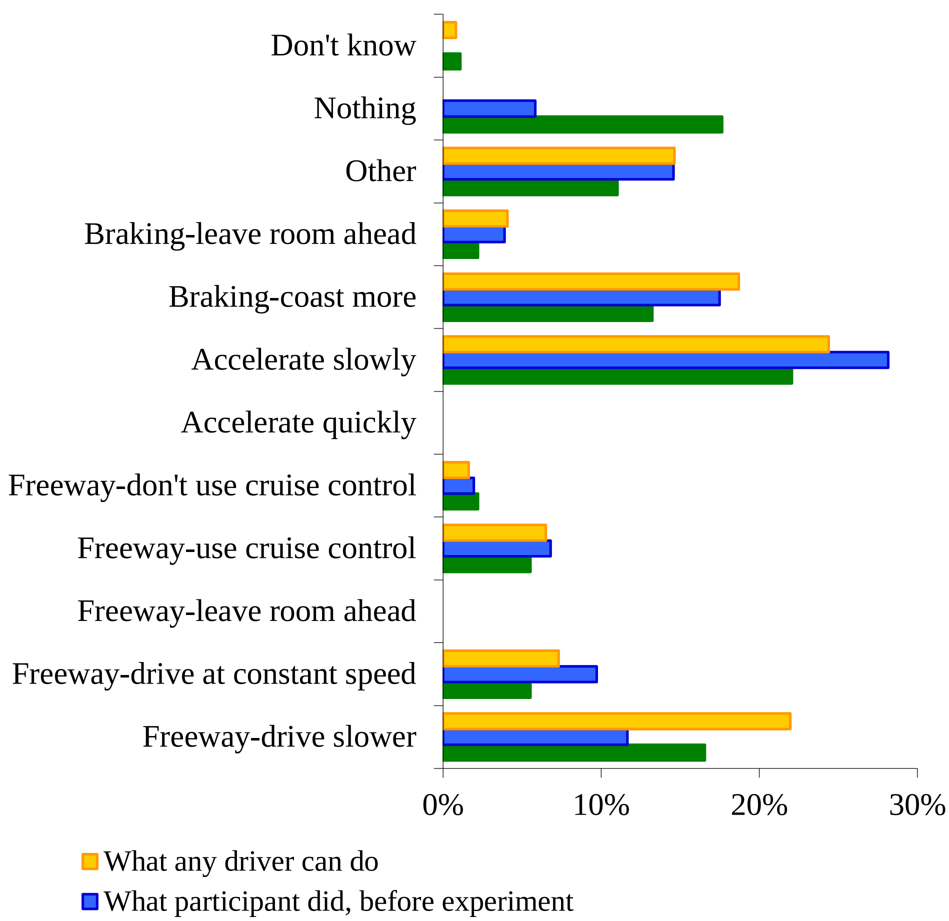
Whether or not it was a goal for their driving prior to the field test, we wanted to know what drivers think can be done to increase on-road fuel economy. We asked this question three different ways. First, what did the participants think any driver could do to increase fuel economy while driving? Second, what things did they do prior to the field test? Third, as a consequence of their participation, what new things did they try or what things they were already doing do they do more? Our expectations of the first two versions of the question are that they are two different ways of prompting them to think about the possibilities rather than a strict logical sequence. If the questions were a strict logical sequence then no single answer could have a higher number of responses for the second version ("what do you do?") than for the first ("what can anyone do?")[1] Taken as part of a conversation, some respondents may follow this logic. However, for others the second question may simply prompt recall of more ways to increase fuel economy because the respondent moves from thinking fuel economy in the abstract (anyone's driving) to more concrete (their driving).

[1] No single action that can be taken to improve fuel economy can have a higher number of responses for the "you" vs. "anyone" versions of the question. However, the responses "don't know," "other," and "nothing" can.

Despite our phrasing of all three versions of this question around the specifics of driving, respondents often also—or only—offered non-driving behaviors, e.g., trip planning behaviors such as trip chaining, mode switching, and buying a more efficient, a hybrid, or an electric car. We separate driving responses from all these others, and focus on the in-vehicle driving behaviors here.

Answers to all three versions of the question are summarized in Figure 26. Example quotes from some of the categories are in the side bar. The researchers created the response categories based on their reading of the interview transcripts. The categories are grouped according to freeway driving and other driving. Additional evidence of the differences in the perceptions of the amount of control a driver can exercise on fuel economy in freeway vs. city driving clearly indicates that respondents believe they are far more constrained in how much difference they can make in city driving. While nine-of-ten participants believed they could have some effect on highway fuel economy, only about six-of ten said they could affect city fuel economy.

Figure 26: Driver actions to increase on-road fuel economy



The three most frequently mentioned things any driver can do while driving to improve fuel economy were 1) accelerate more slowly in general, 2) drive slower on the freeway), and 3) coast more, especially to stops. In describing their own actions, participants most frequently stated they 1) accelerate more slowly in general, 2) coast more, especially to stops, and 3) drive a constant speed on the freeway.

For both these questions, "frequent" is only relative to other responses, not across the sample. Few participants name more than two things any driver can do or they do to improve on-road fuel economy. This is reinforced by Figure 27; the data are created by taking all the unique actions each driver names in response to what "any driver can do" plus what they themselves do, i.e., it is the most inclusive list of actions drivers know to take to improve on-road fuel economy. Looked at differently, the range of actions participants name is from zero to six; the median is two.

The third question asks what did participants start to do for the first time and what things—that they might already have been doing to increase their fuel economy—did they do more in response to the feedback provided them in the field test. Thus, fewer drivers are not practicing "accelerating slowly" after the field test than before. Rather, a smaller percentage of participants claim to have tried moderating their accelerations or increased their efforts to moderate their accelerations in response to the field test than claimed to already be doing so. The most frequent new or increased behavior—though claimed by only about a fifth of drivers—was driving slower on the freeway. Similar percentages made a claim to accelerating more slowly. A similar percentage claimed the feedback prompted no new or increased fuel saving behaviors.

What can a driver do?

"Keep your foot right on the pedal. I mean accelerate more slowly, coast instead of brake whenever that opportunity presents itself. Obviously you gotta use your brakes sometimes, but yeah. I say cruise control or coast and just stay on the gas pedal, that helps the most."

"Getting to my cruising speed as quickly as possible and getting there and then cruising was giving me better mileage."

"I just think by being safe and not being a very excited driver—accelerating too quickly, braking too quickly…Being a mellow driver. That doesn't mean driving too slow or too fast but just easing into it and not just going straight for it."

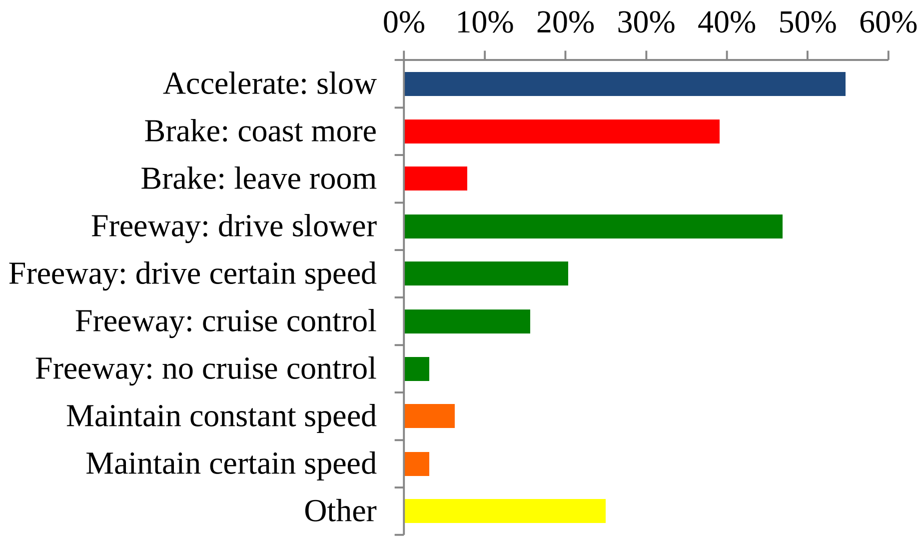
"Maybe the only thing you can do is on long trips don't go as fast as you're allowed to."

"Basically you can imagine if you only go 60 or 65 you would be saving gas. By and large, 45 mph tends to give you the best mileage."

"Except I can tell you that she uses more gas than I do because when there's a red light coming up, she keeps her foot on the gas until pretty close to the [light] and then she brakes. Whereas I take my foot off as it gets close to the stop and only brake at the last moment."

"I don't like driving, so if I'm driving, I just want to get to where I'm going…I don't speed but I'm definitely trying to get through the stop sign as fast as possible, and get through the stoplight as fast as possible and just get annoyed if someone is driving slow.

Figure 27: All unique actions named by respondents to improve on-road fuel economy

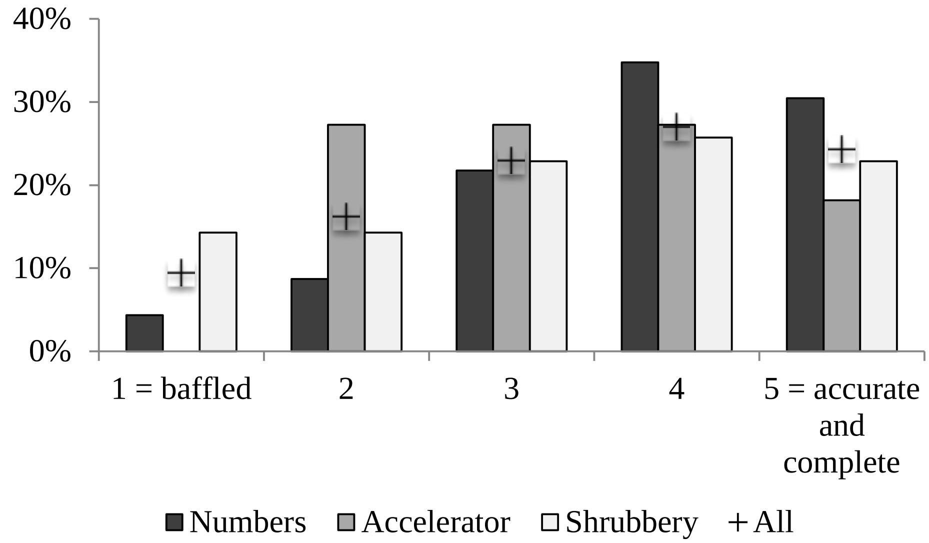


Respondents' understanding of the feedback

Researchers scored respondents' understanding of feedback on a five-point scale based on reading the participants' statements in response to this open-ended question in the interview protocol, "what did the new display show?" The value of "1" indicates no understanding of the display and "5" indicates very high understanding. The distributions over the whole sample and for each display—Numbers, Accelerator, and Shrubbery—are shown in Figure 28. Overall, the drivers appear to have understood the displays. The overall mean score was 3.5 and the median score was 4. There is no statistical difference ($\alpha = 0.05$) in the mean sores across the three displays. Figure 28 shows there may have been proportionally more drivers being scored lowest score for the Shrubbery display. However, a test of the equality of variances around each of the display means does not conclude the variances differ. Further, if the scale for assessing understanding of the display is treated as ordinal, a contingency analysis does not reject the hypothesis that the distribution of scores is similar for all three displays.

Respondents were provided with an explanation of the feedback screen they viewed when their display was turned on, i.e., when they started their with-feedback driving period. Researchers did not review this guide with participants. The decision not to do so was made in the interest of verisimilitude. When they buy a car, car buyers are provided with an owner's manual—which would explain any fuel economy display the vehicle might have. Typically though, no one from outside the household sits down with them to be sure they have read and understood it. Further, this lack of explanation by the researchers is more consistent with the overall project goal to test whether or not feedback makes any difference to real-world, on-road fuel economy. For these reasons, the slightly more than ¼ of participants who had a poor understanding (scores 1 and 2) of the feedback are, in some sense, a positive outcome for the purposes of this research.

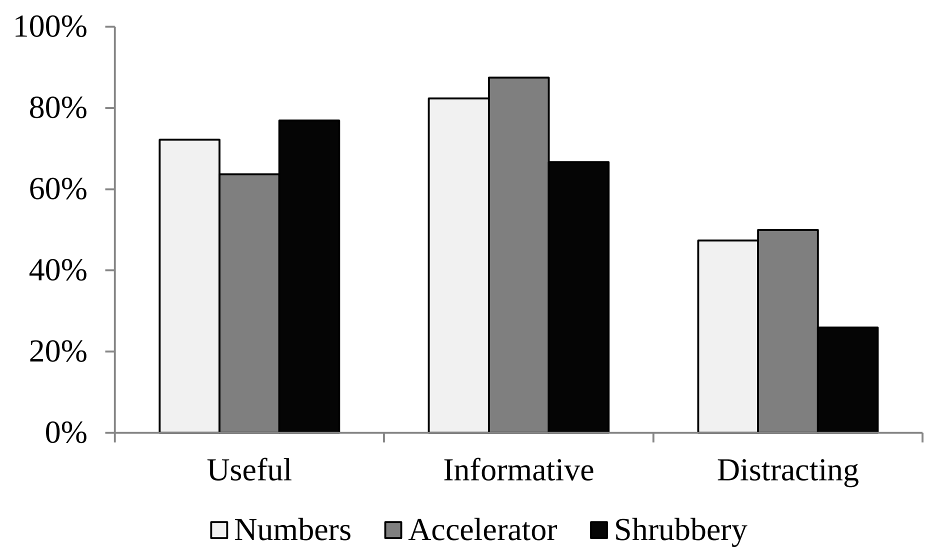
Figure 28: Comprehension of the feedback display



Was the Feedback Useful, Informative, Distracting?

Figure 29 illustrates that approximately three-fourths of participants affirmed the displays' usefulness and information value. In contrast, only about a third said the feedback device was distracting. Based on the range of the strength statements about distraction—from mild comments to real complaints—and based on the specificity of the complaints about the specific device, we hear little about driver distraction that raises any warnings about a general safety concern of providing drivers with fuel economy feedback.

Figure 29: Was the display useful, information, distracting?



Would participants want fuel economy instrumentation in future vehicles?

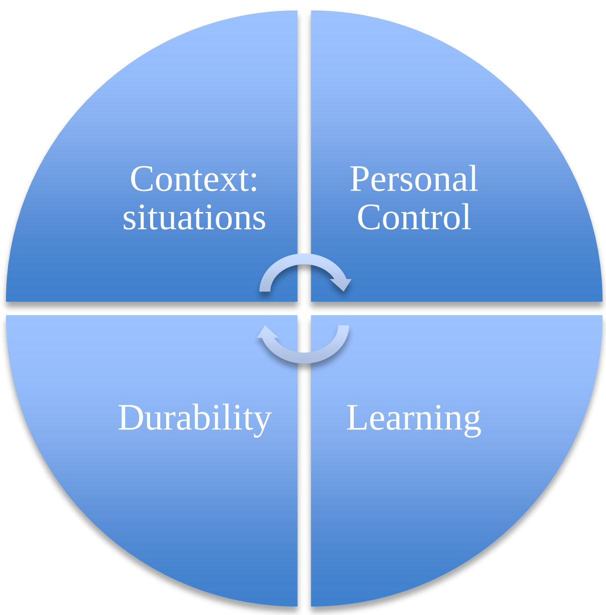
One outcome of participation in the study is likely to be an opinion toward fuel economy feedback in vehicles in general. As background to that question, approximately three-fourths of the participants state the car they drive already has some sort of fuel economy display in it, and about two-thirds of these say they use it. Put another way, about half the participants had a fuel economy display in their car that they claim they already use. A partial indicator of the durability of any changes in on-road fuel economy in response to fuel economy feedback may be whether participants want such feedback in their next car. The 94 percent of respondents who say they would want to have a fuel economy display in their next car, i.e., a vehicle they would acquire some time after their participation in the field test. Further, offered the opportunity to turn this feedback off and on, 84 percent decline, opting for a display that is always on. In addition to the perceived value of such feedback, this level of acclaim for fuel economy feedback may be explained by habituation to the feedback many already have in their vehicles, learning during the course of the field test, and social desirability bias, i.e., some participants may have been providing a socially friendly answer to researchers studying fuel economy.

RESULTS: THEMES—CONTEXT, CONTROL, LEARNING, DURABILITY

Here we map the interviews as sets of related themes. These mappings will show the different points within drivers' experience over time that feedback can enter to link concepts, enable learning, and affect habits, all which may affect whether the behavioral changes they enacted during the field test would last over time (in the hypothetical case of continued feedback). The themes most relevant to the research questions of this project are listed here and illustrated in Figure 30:

- Contexts: Situations in which it is good/bad to use fuel economy feedback
- Perception of personal control over on-road fuel economy
- What did participants learn?
- Durability of any behavior changes made during the field test

Figure 30: Relating the interview themes



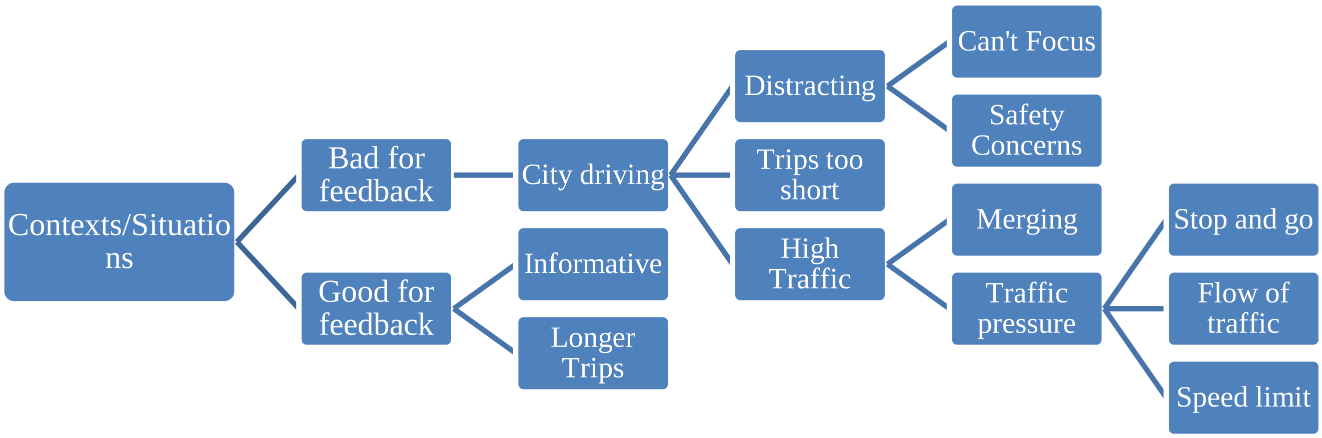
These themes can be related to each—again, partly by design of the overall research project and partly by the experiences related by the participants. The relationship between research design and interview themes is illustrated in Figure 30. Driving takes place in a variety of contexts, thus the variety of cities chosen for the project. The behavioral theory described in Stillwater and Kurani (2013) posits the role that a sense of personal control has in behavioral outcomes. This control may differ across people and within people across contexts. One of the functions of feedback is to facilitate learning, including that one may have more control over a behavior—possibly different amounts of control across different contexts—than one thought. These lessons may evoke new actions, emotional responses, and comparisons to other information. The durability of any learned or reinforced behaviors is more likely in some contexts, among people who perceive they have some control, and trust the information. But, even if all these conditions align, the durability of effects can still be susceptible to resistance, possibly due to resistance to the feedback itself.

Each sub-section below illustrates the elaboration of levels of meaning within each theme and provides example quotes from participants. Results are presented in figures that relate a theme (at left) to more specific meanings (moving to the right).

Context: Situations in which it is Good/Bad to use Fuel Economy Display

This theme differs from that of personal agency and control (discussed below) in that it focuses on the context in which driving occurs, rather than the driver. Descriptions of contexts (Figure 31) include those driving situations in which something about the context: traffic levels, roadway design, attention required for driving tasks, etc. affect whether particular situations are seen as amenable (“good”) or not (“bad”) to adding the goals of improving fuel economy, and especially to paying attention to an additional bit of information displayed to the driver in the vehicle. The primary distinction between “bad” and “good” situations to pay attention the display appears to be city (bad) vs. highway (good) driving. City driving is described as requiring a higher level of attention and affording less room for maneuver than highway driving. City driving also raises the issue of whether a trip is long enough to make a difference, as if the speaker tallies fuel savings on a trip-by-trip basis rather than over all their driving.

Figure 31: Thematic structure: situations when it is good/bad to use display



Situations when it is bad to use feedback

City Driving contains several ideas elaborated below, but much of what drivers say has to do with whether it is possible to pay attention to feedback or do anything about their vehicle's fuel economy while driving in city traffic.

"And because it's, again, mainly in the city, it's hard to look at it all the time and make sure while you're driving."

"Yeah, I think especially on, yeah, city driving – the lights are gonna stop you regardless. Between the lights and the traffic, something's gonna hold you up. "

Distracting

Can't focus (on context and display at the same time): "Sometimes I would just have to say, 'No, I'm not going to look at it. I have to focus, there's a lot of traffic here,' or whatever. I can't be looking at that thing while all this stuff's going on around me."

Safety concerns: "I do have a little bit of trouble paying attention to a gauge in the car when I'm driving just because I don't want to kill anybody else or myself."

Trips too short: "Most of my trips aren't really long either. Maybe if I were taking long trips I could have done better"

High traffic levels

Merging High traffic can both cause drivers to feel the need to aggressively accelerate to enter traffic and to wait longer to enter traffic. Both use more fuel than being able to enter traffic with more moderate accelerations without waiting for an opening.

"When you have to come out and it's like you merge…you gotta yield but you gotta merge in too. Sometimes you have that, well and it's like, if you wait that second then you're waiting for the two cars that come screaming by. But it's two lanes there, too. So you can always pull out here. And there's been a few of those where it's like, 'aw man, you didn't take those two seconds to say I'm gonna wait for these guys who are far enough away and just wade into traffic.' Other than that I haven't really found any needs to stick my foot in it."

Traffic Pressure The distinction of traffic pressure has more to do with how the flow of traffic can limit a driver's actions—causing them to speed up, slow down, or drive a specific speed despite what a driver might want to do to increase their fuel economy.

Stop and Go: "But there's a lot more speeding up and slowing down than I would like and I don't feel like I have much control over a lot of that."

Flow of Traffic: "Obviously there are other things like what the traffic, the flow of traffic is. I think that – there's a high density of automobiles on the road. You don't have much freedom."

Speed Limit: "I set it to the speed limit because I don't really feel like I need to go above the speed limit. I just set it to that and drive accordingly."

Situations in which it is good to use feedback

Informative: "It's informative from the sense of the kind of gas mileage you get as far as when you're in, you know, stop and go traffic versus, you know, on the freeway..."

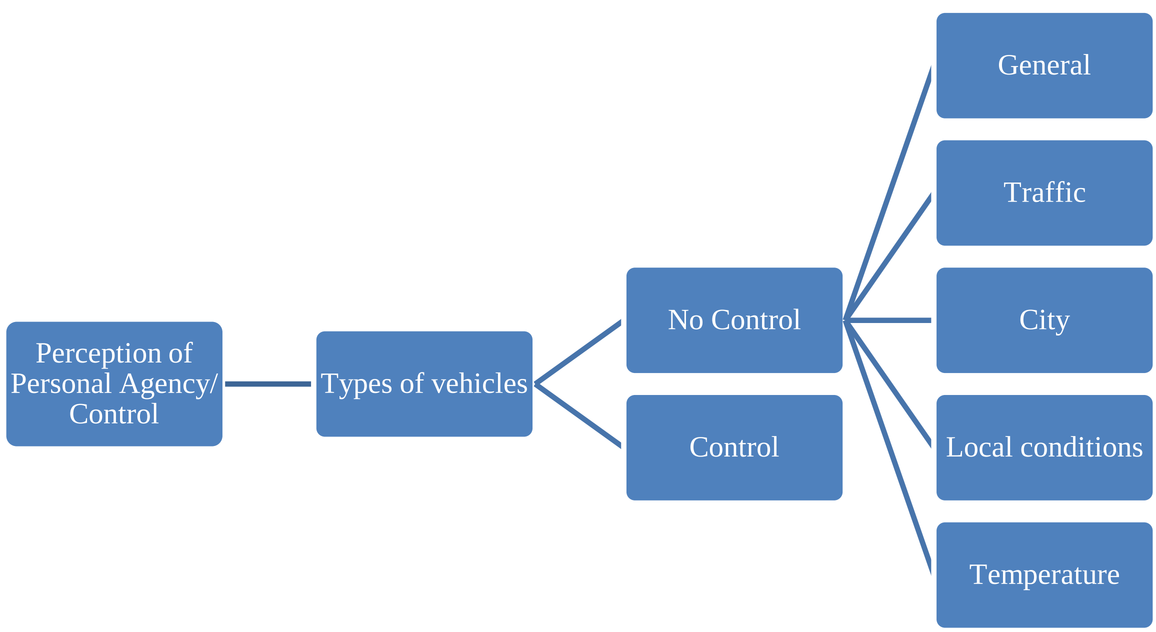
During Long Trips: "It was kinda fun, I mean especially during our long trips. We've seen—we're like, ooh, where are we? We're maxing out right now."

Perception of Personal Agency/ Control over Fuel Economy

This theme describes whether people believe there is anything they can do as the driver to influence the on-road fuel economy of their vehicle. The main division is between those participants who don't and those who do believe their actions as drivers affects fuel economy. Those who did not believe they could exert any influence offered a variety of reasons as illustrated in Figure 32.

> **Types of Vehicles** The degree to which some drivers felt they had control over the fuel economy of the vehicle they drive was dependent on which vehicle they were driving. The distinction tended to be that low fuel economy vehicles such as larger trucks afforded less control. In some instances, the feedback was able to help the driver to form a sense of their ability to control the on-road fuel economy of even these vehicle types:
>
> "…but actually seeing my own effect on it and not just thinking it's out of my control, that's just how the car is unfortunately. It only gets this many miles per gallon. We should've bought a more efficient car, blah, blah, blah, I see that actually I do have some control over it. I can maximize what it can do and probably I'm doing better now as a result of that information.

Figure 32: Thematic structure: perception of personal agency/control over fuel economy



> **No Control** This theme describes people who believe, in general, they have little or no control over their car's fuel economy while driving. If they believe they can affect fuel economy, it would be through the car purchase or travel behavior, e.g., to curtail driving whether through trip chaining or skipping trips altogether.

General: "It's more information, but I don't know that I can say that it's information I can act on or if it provides me a path to do something different. It's a reading. It's there, but is it going to change the way I drive? I don't think so."

Traffic: Some drivers describe general limits that traffic puts on how long it takes to get places, how fast one can or must drive, and what routes make the most sense. As one puts it,

"I think the real factor … is the traffic conditions that control how long it takes to get there."

City: "Yeah, I think especially on, yeah, city driving. The lights are gonna stop you regardless. Between the lights and the traffic, something's gonna hold you up."

Local conditions: While the limits of a driver's control over fuel economy can be stated more generally, as in the three ideas above, sometimes it is the very specific conditions where they routinely travel that are described limiting control:

"Topography and traffic limit what you can do. [I feel] delight in coasting downhill and despair at driving back up to the house. What's really weird is it's hard here because it's such a hilly area that we varied back and forth. Going down was really great. Going down to the store but coming back up we'd use about two…Most of the time we were coming up with two or one and a half but going down was four so I guess the average was right around there."[2]

Temperature: "Temperature does have an effect on a lot of the things one encounters either in engineering or in whatever but obviously things that are beyond the control. So I really don't think there is too much that one can – as long as one is an intelligent good driver, beyond that there isn't too much you could do."

Control Those who believed they do have a measure of control may have understood, as evinced by the quote below, that control is exerted through small actions multiplied over many driving situations and long periods of time.

[2] In this context, "using two," "coming up with two or one and a half," and "down was four" are all references to the scale used on the graphical fuel economy display. As these five-point scales are calibrated to the combined EPA fuel economy for their car, less than two-and-a-half is less than that EPA rating and higher is more than that rating.

"Make a difference? Yes. How big? I guess it matters how long you're doing it. Obviously driving bigger or hauling a heavier load is going to be more of a difference but it's not an instant gratification thing. It is over time you have to change your habits, not just change this instance, yeah. Yeah, it could definitely make a difference but you gotta be willing to change your habits and sometimes old habits die hard, you like the sound of the engine going, fine, go ahead, stomp on it once in a while but everything you did last week just went out the window."

What did Participants Learn?

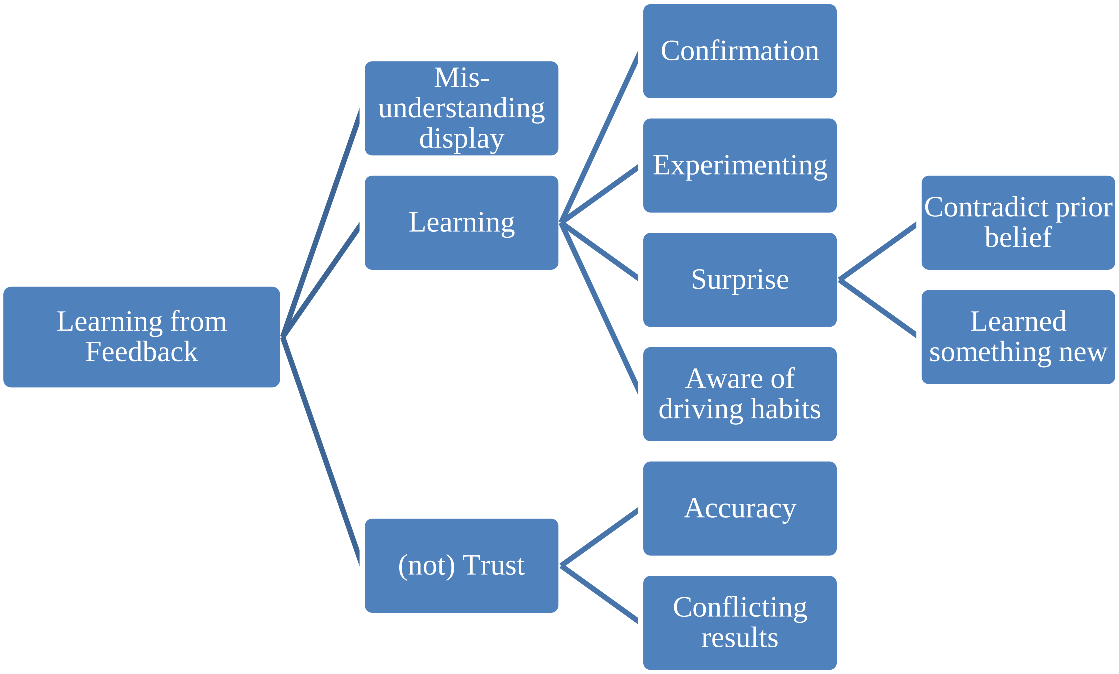
The theme of personal control can be linked with feedback to learning, e.g., participants who previously thought there was nothing they could do to control their on-road fuel economy learn they can exert some control. Participants differed in whether they felt they learned anything new during the field test or only confirmed things they already knew (Figure 33). Participants who felt they did not learn anything from the display often expressed some confusion about what the display means or an inability to connect their actions with changes in the display.

Misunderstanding the display: The possibility of learning was sometimes forestalled by the driver's misunderstanding of what the display meant or attempted to convey.

"The bottom one, I just assumed the slower I was driving the higher it would be. That didn't actually seem to be the case."

"I really – it just seemed odd to me that the difference between driving in town and driving on the highway, I couldn't really tell much of a difference in the display."

Figure 33: Thematic structure: learning



Learning

Confirmation of prior knowledge or beliefs: "I feel about the same, which is it basically confirmed what I knew already. I have crappy fuel economy in the city, for city driving. But that's how it always is."

"No, I mean, I knew going into it, that [my car's fuel economy] was 28 miles per gallon and that's an improvement over my previous car"

Experimenting: "I thought it was interesting just to see what gas mileage or how gas mileage changed when you did things like put on the air conditioner, accelerated quickly, things like that, drove up a hill, that sort of stuff."

Surprise

The theme of surprise is characterized by an emotional response—happy or sad—to something learned.

"I think the thing that I learned is that there's less fuel economy than I thought I had. It varied more with in-town driving than I thought it was going to."

General: "The instantaneous gas mileage was kind of fun to watch, when you could sort of bump it to 115 [MPG] with the right combination of downhill and coasting."

Learned Something They Didn't Know: "I was surprised at the difference from just taking your foot of the gas and not really coasting but getting close. And that's probably a difference, where before I just maintained the RPM."

Aware of Driving Habits: "It made you more aware of your driving or your acceleration, that kind of stuff. I think it even made you maybe more aware of the speeds that you were driving. So not that it changed [me]—for my age and stuff I don't care about driving fast anymore. And so I just think that it did make you constantly aware of the fuel that you're using. And with the cost of fuel the way it is to continue going up I just think it made you more aware of that. I think to me it just maybe showed that I was driving where I was getting the maximum amount of fuel that I probably should be getting out of my driving."

Trusting, or not, the feedback display

The display itself called its own trustworthiness into question for some participants. This seems to arise in situations where the drivers are not able to connect the display values—and especially changes—to what the driver perceives is happening. For some participants, the fuel economy display was an additional or new source of fuel economy instrumentations. These people might recall the EPA ratings of their car, have on OEM fuel economy display in their car, or calculate their fuel economy from tank-to-tank when the refuel. Whether the information displayed to them as part of the field test agreed, or especially, disagreed with these other measures would raise questions about what source of information could be trusted.

Not Trustworthy

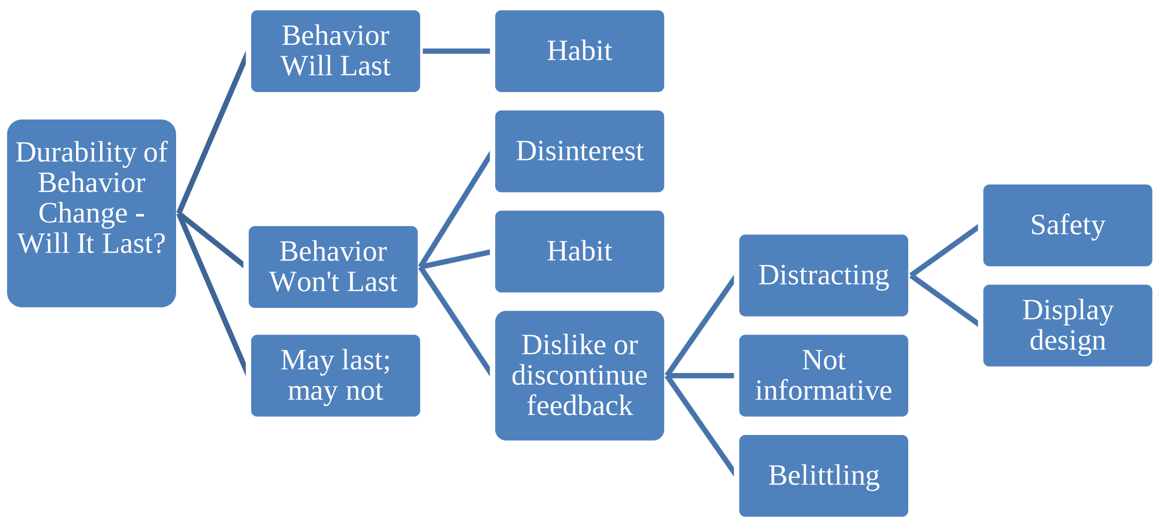
Conflicting Results: "[the display] seemed to give conflicting results. I think mostly because of the driving circumstances, not because of [turning] the air conditioning on and off. It's just the driving conditions changed just about every second, uphill, downhill, etc. We didn't have consistent driving habits or driving conditions under which we tested out things like rapid acceleration."

Skeptical of accuracy: "I usually got two or three [shrubs at the top of the Accelerator display]. And sometimes it would start with nothing and then build, other times it would start with like one or two and then go on. So I just didn't get a feel that it was correctly portraying what was really going on. The [Accelerator] bar I think does."

Durability of any behavior changes made during the field test

Drivers' statements on their likeliness to continue any of the changes in their driving beyond the field test reflect the full range of possibilities from yes, to maybe, to no (Figure 34). Importantly, this discussion helps to separate idiosyncrasies of the specific conditions of the field test—and especially the data recording and display device—from more general conditions. Much of what drivers talk about in terms of continuing or discontinuing any eco-driving behaviors is expressed in terms of habits. We choose to keep "habit" the subordinate concept (to whether behaviors will last or not) because many of the reason people give for suspecting their behavior won't last are different than habit.

Figure 34: Thematic structure: durability



Behavior will last

"I thought it was valuable information and I probably will maintain some of the habits that I picked up during the month it was on for me. So yeah, good, I appreciate that, thanks."

"I mean I look at it like that. I'm fairly trainable. It just takes some time to get into that habit.

Behavior won't last

Disinterest "I would consider keeping it in the car, but I don't know how much more helpful it would be in terms of changing my behavior or helping my behavior."

Habit: "Again I don't think it's going to change my driving habits. For as long as I've been driving I just don't think that I'm going to change what I do."

Dislike or Discontinue use of Fuel Economy Feedback

Additional reasons why the effects of the experimental display might not be durable are more specific to the actual display and screen designs used in this study. Despite their referral to the specific device, these statements contain guidance for general design. In particular, the most abstract display—Shrubbery—drew negative responses regarding interpretability and even whether the designers were treating drivers with respect.

Distracting "I thought it as more of a distraction to me. But again, maybe it's my age and point of life I'm at. So, I ignored it a lot."

Safety Concern: "And the other point is a safety point. I think when you have too many gadgets, you just play with this, look at this, it may distract you and cause an accident.

Display design: "It was just like a big chunk of your like lower windshield felt like it this – the display there. I definitely think it could've been a little bit smaller."

Not Informative: "Yeah, I want to see what difference this makes, but I didn't see any information or concrete indicator that this really works – this really helps or not."

Belittling "I'm sorry, I found the trees childish. I absolutely did. In fact I even contemplated putting a piece of tape over it because it was an insult to my intelligence.

May last; may not

"I had a really long commute and gas was pushing, it was almost $5 a gallon for a while. And so that's when – I don't know there's some mark when the rest of society tends to notice and change their behavior and it affected me too, and so when gas prices went down even that same summer, the end of the summer I kind of stopped doing it. But I never completely stopped doing everything. I certainly don't drive 55 on the freeway anymore. And it also unfortunately depends on if I'm in a hurry or not."

CONCLUSIONS

Evidence for the existence of the effect of driver feedback has been shown by the correlation between real-time fuel economy feedback and reduced on-road fuel consumption. Over 142 driver-vehicle combinations, three display types, and six cities in three distinct metropolitan areas, the presence of fuel economy feedback is correlated with a 2.7% reduction in fuel consumption (gp100m). Further, a test of the three display designs suggests that different fuel economy feedback displays are likely to reduce fuel consumption by an average of two to three percent. A real-time and trip average fuel economy bar chart (Display 1: Numbers) was associated with an average 2.7% overall improvement; 3.5% drive-cycle adjusted. The second most effective was the leaf-based depictions (Display 3: Shrubbery) of real-time and trip fuel economy (2.9% overall improvement; 2% drive-cycle adjusted). The least effective was an acceleration/deceleration meter with a trip-level stem-leaf indication of trip fuel economy (Display 3: Accelerator) associated with a 1.6% mean improvement, 0.3% drive-cycle adjusted.

The drive cycle adjustment has to do with the range of behaviors one is willing to attribute to the presence of feedback. Greater reductions in fuel use assume that changes in drive cycles, i.e., trip types identified by distance, speed, and stops per unit distance, can be attributed to fuel economy feedback. The lesser, drive-cycle adjusted figures assume that only changes to on-road behaviors such as accelerations, decelerations, and median trip speeds are prompted by fuel economy feedback.

This study did not investigate the widest range or most theoretically promising feedback designs. Given that starting point, the overall results indicate that applying these graphical feedback designs to standard ICE passenger vehicles in the US could reduce fuel consumption by an amount equivalent to taking 4 million cars off the road entirely.

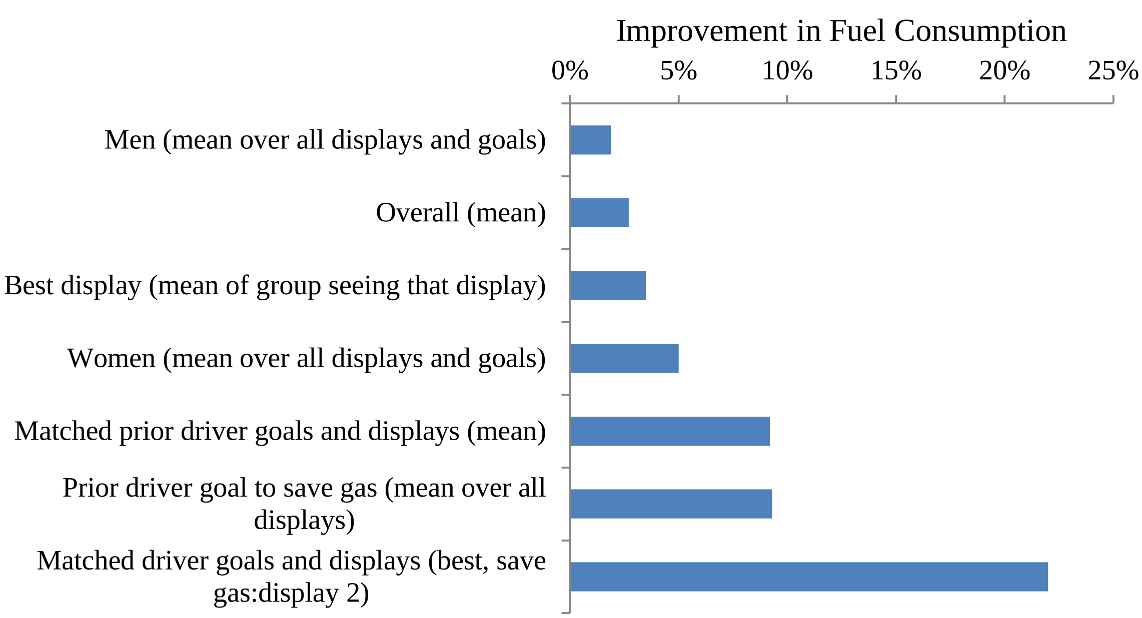
Statistically significant and substantively important differences are found in which behaviors each display type prompted. For example, strong evidence was found regarding the effects of behavioral feedback, e.g., showing drivers their actions that affect fuel economy, such as rates of accelerations and decelerations, rather than fuel economy directly. This feedback style (acceleration rate based) resulted in both reductions in accelerations and increases in deceleration, i.e., excessive braking. One implication is the importance of improved designs of behavioral feedback to retain fuel consumption reducing effects while limiting the adverse effects.

Having unpacked the overall mean effect by display type, we further unpack these mean effects by driver goals: differences in driver goals are related to the largest variations in effects. The results of the goal-based analysis showed that eco-driving behaviors can be activated when the right display is shown to people with a complimentary goal. The greatest observed reduction by a sub-group of respondents defined by a driver goal and a display type was a 22% reduction in fuel consumption rates by drivers whose goal was to save gas and who saw Display 2: Accelerator. We estimate that if each driver saw only the most effective display for their stated goal the average overall reduction would have been 9.2%. If all passenger vehicle drivers in the US saved this much energy, the reduction would be equivalent to taking 11 million cars off the road.

In addition to behavioral variations due to driver goals, driver sex and age are associated with the efficacy of the feedback. Female drivers reduced their fuel consumption by 2.5 times more than men (women, 5% overall: men, 1.9% overall). Young drivers reduced their fuel consumption by close to 5% overall, but each additional decade of driver age was associated with a 0.75 percentage point worse performance.

The results suggest two basic lessons: 1) relatively simplistic graphical fuel economy feedback is effective in reducing fuel consumption averaged across a wide variety of drivers, vehicle types, and land use settings; and 2) some display types are more effective than others at motivating more efficient driving styles, especially when the driver's goals align with the feedback design.

Figure 35: Range of non-zero measured and estimated effects



Beyond these quantitative measures, drivers in the field test completed entry, interim, and exit questionnaires and interviews. Much of the questionnaire data were used to characterize who these field test participants were in comparison to other samples of households and drivers. Broadly speaking, the field test was conducted in three distinct metropolitan areas located along Interstate-80: The San Francisco-Oakland Bay Area, the California Central Valley city of Davis, and the Reno-Sparks metropolitan area of Nevada. Conducting the study city-by-city over the span of a year-and-a-half resulted in data from a wide variety of seasonal conditions and land uses. The drivers themselves differed from other populations primarily in that they are, on average, older and wealthier. They owned similar numbers of vehicles as did other samples of car-owning households, though they tended to own newer vehicles. Importantly, especially given the importance of drive cycles, i.e., trip types, to the estimated effects of fuel economy feedback on on-road fuel economy, the aggregate distribution of trips by trip distance produced by the field test households looks like the distribution from the NHTS 2009 data.

The driver interviews reveal that while many participants claim that improving their fuel economy is a goal for their driving, they know few ways to accomplish this. The most commonly mentioned actions a driver can take—given they are already driving their car for a trip—were to accelerate more slowly, to drive slower on the freeway, and to coast more, especially to stops. However, the median number of unique actions any participant could name—despite a series of three open-ended questions—was only two.

One specific issue that the lack of driver knowledge and on-road impacts jointly reveal is the importance of knowledge about synergistic safe and efficient behaviors. Eco-driving researchers have identified a number of synergistic behaviors including reduced accelerations and decelerations, moderating freeway speeds, and increasing following distance. However, in this experiment safety goals were only weakly associated with improvements in fuel consumption. Worse, drivers whose primary driving goal was to drive safely and who saw Display 2: Accelerator display increased fuel consumption during the with-feedback phase. These mixed results regarding safety and fuel consumption suggest increased driver education and careful feedback design could result in greater savings overall.

The interviews further reveal a set of four interrelated themes—ideas that exist across the interviews—informing why and how drivers report they do and don't respond to fuel economy feedback. The four themes are 1) the contexts in which drivers describe their driving and reaction to feedback, 2) their perception of whether they can exert any control over fuel economy in different contexts, 3) what they learn—or don't—from the feedback about how and how much their actions affect their vehicle's fuel use, and 4) whether their assessment of how likely they are to continue any eco-driving behaviors beyond the period of the field test depends on what they may have learned, including their control in different driving contexts. The linked sets of ideas within each theme inform not only how feedback can affect behavior, but suggest how to improve the feedback designs. Drivers articulate many ways in which city driving is a context in which it is difficult to pay attention to feedback. They articulate many ways in which they feel they can't exert personal control. Thus one avenue for future research is context-specific feedback, in effect modifying the feedback stimulus in different contexts to elicit desired responses. A related avenue is continued exploration of the role of feedback in exposing drivers' existing habits to them and the development of new habits such that eco-driving becomes a matter of consistent practices rather than stimulus-response.

In brief, the results suggest two basic lessons. One, relatively simplistic graphical fuel economy feedback is effective in reducing fuel consumption averaged across a wide variety of drivers, vehicle types, and land use settings. Two, some display types are more effective than others at motivating more efficient driving styles, especially when the driver's goals align with the feedback design.

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