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Comprehending Consumption: The Behavioral Basis and Implementation of Driver Feedback for Reducing Vehicle Energy Use

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Comprehending Consumption:

The Behavioral Basis and Implementation of Driver Feedback

for Reducing Vehicle Energy Use

By

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DISSERTATION

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Table of Contents

Preface to the Dissertation

A former employer and engineering mentor of mine presented me with a riddle: an open train-car full of water sits on frictionless tracks. At some point a downward pointing valve on the left side of the car is opened and the water begins to gush out. Does the train-car move?

I was puzzled by the riddle because of the contrary laws that applied. The first law is F=MA, implying that for the train car to move, the water must apply a force to it. The second law is one of action and reaction. There does not seem to be a force applied to the train-car, and yet it is clear that an action has occurred. After forgetting about the riddle for a decade, I remembered it one night at midnight after a day spent working on my dissertation and I suddenly knew the answer.

Let's imagine a parallel universe in which train-car motion is better funded and a young researcher much like myself has received a grant to solve the train-car problem once and for all through detailed measurement and statistical analysis. His hypothesis is that microscopic eddies in the water would exert an uneven frictional force on the sides of the train car, forcing it to move a small distance to the right. He would carefully assemble the train-car system inside of a closed, climate-controlled room. The tracks would be magnetic levitation rails to minimize friction, and a series of laser beams would measure the minutest motion of the train-car, such that coughing in the laboratory would cause havoc. After a year of measurements the student would perform a rigorous statistical analysis and correctly (although with some disappointment) conclude that the train-car had not moved.

Yet he would be wrong. For among all of the perfect measurements and detailed statistical models he would have missed the motion (however slight) of the entire earth, his lab, and the train car as it all moved (along a vector pointing from the center of the earth towards the train-car) in adjustment to the new system. The train-car did move, but the observer also moved exactly the same distance.

I mention this engineering parable because it seems applicable to the research at hand. I decided to conduct this research largely out of concern for the unsustainable level of energy consumption in developed nations. Driving behavior seemed like an interesting and approachable micro-cosmos of human behavior and energy outcomes that could be carefully measured and analyzed. However, during the study it has become clear to me that I am also a part of a dynamic system along with the research and its participants, just as the rail-car and observer were a part of the same dynamic system. Each interaction with a research subject has both changed my outlook and research questions and changed the subject's attitudes and beliefs, many of which are reported in this research. Also, during the research period large changes in governmental policy related to fuel efficiency have taken place, electric vehicles went into commercial production, and political battles have been fought over energy independence, wind farms, and coal. The world is a bit different at the end of this study than it was at the beginning, and people are a bit different as well.

Introduction: Comprehending consumption: technology, magic, and energy feedback

Many currently popular behavior change theories within the energy context were first generated in the 1970's, notably including the theory of planned behavior and the norm activation model. The origins and applications of the models (and the variants thereafter) suggest that these models were generated within a normative context of the 1970s – a time in which many people in the US began to believe that human behavior was having a distinctly negative impact on the local and global environment. This was the era of the popular book *Silent Spring* as well as the Clean Air Act and creation of the US Environmental Protection Agency (EPA). However, just as behavior researchers were focusing on the individual as an actor in the emerging ecological crisis, transportation policy makers were turning away from legislation that might constrain individual transportation choices. This early technological orientation was reinforced, if not created, by a political battle over the ability of the EPA to require state agencies to regulate driver behavior in the form of Transportation Control Measures (TCMs) designed to meet requirements of the 1970 Clean Air Act Amendments. The controversy and legislative failure of those TCMs marked a turning point in US transportation policy away from individual driving behavior and towards technological and market solutions to transportation emissions (Quarles, 1977).

On a parallel track, although appearing slightly earlier in the literature in the 1950's and 60's, are a number of studies concerning feedback and residential energy use. These studies placed the usefulness of feedback in a generally economic framework, assuming that knowledge of energy use would lead to curtailment of unnecessary home use for the purpose of direct economic savings to the consumer (Greene, 1986). But why is this type of feedback necessary at all?

The physicist and science-fiction writer Arthur C. Clarke famously stated that, “Any sufficiently developed technology is indistinguishable from magic,” a statement that is simultaneously reflective of reality and a potent analysis of why technology has created such a pervasive regime of over-consumption and resource depletion. Being indistinguishable from magic is precisely the problem that energy behavior change researchers are assiduously attempting to solve. Magic implies a complete lack of consequences (at least in the terrestrial realm). Magic is a state of the universe that defies natural laws, and it is these same natural laws that require energy to be used for events to happen. By being indistinguishable from magic, technology energy use and other environmental consequences are hidden from the consumer as much as possible. The resource depletion that is inextricably required to perform actions is deftly swept beyond the view of the consumer.

Clarke's statement is a reflection of current reality, but certainly not a definition of what is possible. The invisibility of the consequences of technology use is due to the desire of technology designers to make their products commercially successful or possibly their lack of awareness of a different design philosophy. From the normative point of view of behavior change research, technology is *not* sufficiently developed if it is indistinguishable from magic. In fact, the thrust of behavior change research in feedback is to take magical technology and transform it into something with visible environmental, social, or financial implications. By easily comprehending their own consumption, individuals can make both individually and socially responsible choices. How and when that potential translates into actual choices is the subject of this dissertation.

The first chapter discusses the use of mile-per-gallon fuel economy as a metric for driver feedback and finds that the metric is unable to transmit accurate information about the impact of driving style on energy use. An alternative energy economy metric is created and used throughout the rest of the chapters. The second chapter reviews behavioral theories and discusses the problems with applying those theories in addressing driver behavior. A number of practical solutions are discussed, but it will take new research to explore many of these complex issues. The Theory of Planned Behavior and its variants are identified as useful frameworks for generating hypotheses about in-vehicle behavior change due to feedback. In the third chapter the theory of planned behavior is tested against driver responses to an existing feedback system available in the 2008 model Toyota Prius. Overall it appears that the driver responses support the use of behavioral theories to both measure and design feedback systems, although the theory of planned behavior oversimplifies many of the factors and does not provide guidance on how to approach issues of the context of the behavior. The fourth chapter presents a novel feedback design based on behavioral theories and drivers' responses to the feedback. A number of behavior-theory-inspired additions are the focus of driver attention and indicate that existing feedback designs lack some important types of feedback, with the inclusion of a personal goal being the most important. Finally chapter five presents the quantitative results of a year long study of fuel economy in response to feedback. The novel feedback design is found to generate a statistically significant increase in fuel economy overall, but more importantly the feedback influences drivers' goals and attitudes. This finding supports the underlying behavioral theory and suggests that energy related behavioral decisions are dependent on the quality and behavioral relevance of information that people have about their choices and the resulting consequences.

A note on keywords and acronyms

This area of research comprises a number of different sub-fields, each with its own literature and terminology. Feedback literature has emerged in transportation related to safety, human factors, and energy; in residential energy use research; and in a number of other areas. Early fuel economy feedback research usually referred to the systems simply as feedback, or fuel economy displays. Later, the name Human Machine Interfaces (HMI) was applied to the driver interface, although HMI is a general term that covers a broad range of subjects relating to the largely perceptual and ergonomic interaction between people and the machines that they control. Advanced Vehicle Information Systems (AVIS) has been used recently in some transportation specific applications of HMI design. In Vehicle Information Systems (IVIS) relates more specifically to combining multiple information streams for the driver in the vehicle. Advanced Traveler information Systems (ATIS) has been coined in the relatively new field of real-time mapping, route and other guidance and reflects the emphasis on the driver, rather than the vehicle.

An alternate stream of related research is specifically related to ecodriving, i.e. specific techniques for fuel efficient driving that are generally taught in driving classes or described in educational material, rather than integrated into on-board devices. Although the feedback genre is arguably under the umbrella of ecodriving because of the shared end goal of fuel efficient driving behaviors, the majority of the ecodriving terminology and literature is specifically focused on driver education and teaching specific driving techniques (Beusen et al., 2009; Johansson, Gustafsson, Henke, & Rosengren, 2003; Zarkadoula, Zoidis, & Tritopoulou, 2007), whereas the feedback literature is focused on driver response to in-vehicle display (Arroyo, Sullivan, & Selker, 2006; Barkenbus, 2010;

Larsson & Ericsson, 2009; H. Lee, W. Lee, & Lim, 2010). Finally, some researchers combine the two by providing both feedback and ecodriving training to compare effects (Greene, 1986; van der Voort, 2001).

As the current trend in research is to display many types of energy relevant information (not just fuel economy) and the focus is again on the interaction between the driver and the interface, I recommend the terminology Human Machine Energy Interface (HMEI) to refer to the energy-specific component of interfaces, and I will use the acronym HMEI for the duration of this dissertation.

Chapter 1: The MPG mistake: A proposal for a new measure for real-time in-vehicle feedback

Introduction

The basic methodology of measurement and feedback permeates all areas of industry and government from manufacturing quality control to health policy to and energy policy. The belief that proper measurement and feedback lead to desired changes is so common that it is almost a cliché. Transportation has long had its own metric for energy, miles-per-gallon (MPG). Although various specialty versions of MPG now exist, such as miles-per-gallon-equivalent (MPGe) or gallons-per-mile (GPM), there has been little reason to question the use of fuel and distance to measure and represent the performance of our vehicle (or driver) fuel use, until now. A resurgent interest in vehicle fuel economy has brought with it interest in the display of real-time MPG. Legislators, and manufacturers have shown renewed interest in real-time feedback in passenger and freight vehicles for the purpose of encouraging better driver behavior and lower energy use (Abuelsamid, 2010; Barkenbus, 2010; Company, 2008), although research on driver response indicates that consumers are lukewarm to the concept (Jenness, Singer, Walrath, & Lubar, 2009). Although this feedback can come in a variety of forms, only one form has been widely applied by industry and researchers in passenger vehicles: real-time MPG (or the International System of Units equivalent in most countries). This chapter presents evidence that MPG, or any other primary fuel based metric that only includes 'tank' energy used, rather than a real-time energy balance, is an inappropriate and misleading metric for instantaneous feedback in vehicles, and that manufacturers, 3rd party feedback designers, and drivers would be better served by the use of a more complete energy economy metric.

Background

To provide a historical background and current context I present a short history of the MPG metric and a brief discussion of thermodynamics to set the stage for the analysis of the fuel economy metric. The discussion below charts a slowly rising level of the sophistication of consumer information about fuel economy – a level that has largely been set by government regulations. Recent changes in the design of official fuel-economy labels push that level of sophistication yet higher, whereas in-vehicle fuel-economy feedback has hardly changed in the last 90 years.

The origins of the MPG metric and consumer feedback

A review of US patent applications shows that the concept of automobile economy has been in common use ever since the horseless carriage replaced the horse-drawn carriage. The specific modern use of the metric of miles per gallon, however, appears to have come into vogue around 1915, as automobiles began to become a major industry. The first patent application to use the term with its current meaning was for a real-time fuel consumption rate monitoring device filed in 1915 (Greybill, 1920):

> "More particularly the method provides for the operator of a gas engine, a visible indication at any time of the fuel efficiency of his engine. For example, the driver of a motor car can tell by a glance at an indicator on the dash whether his car is operating at its normal rate of eighteen miles per gallon of gasolene, or at only fifteen miles per gallon, which latter reading would instantly tell him that some condition of operation required attention. For instance his last supply of gasolene might have been of a poor grade, the carbureter might require adjustment, the valves need grinding or some other part require attention that would cause a lowering of the fuel efficiency of the engine."

The inventor was interested in using the metric as a diagnostic tool, rather than as driver behavior feedback, a use of fuel economy information that is still common today. However, it can easily be imagined that users of his device would be particularly sensitive to avoiding accelerations and grades while checking their engine health, as these situations would alter the meaning of the reading in complex or non-intuitive ways; the same problem that the rest of this chapter will focus on solving.

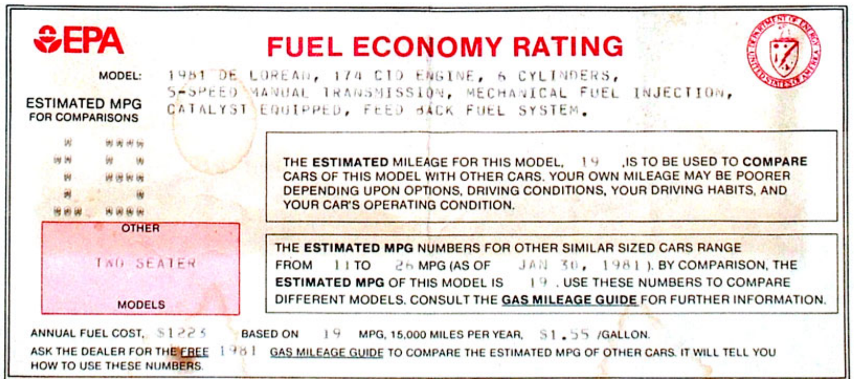
The cultural context and consumer value of fuel economy and fuel economy information during previous times is difficult to determine from the vantage point of 2011, but a few available way-markers indicate an increasingly sophisticated relationship between consumers and their vehicle fuel economy. The early (pre 1950) consumer relationship to fuel economy is characterized simply by unregulated industry advertisement of vehicle fuel economy. That relationship began to change with the first government research on fuel economy, although the target of that research was experts, rather than consumers (Carmichael, 1953). The largest shift in that relationship started when standardized fuel economy measurements were released to the public by the nascent US EPA in 1973, followed soon thereafter by recommended voluntary fuel economy labels on all new cars. Although vehicle manufacturers and dealers protested the perceived intrusion of the government into the industry, consumers were genuinely interested in the new information, if confused by the complexities of measurement and comparison (AP, 1973; Schmid, 1977). In 1975, just two years after recommending fuel economy labeling the EPA wrote the MPG fuel economy metric into the pages of national policy when the Corporate Average Fuel Economy (CAFE) standards were first enacted (NHTSA, n d).

Fuel economy labeling schemes and metrics

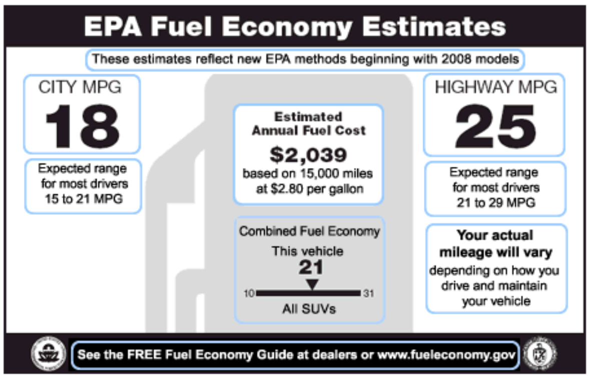
The MPG rating created for consumer labels and CAFE standards was initially based on a single dynamometer drive cycle known as the “LA 4,” a simple methodology that provided an accurate comparison of vehicles on that particular Los Angeles-based test-cycle but did not include any measure (nor therefore consumer information) of the effect of driver or drive-cycle variability. Various amendments and changes were made since then, primarily concerning the representativeness of the drive-cycles used and reported, and clarifying how consumers should use the information. More recent amendments have made the measurements better representations of average US driving habits and now indicate a range of fuel economy outcomes based on variations in drive-cycle. However, the drive-cycle methodology still effectively removes the impact of driver behavior from the official estimate of MPG while emphasizing vehicle technology and drive-cycle.

EPA-designed window stickers have similarly become more careful in wording, resulting in the current display of separate city-highway ratings, combined average, expected MPG range, estimated fuel costs and relative savings, environmental ratings, and a disclaimer stating that “Your fuel economy will vary.” Figure 1 shows a few historical variants on the EPA label, including the dramatic increase in information about both the variability of the metric and the environmental consequences of driving. The 1981 label shows the single fuel economy measure, whereas recent labels show drive-cycle variation (city, highway, combined) and an expected range for most drivers, which is not specifically identified as drive-cycle or behavioral variation. All of this information and disclaimer is intended to provide new (and now used) car buyers with important comparison information, reduce the likelihood of unrealistic expectations, as well as develop a healthy sense of control over their fuel economy destiny.

A.



B.



C.

D.

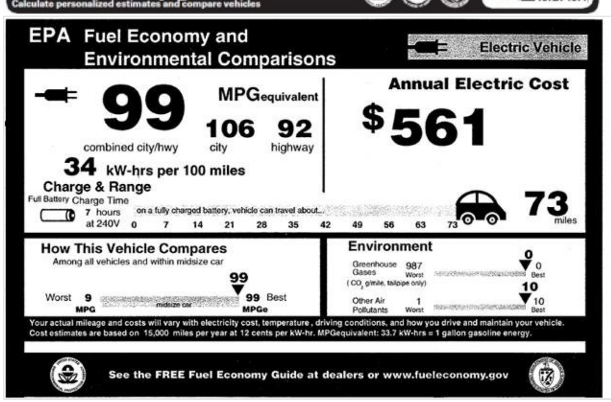


Figure 1 A-D: EPA window stickers. A. 1981 DeLorean (www.delorianmuseum.org 2011)*; B. 2010 gasoline vehicle; C. projected 2013 sticker for a gasoline vehicle showing additional savings and environmental information; and D. 2011 electric vehicle showing the use of MPGe in the Nissan Leaf sticker.*

The distinct energy content of different fuels, drive-cycle variability, and drive-style variability each play a role in fuel economy and each are addressed by the increasingly complex labels. Each fuel type has important implications for vehicle design, life-cycle impacts, and occasionally driver behavior (such as the range restrictions associated with some fuel types). However, from the consumer point of view, each is simply one more variety of energy, differentiated primarily by cost, refueling experience, or symbolic value. Regardless of the source, every joule of energy is the same once converted into distance driven; what we call fuel is simply one transient stage of energy storage at the end of a cosmic journey starting with sunlight (fossil fuel) or stardust (nuclear or geo-thermal) and ending with exhaust heat and increased entropy. This tank-energy based comparison led the EPA to introduce the source-neutral MPGe measure in 2010 so that gas vehicles could be compared to alternative fuel or mixed fuel vehicles, the “e” in MPGe, literally meaning “equivalent”, signifies the use of an energy-based, rather than volumetric or other fuel specific measurement.

However, the specific effect of driving style on fuel economy is only referred to in the new labels in the statement that your fuel economy will vary in part due to your driving style. Rough indications of the magnitude of this impact are left to the Department of Energy’s fueleconomy.gov and various nonprofit ecodriving websites such as the UK’s ecodrive.org or the Alliance of Automobile Manufacturers’ ecodrivingusa.com. Of course, the label may not be a good place for driving behavior information unless there is a strong relationship between vehicle choice and driving style effectiveness. Otherwise, this information is likely to be more effective in the vehicle itself since it is only during driving that driving style behavioral choices can be enacted.

Finally, recent research has chipped away at the MPG metric in other ways. For instance, some studies suggest that the inverse fuel economy metric, gallons per 100 miles (GPM), or the metric equivalent liters/100km, may be more practical in some cases than MPG since individuals tend to miscalculate savings when presented with MPG values (Rowan, Karner, & Niemeier, 2010). However, for the duration of this paper I will put these issues of the best measurement system and ratio aside and focus on the concepts behind any distance-and-fuel based metric, using MPG as the example for clarity and simplicity.

Table 1: Selected fuel economy measures and uses

Fuel Economy Metric	**Use**
MPG (miles-per-gallon)	Passenger vehicle fuel economy metric (historic US-specific measure)
GPM (gallons-per-X-miles)	Inverse MPG measure that simplifies calculations of the percentage effect of fuel economy improvements given a fixed driving distance (2006)
MPGe (miles-per-gallon-equivalent)	Fuel-neutral metric (US EPA 2006), also known more precisely as miles per gasoline gallon equivalent, or MPGGE
MPE (miles-per-energy in gallons)	Real-time energy economy metric used for the duration of this dissertation

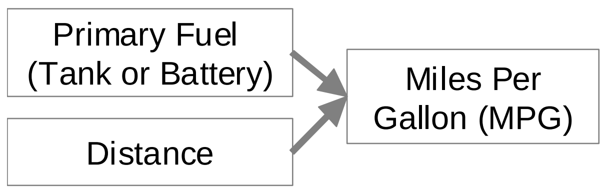
The thermodynamics of fuel economy

A car is an open thermodynamic system; energy can be introduced (at a refueling station) transformed (using the engine to turn chemical energy into kinetic energy) and released (warming the surrounding environment with the exhaust). Regardless of the primary fuel source, be it gasoline, hydrogen, or electricity, the same basic principles apply. Lack of an exhaust pipe does not mean that an electric vehicle does not generate environmental heat. Leaving aside all issues of the original source of the energy (for instance, a power-plant or refinery) and focusing only on the vehicle, the energy in the battery of an EV will be transformed into heat in the process of moving the vehicle, this heat will simply be dissipated through the battery enclosure, electric motor, tires, or air resistance, for example. The important thermodynamic law in this case is the first law; energy cannot be created or destroyed, only transformed.

The fuel economy of a vehicle is a measure of how effectively the energy stored in the chemical bonds of a fuel is transformed into kinetic energy of a vehicle moving along the road surface. By measuring the amount of primary fuel used and the distance traveled it is simple to calculate fuel economy, something that many drivers do on a tank-to-tank basis. However, this calculation hides a complex series of energy transformations that can have important implications for understanding fuel use, and which become critically important in measuring real-time energy use.

The surprising complexity of the MPG metric is due to the nature of the multiple energy transformations that mediate the primary fuel use and distance driven relationship. It is important to note that distance is not a thermodynamic quantity like energy. That is, there is no physical law that determines how much distance can be driven given a certain amount of fuel. Consider a “space car” driving in idealized frictionless space: a tiny amount of fuel could accelerate the vehicle to some arbitrary velocity and without friction the vehicle would drive on forever, achieving an infinite fuel economy. On earth of course, there aren't any frictionless environments, but the thought experiment shows that distance driven is an outcome determined not only by the fuel used, but by the resulting transformations of vehicle speed into other quantities such as frictional heat. In an earthly context that includes friction, the distance traveled is determined by the engine efficiency and the resulting rate of kinetic energy dissipation over time due to friction. In an even more realistic conceptual system that forms the basis of the rest of this analysis, other energy transformations can also have an impact on distance traveled. Gravitational potential energy is gained or lost by the vehicle during altitude changes, and battery energy is gained or lost due to the operation of hybrid systems. Each of these energy transformations is a potential “bank” of energy that can absorb kinetic energy at one time and release it at another time, as shown in the top half of the Figure 2 schematic.

A.



B.

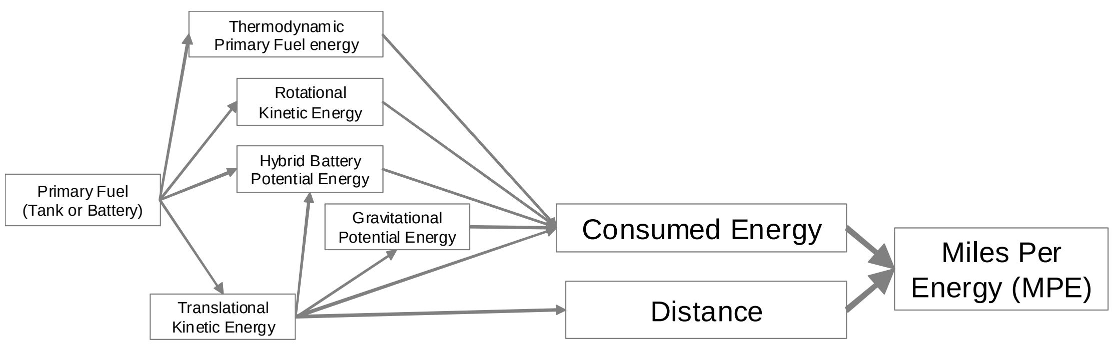


Figure 2: Energy transformations in the car. MPG factors are in part A and additional MPE factors are shown in part B. The factors shown in part B become more important during real-time measurement.

On average and over time, the contribution of kinetic, potential, and chemical-potential (such as a battery) energy banks in Figure 2 average out since all uphill drives head down eventually, every speeding car comes to a halt, and every hybrid system eventually contributes the same energy that it stores (entropic losses excepted). This tendency towards the mean allowed Miles-per-gallon to be a functional metric for rating vehicles on average or over time, and until recently was sufficient since most individuals haven't had the ability to track fuel economy over a trip or parts of trips.

However, on an individual and short term basis, these energy banks are extremely important. For example a trip up into the mountains will have a much lower fuel economy than a trip down from the mountains. This is because fuel energy is stored in a gravitational potential energy bank on the way up and released on the way down. Rather than reporting only the primary energy used in this case, it is more reasonable to subtract the amount of energy used to raise the vehicle, as that fuel is effectively stored for later use as gravitational potential energy. When descending, it is more reasonable to add this energy to the amount of fuel energy used to determine how much total energy is actually used to drive down. The same argument can be made for hybrid battery energy and kinetic energy. Each is an energy bank that can absorb primary energy at one time and release it at a later time. This entire system can easily be represented as the sum of each energy flow, as shown in equations 1-4.

Equation 1:

$$E_{consumed} = E_{\substack{primary\\fuel}} - E_{\substack{kinetic\\translational}} - E_{\substack{kinetic\\rotational}} - E_{\substack{Hybrid\\storage}} - E_{\substack{gravitational\\potential}}$$

Where $E_{\substack{primary\\fuel}}$ *and* $E_{\substack{hybrid\\storage}}$ *are calculated using their thermodynamic equivalents using joules. The higher heating value of combustion fuel is used to calculate thermodynamic equivalency.*

Equation 2:

$$E_{\substack{kinetic\\translational}} = \frac{1}{2} \times m \times v^2$$

Where m = vehicle mass (kg); v = velocity (meters per second).

Equation 3:

$$E_{\substack{kinetic\\rotational}} = \frac{1}{2} \times I \times w^2$$

*Where I = rotational inertia (kg*m); w = rotational velocity (radians per second).*

Equation 4:

$$E_{\substack{gravitational\\potential}} = m \times g \times h$$

Where m = vehicle mass (kg); newline g = gravitational constant (meters per second-squared); h = height above sea level (meters).

The MPG mistake

The instantaneous MPG metric diverges from the MPE energy economy shown in Table 1 any time that secondary energy banks (potential and kinetic energy storage) are active since MPG only includes the influence of the primary energy source. For instance, while accelerating the MPG will underestimate energy economy (as kinetic energy is being banked), and when decelerating the MPG will overestimate energy economy (as kinetic energy is being depleted). This means that drivers attempting to maximize fuel economy will accelerate and decelerate at non-optimal rates even if they perfectly follow MPG based feedback. An exactly analogous problem occurs with the MPG metric during use of the hybrid system and when driving on grades.

Although optimal acceleration is an important issue for the design of in-vehicle feedback and provides a convincing case for MPE on its own, decelerations are arguably more important since braking outcomes are more sensitive to behavior than acceleration outcomes. Unfortunately for drivers with MPG feedback, decelerations are where the MPG metric completely fails to provide usable information. When decelerating the engine no longer powers the vehicle, since by definition there is already too much kinetic energy. Different types of vehicles will use a different amount of fuel while decelerating. Most standard vehicles will simply idle at a constant rate, and this wasted fuel is then used in the MPG formula and generates an accurate, although misleading measure of fuel economy. Newer vehicles including hybrids and electric vehicles will use no primary fuel during deceleration, meaning that the MPG metric will tend towards infinity. In either case, the use of MPG results in a disconnect between the motive energy used and displayed (as MPG reflects only one source of motive energy), preventing the driver from optimizing her deceleration rate based on MPG feedback. Again, this disassociation between fuel use and distance traveled is simply an outcome of the metric and is meaningless for the energy outcome of the deceleration event, which is of course dependent on the specific context of the deceleration and in particular on the amount of mechanical braking that results in wasted kinetic energy.

To put these observations into context, a series of recordings were made to track the fuel economy and energy economy of a 2008 model Toyota Prius during real-world driving, one of which is shown in Figure 3. The OEM Toyota Prius MPG meter truncates the feedback to 99.9 MPG in order to avoid strangely high (although accurate) readings. To show the relationship between MPG and MPE the same data is plotted twice; once with a log-scale to show the full range of the MPG measure; and once truncated to 199 MPG to show the behavior of the metrics at meaningful levels.

In the bottom plot of Figure 3 it is possible to see two adjacent acceleration and deceleration events, the second having slightly stronger accelerations and slightly higher top speed. However, the two events have very different energy implications. In the first event, the driver only lightly brakes, whereas in the second event, the driver brakes

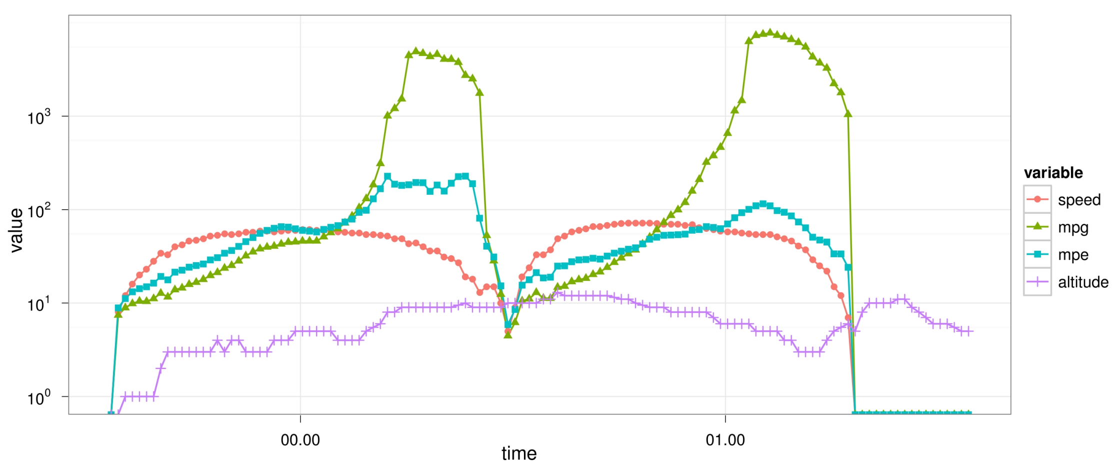


Figure 3: A comparison of primary fuel and total energy economy measures during two similar acceleration/deceleration events, each lasting approximately 45 seconds. The data are plotted using a log scale on the y-axis to show the full range of the MPG measure, which reaches over 4000.

case and quite low MPE in the second case, especially during the deceleration event. As predicted, the MPE value is also higher than MPG when accelerating due to the banking of kinetic energy. The same trends are a general feature of all of the recorded driving events.

To generalize to other vehicle types or situations a simple model was created to estimate the magnitude of kinetic energy banking during acceleration in comparison to energy used for steady-state driving at a known fuel economy. The results, shown in Figure 4, suggest that the kinetic energy banking from even moderate accelerations (1 mps^2, equivalent to 1/10G) can account for a similar magnitude of energy to steady-state driving during the period of the acceleration.

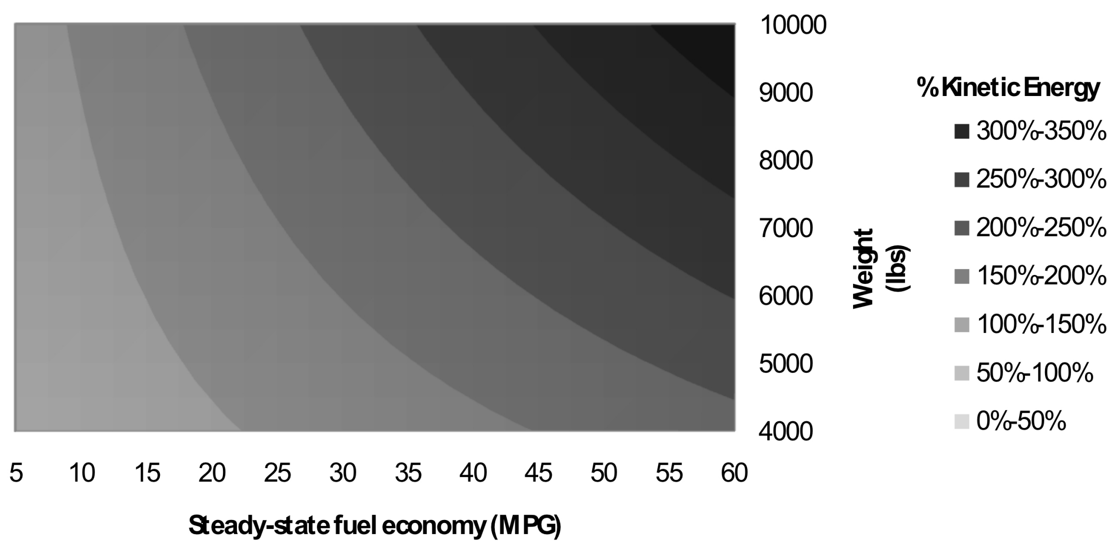


Figure 4: A static model of kinetic energy banking due to acceleration. The kinetic energy gain from the acceleration is compared to steady-state energy consumption. The plot shows the effects of steady state fuel economy and vehicle weight on the relative magnitude of kinetic energy banking. The plot assumes a moderate acceleration rate of 1 mps^2, higher accelerations will have higher relative magnitudes.

The temporal nature of these three energy transformations is unimportant for vehicle designers who focus on drive-cycle-based energy analysis that doesn't have a behavioral component. However, it is critical for real-time feedback applications. The temporal shift means that the driver will not see the fuel economy benefit of the action (such as accelerating or driving uphill) until a later, seemingly unrelated period of time, and will therefore be unable to optimize the vehicle control during periods where the fuel economy and energy economy diverge. The MPG measure is flawed feedback that reduces the ability of drivers to learn from in-vehicle instrumentation and drive with more energy efficient styles.

Discussion of the implementation of an MPE measure

One possible barrier to wide implementation of the MPE metric is that the mass, altitude, and rotational kinetic energy of the vehicle are difficult to measure. However, simple approximations can solve these problems and make MPE a candidate for implementation in a commercial context. Below, each issue is described and a possible solution is proposed.

Measuring mass

An estimate of mass is required for the translational kinetic and gravitational potential energy calculations. However, the exact mass is a combination of the OEM vehicle mass, cargo mass, and passenger mass. Of course, cargo mass and passenger mass are variable and not measured by existing vehicle sensors. Ignoring this extra mass results in a negative bias in the measure. However, it is clear that at least one person's mass (the driver) should be included, and it may be possible to sense a front-seat passenger as well due to the inclusion of front-seat passenger airbag sensors in many modern vehicles. Without directly querying the driver about passenger and cargo mass it is not possible to easily estimate the total vehicle mass. However, even with 200kg of extra passenger or cargo mass the estimate of total mass is only biased by 10% in a Toyota Prius. Thus, a solution to this problem is to include a default estimate of the driver mass (for instance, 60kg) and ignore the additional passenger and cargo mass.

Measuring rotational inertia

The rotational kinetic energy of the vehicle is equal to the individual rotational energies of all the rotating parts. However, cars are complicated machines with many parts that rotate at different speeds. In addition, gear changes result in different rotational speeds for a subset of parts. Although the rotational inertias and rotational speeds in any gear will be known and easily tabulated by a manufacturer, they present a problem for 3rd party researchers or feedback designers that may not have access to detailed vehicle design specifications. A simple solution to this issue is to estimate the rotational energy of a single hypothetical part that has a mass proportional to the vehicle mass and is assumed to rotate at a fixed ratio based on ground speed. However, a satisfactory estimate of vehicle rotational inertial is considered beyond the scope of this dissertation and therefore left for future research.

Measuring altitude

Estimation of altitude is challenging because of the lack of a standard built in vehicle sensor for altitude or grade measurement. Direct estimation of altitude is possible using GPS or a pressure-based altimeter. However, it is also possible to calculate road grade either with a vehicle-mounted tilt sensor or accelerometer. Taking the GPS case first, altitude measures are somewhat inaccurate due to basic issues of satellite geometry for ground-based receivers and tend to have both high-frequency and low-frequency errors. To deal with high-frequency GPS error the recordings shown in Figure 3 uses a 15 second average; this means that small hills and changes in road grade aren't immediately apparent or are muted in amplitude, a type of error that is less problematic than the alternative rapid fluctuations in readings that would otherwise plague the system. Low-frequency errors can safely be ignored since they generate only tiny amounts of potential energy in a given period. Accelerometers are inexpensive sensors but not ideal for this application due to long-term integration errors that slowly add increased error to the estimation, although accelerometer data has been shown to provide accurate estimates of road grade after sophisticated processing (Rogers & Trayford, 1984). The first option- that of a vehicle mounted tilt sensor could most easily solve this problem for manufacturers, and a GPS-based sensor could most easily solve the problem for 3rd party feedback devices that are not mounted in a fixed position to the vehicle.

Conclusion

Although the MPG metric has been a workhorse for consumers, policy makers, and researchers for many years, it is clear that the metric is critically flawed for real-time applications. One way to solve problems with the MPG metric is by including the contributions of kinetic, potential, and chemical energy to real-time energy economy, termed MPE (miles-per-energy). New vehicle types such as hybrids and electric vehicles (and mixtures thereof) are even more sensitive to the MPG metric errors due to their increased efficiencies and multiple fuel sources. Real-time feedback has been shown to have great potential for encouraging improved driver behavior, but this potential is limited by incorrect and misleading real-time MPG measures. The MPE measure presents a simple fuel-economy-like measure that can provide drivers with more accurate real-time information during many important driving events such as accelerations and decelerations, driving on grades, and during the use of hybrid fuel modes.

The MPE measure can foster improved driving behavior and fleet-wide reductions in fuel use if it is included in new vehicles. The MPE measure is additionally useful in the current context of multi-fuel vehicles and hybrids as it naturally incorporates the influences of multiple energy sources into a unified feedback measure.

Chapter 2: A review of behavioral theories for driver behavior applications

Introduction

The sociological field of behavior change has many potentially important lessons for transportation researchers studying driving behavior and feedback. In this chapter I present a basic review of each field and then discuss how to implement improved driver feedback based on behavioral theory. Two related problems with implementing theory based driver feedback are discussed; those problems are the generality of behavior theories and the driving context which can vary widely even within a single trip. The challenges of the driving context for feedback are discussed and detailed solutions are proposed that mesh with behavior-theoretic concepts. Overall, the most challenging issues are related to the theoretical treatment of energy, time, and the concept of social norms.

Behavior change theories

The psychosocial field of human behavior modeling is extraordinarily broad. Below, I will briefly discuss a variety of model types in order to provide the context for the use of the agent-based behavior theories used in the rest of this chapter and the dissertation as a whole. Although the reasons for using this particular category of models will be discussed, it is important to note that the model choice in many ways limits the bounds of the possible hypotheses and resulting analysis. For a broad review of behavior models that are useful in behavior change research, please see Jackson (2005).

The array of behavior models is so broad because models have been developed in many different fields for many different purposes, only some of which are clearly applicable to driver behavior feedback as it is formulated here. In particular, theories that ascribe the source of behavior to social level factors, including theories that emphasize social structure over individual agency in human behavior, are difficult to apply in this case since they do not emphasize the role of the individual in decision making. In a broad sense, the study of the energy or mode-choice effects of urban design and land-use present applications of structure-focused theory to driver behavior and mode choice. These areas of study emphasize the importance of infrastructure, and more generally any features outside the vehicle, to driver behavioral decisions.

Agency-focused models lay the onus of behavior on the individual agent and this perspective makes them particularly useful in the study of individual drivers. These models, including both utility theory and theory of planned behavior (TPB) and its variants, provide more room for hypotheses about driver feedback since the individual is considered a primary decision maker and the level at which feedback would be hypothesized to act. The theory of planned behavior and norm activation model are both examples of this type of behavioral model that place additional emphasis on the decision process and social factors rather than simply on individual utility (Jackson, 2005). Utility theory was historically built on concepts of individual utility maximization based first on economic and then on other factors, eventually becoming completely general in interpretation (Jackson, 2005; Smith, 1776). In contrast (and in response to utility theory) a distinct set of behavior models such as the theory of planned behavior include what might be called meta-utility factors that are meant to better reflect the actual psychological and social processes that occur in decision making. For example, although a personal goal may not have any intrinsic utility, the presence of a goal may influence decision making in a wide variety of circumstances. This category of meta-utility factors also includes perceived social norms, and perceived behavioral control (Jackson 2005; Ajzen 1980; Perugini and Conner 2000). Behavior theories that include meta-utility factors appear to have more relevance to social and environmental choices where the utility to the individual isn't clearly quantifiable, for example when environmentally sound behavior may take have a time cost or have negligible economic savings for the individual (Jackson, 2005).

While individuals control their own behavior, the agency of drivers is often limited by the structure of both society and socially produced systems such as road infrastructure, and this structure provides the context in which an individual operates. Driver choices are informed by social norms and rules (such as traffic flow and speed limits) as well as socially constructed infrastructure such as freeways or traffic calming construction that limit the driver's ability to choose a driving style. Since the agency-focused behavioral theories used in this study don't specifically include this type of structural factor as a source of behavior, and more importantly since structural factors such as driving laws or roadway infrastructure are not directly influenced by driving behavior they are treated as issues of context rather than model factors. It seems perfectly reasonable however (although beyond the scope of this discussion), that driver goals, attitudes, or other individual factors should in the long-term, through support of legislation, influence these structural factors. Finally, it may be the case that these structural factors could play a role in the formation of driver goals or attitudes as well.

The theory of planned behavior and related models

The theory of planned behavior (TPB) forms the core framework chosen for study in this dissertation. The TPB is one of a number of rational behavior models that include specific decision-making factors such as attitudes about the behavior, or perceptions of behavioral control. The theory of planned behavior has generated a particularly large literature of applications from studies as diverse as drug abuse prevention to drivers' propensity to speed (Tonglet, Phillips, and Read 2004; Conner and Armitage 1998). One persistent problem with applications is the experimental context, in particular the actual ability of individuals to change their behavior given the various constraints that they may face, or, one might add, various alternative goals that they may be simultaneously interested in achieving.

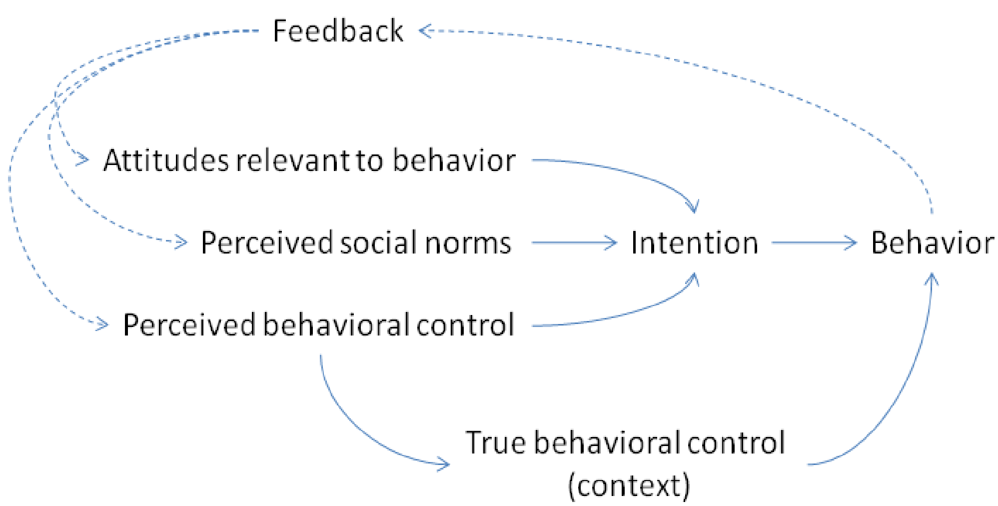


Figure 5: Theory of Planned Behavior. Dashed lines show the additional effect of feedback in creating potential for behavior change.

The TPB is a rational expectancy-value model, although the many variations on the original model formulation suggest that the model's efficacy is due largely to the core cognitive factors included rather than the expectancy-value structure as originally proposed by Ajzen (Ajzen, 1980). The basic cognitive factors included in the original TPB include perceptions of social norms, and perceived behavioral control as shown in Figure 5.

More recent research indicates that a variety of other factors play critical roles in behavior change, notably including goals, as described in the extended model of goal directed behavior (EMGDB) as well as personality (Jackson 2005; Perugini and Conner 2000). Ajzen's 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).

The TPB and driving behavior

The few studies that have applied the TPB in a driving behavior context have almost all focused on the use of the TPB to predict or reduce speeding behavior, an outgrowth of the health and safety related core of TPB research. The core concepts of speeding attitudes and perceived social norms were repeatedly found to be predictive of speeding behavior, although perceived behavioral control had mixed predictive power (Fleiter, Lennon, & Watson, 2010; Tonglet et al., 2004). It seems reasonable that the concept of behavioral control is not applicable to speeding behavior, since speeding is almost always possible. Ecodriving behavior on the other hand, seems much more likely to be related to driver perceptions of their own control over fuel economy. The findings of these papers also support the structure of the TPB for use in a transportation context where utility is an abstract concept and behavior may be more readily understood as a social and psychological decision process (Fleiter, Lennon, and Watson 2010; Forward 2006; Elliott, Armitage, and Baughan 2007).

Consumer research on fuel economy indicates that financial savings are of ambiguous importance to driver behavior. One study found that although saving money is attractive to drivers, it is unlikely that they have enough information or sustained interest to modify their behavior (Turrentine & Kurani, 2007). In addition, in Chapter 4 I find that our subjects were generally not motivated by cost information to change their driving behavior, whereas non-economic factors, in particular personal goals, did have a clear impact. Given this combination of ambiguous financial value with clear symbolic, attitudinal, or social value, it makes sense to apply non-economic behavioral theories (Jackson, 2005; Kurani & Turrentine, 2002).

Integrating feedback into behavioral theories

The TPB and related theories were originally meant as predictive models of behavior. Feedback theories on the other hand assume that these models can be integrated into closed-loop systems as shown in Figure 5. By integrating feedback into the TPB, it is hypothesized that information about the behavioral outcomes can influence primary factors (such as perceived behavioral control) and thereby generate a new behavioral outcome, which itself results in new feedback and on and on until the feedback no longer generates a new behavioral choice and an equilibrium is reached. Although this literature review did not find any similar continuous feedback applications of the TPB, it is commonly used in behavioral intervention design, especially in health fields (Ajzen 2002; Armitage and Conner 1999) .

Review of driver feedback studies

The literature on HMEI driver feedback is almost universally focused on studies of ad-hoc designs and their average fuel economy impact on test drivers. This focus on road experiments rather than the mechanisms of driver behavior change means that the literature is full of specific HMEI examples without any clear method by which it would be possible to understand the wide variation in experimental results or improve on existing HMEI designs. This gap in the literature is one of the primary motivations behind this dissertation, and the design of a behavior-theory-inspired HMEI is taken up directly in chapter 4. To my knowledge, this dissertation represents the first formal application of behavioral theory to HMEI design.

Figure 6 presents a review of the HMEI available literature at the time of writing (April 2011) and shows two main features. The first is that very few studies have been completed that include features suggested by behavioral theories, such as multiple temporal periods, or comparison information such as peer performance, goals, or other norms. The large majority of studies were based on simple feedback that consisted of a real-time numeric or graphical gauge display of MPG fuel economy. The second main feature shown in the Figure is that behavioral complexity has different effects depending on the duration of the study. Short term (one or two day) studies had a mean 6% increase in fuel economy, but showed a decreasing effect with increasing behavioral complexity. Long term studies on the other hand had a mean effect of 2% but showed an increasing effect with behavioral complexity. The long term studies reaching the higher levels of behavioral complexity appear to have a 4-5% effect. Sources and additional information about the studies used in this review are available in the Appendix.

The opposite trends may be due to the dynamics of short term and long term studies. Short term studies are more likely to result in a positive bias as individuals try to drive carefully to perform well in the experiment. One experiment even found that in the short term, individuals who were simply asked to drive more carefully increased their fuel economy by 10% (Greene, 1986). The suggestion is that in the very short term, the experimental effect may be responsible for a large amount of the effect attributed to some HMEI designs. In contrast, a simple design included in the review that was tested over many months resulted in no effect. The negative effect of behavioral complexity in short term studies may indicate that it takes drivers time to learn to use these more complex tools; an interpretation that is supported by the findings in chapter 5 that show an increasing effect of a behavior-theory-inspired HMEI over time.

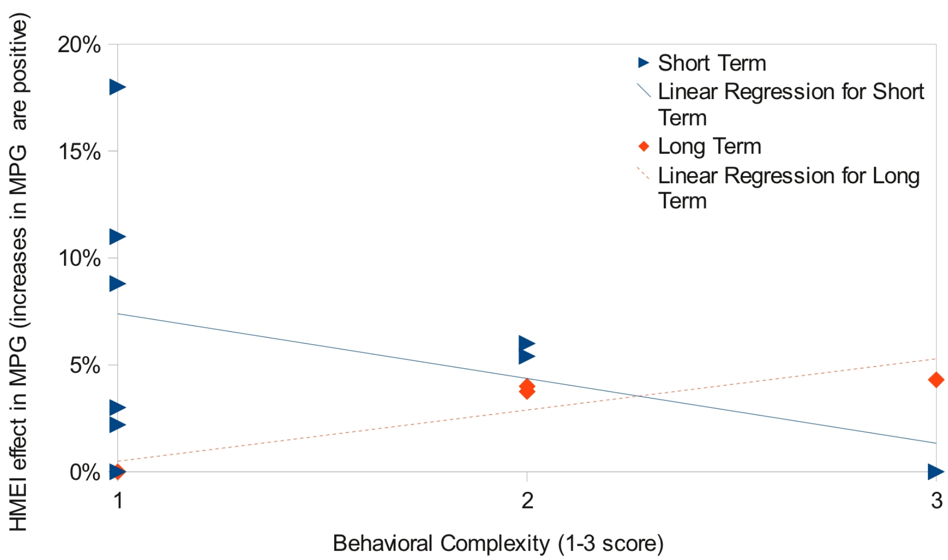


Figure 6: A meta-review of fifteen studies of the HMEI effect on fuel economy. The studies are grouped by study duration, with any study two weeks or longer in the Long Term group. Two weeks was chosen as a divide because many studies clustered within either 1-3 day or 2-4 week measurement periods. HMEI designs are rated for behavioral complexity using an ad-hoc categorization scheme based on behavioral theories, with simple real-time display receiving a 1 score, display with long term averages receiving a 2 score, and a display including goals, norms, or peer comparisons receiving a 3 score. Sources and additional information is listed in the Appendix.

Behavioral theory in the context of driver behavior

The application of behavior change theories to driver behavior presents a series of issues that aren't specifically covered in behavioral theory, yet have important implications for real-world HMEI implementations. These issues encompass a variety of situations and perceptual states, each of which has implications for the way behavior theories might be interpreted. Below I discuss the various contextual issues that need to be resolved in order to apply feedback effectively to driving behavior; how the treatment of time can influence driver perceptions (the temporal context); how structural factors that constrain behavior due to roadway design imply different types of feedback (the roadway context); how thermodynamic energy flows should be treated for improved driver perceived behavioral control (the thermodynamic context); and how variations on the social context of feedback could result in greater driver motivation (the social context).

Temporal context and the effect on goals

The specific period to which feedback is focused can provide qualitatively distinct types of feedback, with the different periods relating to distinct behavioral goals. In the most basic sense temporal periods are grouped into current and retrospective periods, with the current period being near-real-time information, and retrospective periods that can include anything from a full lifetime history to a relatively short period based on a predefined duration, distance, or event. Current information is useful while driving and especially while making behavioral adjustments or simply experimenting, whereas retrospective information is useful occasionally during the trip to observe performance and at the ends of trips or other periods to compare to relevant goals or external norms such as EPA values or other driver's reported scores. Event-based information would be useful in the period directly following the closure of an event, such as a stop or acceleration, or as a source of data for long term behavior scores or advice. An example of a recent implementation of multiple temporal period information is the 2001-8 model year Toyota Prius that includes both a tank average and a series of 5 minute averages. More recent HMEI implementations such as the Ford Fusion Hybrid have extended the fuel economy history to the vehicle lifetime, raising the question of what retrospective period will provide the most useful or motivating information to the driver.

The EMGDB states that driver goals will influence their behavior. Interviews with drivers reported in chapters 3 and 4 indicate that the the HMEI design will frame driver goals based on the periods available in the HMEI. This suggests that the choice of period is potentially important for driver perceptions of achievement, and also raises the possibility that drivers will have distinct goals that are dependent on the period. Thus, an individual might have a lifetime fuel economy goal, a different tank-to-tank goal, and a yet different goal for a 5 minute period.

Periods of longer duration will generally have more moderate fuel economy outcomes due to the averaging effect of many distinct periods. As an example of this effect, a trip goal of 40MPG might be easy to achieve in certain circumstances, whereas a tank goal of 40MPG for the same driver might be very difficult to achieve due to the other trips included in the same tank that have more challenging drive-cycles. As another example of goal specificity, an acceleration goal of 20MPG might be aggressive, but a deceleration goal of 20MPG would be so low as to be meaningless.

Rather than presuming that a single goal is appropriate in these various temporal (or event-based) contexts, it follows from the EMGDB that increased specificity of the goals to relevant periods in which they actually apply would encourage more aggressive behavior changes.

Even in the context of a single trip, the nature of vehicle technology (such as cold-start effects) and the roadway system (such as uninterrupted high-speed highways) result in fuel economy that is somewhat dependent on trip length. Therefore a time or distance based comparison or goal would be more reasonable than a single goal. Short distances present special problems for fuel-economy due to starting periods that are particularly inefficient. One solution to this issue is to provide a distance-based MPG comparison in the HMEI.

Retrospective periods can also be based on specific events rather than on a time or distance based period. A tank fuel economy measure (reset at each fill-up), and day-to-day average (in contrast to a rolling 24 hour history) measures are examples, each of which may benefit from distinct MPG comparisons. Alternatively, on-road events could provide an interesting way to define retrospective averages. Any major change in vehicle operations could trigger the display of an average score. For instance, the end of an acceleration event could provide a score that would be directly comparable to other acceleration events. This method would have an easily understandable relationship to the driver's actions and therefore might be more motivating than time-based averages such as the 5-minute average.

The current period is actually a very short retrospective period. To calculate energy use and distance the feedback display receives data at short (usually sub-second) intervals that describe the distance driven and energy flows in the past period. The calculation is therefore not quite instantaneous, but if it is reported directly (without averaging) it can appear instantaneous to the driver. However, calculations at that rate have various problems due to data precision and the non-continuous nature of engine controls. For instance, rounding errors can make vehicle speeds appear to fluctuate between two values when the speed is actually constant, and in between the two values. In addition, automatic engine controls may fluctuate rapidly to prevent excessive tailpipe emissions. None of these types of signal noise are useful for the driver and may even detract from the effectiveness of the feedback as inexplicable, rapid fluctuations will tend to confuse and distract, rather than inform. Therefore the feedback designer is required to strike a balance between the immediacy of the information and the reduction in noise. The amount of averaging is specific to the vehicle communications protocol, the rate of signal transmission, and possibly other vehicle characteristics. Pilot testing and informal experimentation with a custom HMEI device (described in Chapter 4) resulted in effective averaging periods of 1-3 seconds. Although longer periods would continue to smooth the signals, they reduce the ability of current information to inform the driver of the effectiveness of a specific action as they glance towards the feedback display directly after performing an action (for instance easing off the accelerator and then glancing to see the effect of the change on energy economy).

Combining temporal information

The distinct periods for which current, retrospective or event-based information is useful suggest that a feedback device that provides them in sequence at appropriate times could have a strong behavioral effect without a large number of distinct displays. For instance current and trip-period feedback could be displayed together on a single screen. After an event happens the screen could show the event summary information before reverting to the current information at the start of the next event. At the closure of the trip the same information panel could then display retrospective summaries such as trip, tank, and lifetime scores. This approach could provide a wide range of temporal feedback at appropriate times in a visually compact form.

The roadway context and restrictions on driving behavior

The roadway provides the most obvious contextual factor that might influence how individuals interpret or make use of feedback. Speed limits for example are structural restrictions on driver choice that are, although not strictly enforced, roadway specific factors that constrain the driver's choice of speed and therefore energy economy. Different types of roadway also imply different drive cycles. For instance highway driving might be thought of as primarily steady-state, whereas neighborhood roads are often stop-to-stop and are therefore composed of accelerations followed by decelerations with little steady-state driving. The impact of driving style on MPE is largely dependent on these differing drive cycles, making them important contextual factors that will play a role in both perceived behavioral control and goal achievement. From the driver’s point of view, this means that when the current trip is compared to all trips, the possible variation in outcome due to behavior will appear broader than when compared only with trips that have roughly similar drive-cycles. This misinformation could lead to unfounded expectations of performance, frustration, or an undeserved sense of achievement. There are various possible solutions to this issue including location or route-based comparisons made possible with GPS measurements, distance-based measurements that might generally separate highway from city driving, or drive-cycle based measurements that could compare the current trip to other trips with similar speed profiles.

The solutions to the roadway context presented above are primarily solutions to trip level measures, although the GPS-based location-specific measures could be applied to current information as well. It might also be useful for drivers to separate the issue of trip level outcomes from event-based or current outcomes for better understanding of individual performance. For the current context, event-based information could solve much of the roadway context issue since each acceleration event, for example, would be compared to other acceleration events, irrespective of the surrounding drive-cycle, and thereby avoiding specious comparisons between different types of trips.

The thermodynamic context

On a very basic level, the role of feedback is to provide accurate, relevant information to the driver. MPG fuel economy is only sometimes accurate and is only relevant when the primary fuel dominates the other energy sources, such as during steady-speed driving at zero grade. To have higher accuracy in various driving situations, especially during accelerations and relevant information during decelerations or at other times that secondary energy sources are in use, the additional energy sources (kinetic and potential) need to be included in an energy economy measure as described in detail in chapter 1.

One practical matter observed with participants receiving energy economy information is that it can be confusing to compare to the standard MPG measure. Since MPG is reported by the EPA and may be easily calculated on a tank-to-tank basis, drivers might be disappointed with the low reported MPE value (assuming it is presented in gallon-of-energy units) since it will (properly) include additional energy use. In the case of plug-in hybrid vehicles for example, both current and average MPG values can appear very high since plug-in battery electricity is not included in the MPG metric even though it is used to help propel the vehicle. When including this electricity in the MPE measure the result is a much lower average value that, although thermodynamically reasonable, does not match a driver's notion of gasoline efficiency. Similarly, the use of an energy economy metric precludes the simple calculation of range that is possible using traditional vehicles (an X MPG car with Y gallons will travel X*Y miles before running dry), meaning that energy economy no longer has a direct relationship to gasoline gallons used. To avoid this confusion altogether it could be possible to use a distinct scale and rather than reporting energy economy in thermodynamic “gallons,” one could use miles per kwh (or the author's personal favorite, meters per watt-hour) or some other arbitrary measure that would not be confused with MPG. However, as MPG is likely to have a special resonance with consumers who have used it for many years, some of the built-in meaning of any economy measure would be lost if it were to be reported in alternative units. Any new metric will mean that new driver attitudes, perceived behavioral control, perceptions of social norms, and personal goals will have to be formed before the feedback can have the full impact predicted by behavior theories. More research needs to be done in this area to resolve these issues and develop a metric that is both meaningful and clear.

The social context

The TPB, EMGDB, and Norm Activation Model (NAM) all stress the role of social information to behavior change (Perugini and Conner 2000; Jackson 2005).Social information is generally included as a normative form of information, that is, social information provides cues that transmit information about how a driver should behave, regardless of the utility of the action. For instance, stealing money when one is sure to get away with it may have high economic utility, but would need to be weighed against the social norms surrounding theft. In the context of driving behavior, this type of information could motivate low achievers by providing a goal for achievement. Conversely, a recent study of residential energy found that social comparisons can also have negative and de-motivating effects for some recipients (Ceniceros, 2008).

The problem for a driving behavior implementation of social norm feedback is specificity: which norm of what social group should be used? Many social comparisons could be made – fuel economy outcomes of different household members, peers, other drivers of the same make and model, all drivers, drivers within a nearby geographic area, etc. How these various peer groups might influence the driver is still unclear. One practical issue that constrains the use of social information is the availability of this data within the HMEI itself. If the feedback device is not connected to the internet it can only display a predetermined set of historical peer data or logged vehicle data. The logged vehicle data potentially has social information if multiple drivers use the same vehicle. In this case, it would be possible to display comparison information that would encourage intra-household comparisons. When presenting historical peer data, it is yet to be determined what statistic should be presented for the best effect, for example the peer MPG mean, range, or some type of percentile ranking. Internet connected devices could have various other social components, such as a real-time (or recent) peer comparison to another driver or set of drivers. One benefit of such a system would be that each driver could choose what peer comparison she would like to see, possibly making the information more relevant to each individual and therefore more motivating.

Traffic as social information

Driving is by default a social exercise since most drivers experience traffic which may be thought of as a form of social norm. If traffic is faster than the driver's desired speed it provides both a normative cue (that of feeling slow, “lame”, or just generally left-out) and can lead to unsafe conditions if the driver does not accelerate to the same speed as the herd. The social group here is a transient road group generally composed of individuals unknown to the driver. However, drivers in this study, as reported in chapters 4 and 5 reported strong social feelings when confronted with traffic situations that encouraged faster driving. The situations can generally be broken out into two categories: freeway safety, and feeling slow.

Taking freeway safety first, many drivers increased their freeway speed due to traffic pressure. Although this might be considered safe driving (moving with the speed of traffic), it is important to note that in many cases the traffic pressure is at speeds exceeding the speed limit, a generally recognized risk factor for accidents (Young, Birrell, & Stanton, 2011). The high proportion of speeders present drivers with a paradoxical choice: drive unsafely at safe speeds, or drive safely at unsafe (or at a minimum, illegal) speeds. Although a discussion of speeding is largely out of the realm of this study, it is interesting to note that in Northern California during the study period efficient drivers reported pressure to increase driving speeds by drivers who were breaking current laws. Clearly, better enforcement of current speed limits would buoy the efforts of ecodrivers.

The feeling of being a slow driver is the normative component of traffic pressure. Drivers even in low-pressure city driving feel strongly motivated to speed up when they feel they are holding up traffic, even if they are moving at the speed limit. The implication for behavioral theory in the case of driver behavior is that any social information transmitted through the HMEI will compete with the normative social cues coming from the traffic environment.

Emissions as social information

Driver responses to CO_2 emissions feedback, as reported in chapter 4 of this dissertation, indicate that emissions (given in pounds of CO_2) are symbolically important but lack context by which drivers could make use of the information. One possible solution would be to present CO_2or other emissions feedback as a social comparison. This would provide an automatic context for interpretation (for instance, X lbs for this trip is lower than the average for other drivers), and could be made specific to other peers using an internet connected device or to multiple drivers using the same vehicle. In addition presenting emissions feedback in the form of a social comparison would highlight the social importance of energy conservation, potentially improving the motivational power of the feedback.

Conclusion

Behavioral theories such as the Theory of Planned Behavior, The Extended Model of Goal Directed Behavior and the Norm Activation Theory all provide rich sources of factors for the study and design of driver behavior feedback devices.

It is likely that different temporal periods have different uses to the driver and may be of interest to some individuals but not to others. Certain temporal periods are likely to be particularly important; the current period (real-time or instantaneous) allows individuals to experiment over short periods or observe extreme values that may be of special symbolic importance (such as reaching 99.9 MPG in the Prius); the trip or round-trip average allows drivers to compare between similar trips and set trip-related goals; and very long-term such as tank or lifetime periods are relevant for long-term goals and overall performance evaluation comparable to EPA values or other drivers. Due to the various uses of different periods, it is likely that an effective feedback system will include multiple periods. The various times at which the information is useful suggests a solution for implementation which is to display different temporal periods at different times based on vehicle operations.

The thermodynamic context has a fairly clear solution, which is to include energy economy measures in real-time information in place of the traditional MPG measure. This new energy economy measure can provide large advantages over MPG, although more research is needed to determine what scale should be used to provide the information in a familiar and understandable context without conflating it with MPG.

The roadway context is defined largely by roadway type and drive-cycle. Event-based or location-based feedback may provide useful current information and reduce specious comparisons. Entire trips may be compared using a distance or drive-cycle based scale, and round-trip summaries will generally provide better comparison information than one-way summaries, although the use of MPE rather then MPG metrics reduces the benefit of a round trip measurement due to the inclusion of gravitational potential energy in the MPE measure.

Driver goals may be period specific and a display that includes a driver goal may therefore benefit from managing the driver expectation by displaying goal-related information on scales that are appropriate for the temporal period, or even provide feedback that explicitly includes the period as a contextual dimension. For instance, normative information such as social comparisons could be based on trip distance or another relevant period.

The inclusion of social comparisons in feedback is perhaps the most challenging. Although a peer comparison may be a motivating goal for some drivers, everyday experiences on the road provide strong social feedback in the form of traffic that can easily overwhelm an in-vehicle display. One possible solution is to increase the salience and motivating force of social comparisons by using a dynamic information source capable of providing the display with data about real-time peer performance or other relevant statistics.

Behavior theories suggest that there are a number of ways that current HMEI designs can be improved. Use of temporal periods that have special resonance with driver goals, and including distinct goals for each period could encourage drivers to maintain and improve on their best habits. Display of MPE rather than MPG may provide drivers with a more accurate sense of perceived behavioral control and encourage optimal driving in varying conditions. Distance-based trip outcome, event-based summary, or location-based comparisons are likely to improve the driver's understanding of their true control over MPE and avoid specious comparisons that can undermine the drivers motivations. Finally, inclusion of social emissions comparisons might encourage more environmentally responsible behavior by placing a driver's emissions in a useful context.

Chapter 3: An energy information feedback field test: driver responses and behavioral theory

Introduction

Studies from both industry and academia have reported that improved driving behavior could save up to 25% of passenger vehicle energy use and, by extension, a similar proportion of GHGs without investment in new drive-train or fuels technology, changes in travel patterns, vehicle ownership, or land use (Adell, Varhelyi, & Hjalmdahl, 2008; Barkenbus, 2010; Larsson & Ericsson, 2009; van der Voort, 2001). However, the results vary widely and some field experiments suggests that closer to a 5% reduction in fuel use and GHGs is a more realistic estimate due to the dampening effect of numerous real-world factors (Barkenbus, 2010; Barth & Boriboonsomsin, 2009). and actual energy use rates is distributed among the cumulative actions of millions of drivers, each embedded in the flow of their own trip making and driving style, and each operating within a context that is largely defined by factors out of their direct control such as roadway infrastructure, weather, and the traffic flow that is the result of all other drivers' trip making and driving styles. Feedback provides drivers with a new way to interpret and modify their actions, but it is only effective with their active participation. Whereas previous studies have focused on determining the average effect of in-vehicle feedback , this chapter places the emphasis on how and why (or why not) drivers incorporate feedback into new driving styles in order to better understand the set of factors are most important in fuel economy feedback. The Theory of Planned Behavior (TPB) suggests a number of factors important to explaining behavior change at the individual level. The TPB has been used extensively and successfully in many fields including public health, residential energy use research, and in transportation safety, although to the knowledge of the author it has never been applied to fuel economy feedback (Elliott et al., 2007; Lynne, 1995; Tonglet, Phillips, & Read, 2004).

Methodology

This study is one part of the UC Davis Plug-in Hybrid Vehicle (PHEV) Demonstration Project which ran from mid-2008 until mid-2010 and included 12 Prius vehicles modified to operate as plug-in hybrids. The vehicles were placed in households in the greater Yolo-Solano-Sacramento counties region of north-central California. With the exception of dual use of the battery icon in the Prius energy monitor to sequentially show the state of charge of the supplemental (grid-rechargeable) battery and then the stock Prius battery (once the supplemental battery is discharged), the OEM display is unmodified from the original. Feedback and driver responses about the PHEV functionality in particular are not included in the analysis presented here. For more information about those findings, see Kurani et al. (2010). In addition to the OEM Prius display, participants were given access to a website displaying a large amount of information about the use of their vehicle for the duration of their participation, including summaries (last week and month), comparisons, and a detailed driving log.

Study participants were recruited with the help of project partner AAA based on criteria including adequate insurance levels and location within the Yolo-Solano region of California, and access to a plug to recharge the vehicle among other details, the complete description of which are available in the full report. In total, 43 households and 98 participants are included in this analysis each keeping a vehicle for either four or six weeks. In one subgroup, the PHEV functionality was deactivated for the first two weeks.

In another subgroup, website access was only given for the final fortnight. By the end of the study, however, all participants had at least two weeks of driving with access to both the OEM display and the website. At two week intervals and at the final day of each participant's study period an interview was conducted that spanned a range of subjects including their response to the interface. In some cases the participant volunteered statements about the feedback, and in some cases the interviewer asked prompting questions. In all cases the interviewer attempted to allow the respondent to answer freely and take the discussion in (most any) direction that interested them.

A.

B.

C.

	Today	Last 7 Days	Last 30 Days
		Trip Statistics	
Time Driving	57 m	10 h 14 m	1 d 10 h 7 m
Trips	5	36	109
Distance (mi)	31.5	367.8	1308.6
Fuel (gal)	0.5	6.3	22.7
Net Dc (kWh)	-3.7	-30.6	-104.1
Est. Cost ($)	$2.54	$29.69	$105.79
Est. $C0_2$ (lbs)	11.9	149.4	536.4
		Charge Statistics	
Time Plugged In	1 h 4 m	3 d 13 h 1 m	15 d 7 h 29 m
Charge Sessions	1	10	35
Net Ac (kWh)	0.8	28.5	105.4

D.

	MPG	$c0_2e$ (lbs) / mi	$ / mi
		Today	
UC Davis 1763 00	62.6	0.4	$0.08
Fleet	54.9	0.4	$0.08
National Average	19.8	1.2	$0.20
		Last 7 Days	
UC Davis 1763 00	58.1	0.4	$0.08
Fleet	55.2	0.4	$0.08
National Average	19.8	1.2	$0.20
		Last 30 days	
UC Davis 1763 00	57.6	0.4	$0.08
Fleet	54.6	0.4	$0.08
National Average	19.8	1.2	$0.20

Figure 7 A-D: Description of Feedback Available to Participants. A & B show the OEM Prius energy displays used in this study. C & D show parts of the V2Green website accessible to participants. For a complete description of available information please refer to Volume 1 of Kurani et al., 2010.

This paper presents selected results of the final interviews of 43 households using a basic method of computer-aided content analysis known as Keyword In Context, or KWIC (Weber, 1984). Transcriptions of the final interviews were imported into a common spreadsheet program such that each statement was on an individual row. Information about the household and speaker was also on the row for later analysis. At this point the dataset included approximately 18,000 participant statements (many of them were short utterances). A set of approximately twenty keywords were used to find relevant sections of the transcripts. Then statements surrounding the keywords were read in order to manually flag relevant passages and to develop a preliminary set of themes. During a second reading of the passages sections were identified that fit specific themes. The themes were also expanded or modified as needed during this closer reading. In a final reading, the statements were checked to make sure themes hadn't been missed and that they had been consistently applied throughout the process. Once theme identification was complete, the dataset was reduced to unique theme-participant combinations, that is, themes were not counted twice for a single participant even if the theme was identified twice or more. This list of unique participant-themes is the basis of the content analysis present in the results section of this chapter.

The Theory of Planned Behavior (TPB) provides the basic theoretical model of behavior change considered in this study, and the theory is described in detail in the previous chapters. Reformulated in the context of this paper, the TPB and EMGDB suggest that for drivers to achieve higher fuel economy they must first create either an intention to drive more efficiently (TPB) or a fuel economy goal (EMGDB). Their attitudes about fuel, the environment, and economical driving behaviors (among others) are likely to influence their decision. Their perceptions of social norms around driving, including both on-road perceptions and general beliefs about the behavior of others will help them decide if they should drive differently than in the past. Finally, their belief (or lack of belief) about their own ability to drive in such a way as to increase their fuel economy will influence their decision to act. This conceptual model is shown in Figure 8. As neither the EMGDB nor the TPB mention the influence of behavioral context, such as the timescales discussed in Chapter 2, contextual factors are not shown in the figure, but should rather be considered as the environment in which the process takes place. However, applications of these theories must by definition include either explicit or implicit treatment of time and other contextual factors to provide feedback, since the passage of time or events provide the basic framework for measurement of energy use. Figure 8 therefore represents a generic application of the theory to the driving context that should be customized for each context included in the HMEI. For instance, a trip-based measurement may be compared to other trips based on similar drive-cycles as described in Chapter 2, but instantaneous measures may be placed into the energy context of the vehicle as described in Chapter 1, whereas tank-to-tank measures may be long-term enough to be compared directly, as described in Chapter 2.

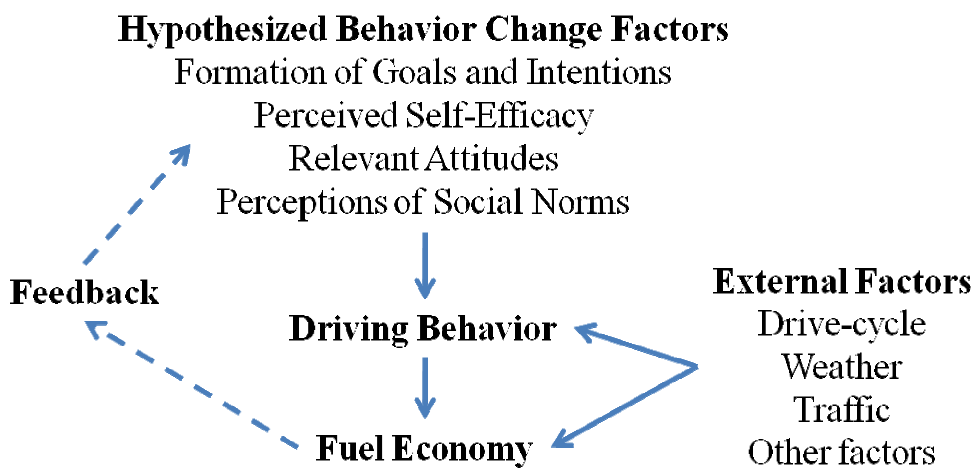


Figure 8: A conceptual model of the effect of feedback on fuel economy.

Results

Themes

Analysis of the driver responses as described in the methods section yielded thirteen distinct HMEI–related themes regarding energy feedback discussed by the participants. The themes and their incidence in the interviews are summarized in Table 2. In the section below each theme is examined and illuminated with a few quotations from study participants. Although the response frequency is included in the results for the purposes of exposition, the reader is cautioned not to extrapolate the proportions to the general public because of the specificity of the northern-California sample, the particularities of the single type of vehicle, and the requirements to participate in the PHEV demonstration. No demographic or other adjustments were made to the data.

Table 2: Content Analysis Results. Themes are listed in descending order of total mentions.

Theme	Total Mentions of Theme		Proportion of Respondents Who Mentioned Theme	
	OEM Display	**Web-Based**	**OEM Display**	**Web-Based**
Changing driving behavior	39	2	40%	2%
Strong emotional reaction	16	2	16%	2%
Experimentation for it's own sake	18	5	18%	5%
Personal goals or competition	27	4	28%	4%
Extension to other areas	16	2	16%	2%
Purely descriptive interest	20	19	20%	19%
Novelty wearing off	13	13	13%	13%
Distraction	21	3	21%	3%
Confusion	25	2	26%	2%
Too much effort needed	2	19	2%	19%
Time pressure	14	0	14%	0%
Traffic pressure	14	0	14%	0%
Additional guidance desired	12	16	12%	16%

Total number of Mentions	324
Total Respondents (n)	98

Changing driving behavior

The ultimate goal of the HMEI is to motivate behavior change, and this change was measured by identifying participant statements that describe changing driving behavior in response to the HMEI. However, it is also likely that the experimental context led many of the participants to engage in this kind of behavior, as the vehicle technology itself may have sensitized them to fuel economy. That said, the statements made by participants point toward a strong association between the observation of real-time feedback and the choice to drive more economically.

174504 Female: “...it sort of became a bit of a game to see if I could cruise up to the stop sign so I could charge up some more and then I’d check the monitor and see if I’d gotten any more wattage...”

174601 Female: “...when you accelerate that the MPG goes down and then when you don’t, when you cruise, it goes up. I cruised more or I tried not to accelerate as much so I certainly paid attention to the little diagram... it's very responsive It doesn’t even take a second to show you what you're doing.”

174604 Male: “And there were times I tried to be as efficient as I can, trying to, you know, try to maximize the gas that I had in that tank by just coasting here and there like down the hill and on the way to Monterey that kind of deal. Because I was trying to push for as many miles as I can on that one tank of gas.”

Strong emotional reaction

Emotions such as liking, disliking, joy, disappointment, etc. may be considered indications that strongly held attitudes or beliefs are being activated or challenged, and therefore fit into the theoretical framework shown in Figure 8 under “Relevant Attitudes”. The specific attitude or belief being activated, if a single one is even identifiable, is sometimes challenging to understand in this type of study, as only the statements volunteered by the participant can provide a clue to the basis of the emotion. However challenging to understand, various circumstances in the study such as achieving very high fuel economy or watching the fuel economy fall after a high period resulted in participants experiencing strong emotions.

175203 Male: “But I felt kind of good because I looked at the website thinking wow it’s still much cheaper than gasoline.”

175304 Female: “Last time I was really excited driving to work because I was getting close to 80 miles per gallon and then when I realized most of my battery had been used up getting there and I was going to you know I wasn’t going to get the same kind of mileage coming back that was kind of disappointing...”

175306 Male: “...it seemed like this idea of keeping it charged because it was so awesome to go down the road and see 99.9 all the time and then the effect of seeing, “oh the battery just shut off,” and all of a sudden, boom. It's in this whole other, you know, disappointing realm like oh we're not at maximum anymore.

Experimentation for its own sake

Experimentation is a specific type of behavior during which the driver tests the capability of the vehicle during a period of learning. Generally speaking, static behavioral models don’t account for this type of experimental, even playful, behavior since it is a form of learning, rather than equilibrium behavior. However, the propensity to experiment is also an indicator of the driver's awareness that she can change the fuel economy outcome, and therefore indicates a perception of self-efficacy, as postulated in Figure 8.

174602 Male: "..yesterday I went to Rio Vista. You know it's pretty much all flat except there were some little hills right at the end. But you know to see if I'd, sort of out of curiosity see if I could get the keep the mileage up really high by you know just driving a little more carefully or whatever."

175004 Male: "Only to play with testing... I mean I didn't do, I did it very consciously to try to drive the same speed situation just to see what it would do."

175007 Female: "Where's the energy coming from? You know, if I drive a certain way is it going to change? And I never really could figure out a pattern, but it was really a lot of fun you know driving it every day, and I felt a little sorry for my other car."

Personal goals and competitive behavior

Goal-setting and competition were closely inter-related themes, suggesting that a competitive drive to achieve a higher score than a person or group might be considered one form of the more general concept of goal-setting. Participants told of setting personal goals, including certain meaningful (to them) fuel-economy values, driving with higher fuel economy than the study fleet average (which was available to them on the website), or, most commonly, performing better than other household members. These statements clearly support the inclusion of personal goals in the behavioral model.

174807 Male: "So again today I just looked at it because I was trying to get it up to 99.9 before we gave it back. I got it up to like 99.1 when I parked at my last client's office and then driving home the battery had run out so it went down to about 97 something."

174807 Male: "I would drive substantially more conservative and slower. I would consciously drive slower to try, and like I said, it became a game. I wanted to see if I could do a whole tank on basically over 100 [MPG]. My original goal was actually to be able to turn it into you without using any gas or hardly any gas from like last time I filled up."

175201 Female (to husband): "You're messing up my fuel mileage."

Extension to other vehicles or areas

Extensions occurred when participants responded to their experiences with feedback by reflecting on energy saving potential beyond the study car, sometimes in trip-choice, vehicle purchase, household energy use, or other situations. As this type of reflection might not lead to higher fuel economy in either the PHEV during their trial use period or their own vehicles afterwards, the potential for in-vehicle feedback to result in other energy-saving behavior changes is an interesting possibility that could potentially be observed within the context of the proposed model in the form of changing attitudes about energy use in general.

175006 Female: “Yeah that's really cool. Like I said, it would be cool to have that little computer thing for lots of different things. I mean I can think of all kinds of applications.”

174606 Female: “I am and I'm perturbed actually that I'm getting 19 to the gallon in my little SUV now.”

175202 Female: “Yeah he’s even driving the van different now.”

Purely descriptive interest

Reading, watching or absorbing the feedback in an almost passive manner is termed “descriptive,” since it is a type of interaction with the feedback that does not involve behavior, attitudes, or active reflection. This kind of behavior could reflect a hidden first stage in behavior change, as the driver processes the information before using it to activate a change in behavior. In this case, passive reading of information could indicate that the behavioral model requires an additional stage (or alternate path) of information processing between feedback and the supposed behavior change factors listed in Figure 8. Alternately, purely descriptive interest could simply reflect a lack of necessary attitudes, perceptions of self efficacy, goals, or intentions which would otherwise combine with that information to generate behavior change.

174604 Male: “Did I use the information? Yeah it’s more entertaining. It’s just to satisfy my curiosity. I didn’t use the information, you know, for example, okay I’m not using as much electricity versus gas or something - let me change how I go down this hill or something like that ... let off the gas. No, it didn’t steer me that way.”

174902 Female: “When I would see it drop to like eight miles an hour while I was flooring it, it was like maybe I shouldn’t drive like this. But I didn’t actually change my driving style.”

175203 Male: “I kept just glancing real quick to see, even when I was driving to the ocean on the hills, to see how long it would take before the gas engine would kick in and then how soon it would kick out and stuff, so I was always constantly just scanning it real quick to see what was going on.”

Novelty wearing off

The frequency of use of real-time or ex-post feedback can dwindle over time as individuals who found it interesting at first either stop needing to view the information in order to achieve their goals, or simply get bored of seeing the information. The sources of the effect are widely varying, but include two major subthemes of 1) a lack of perceived value in the website’s historical information and 2) the reinstitution of older habits, driving styles, or attention after a period of experimentation with real-time feedback.

174505 Male: “Well I think I mentioned before how I tend to watch the mileage, the instantaneous […] gas mileage gauge. And it's tended to slow me down a little bit so I can maximize that mileage. But I did actually notice the last week that, and who knows whether it's because I wanted to get home or what the deal was, but I started to creep up a little bit faster and worried less about the mileage. And maybe the newness was wearing off or whatever. But I noticed that personally with me that at first it was more okay let's see what I can get out of this thing. And then after that it's like less about that and just regular driving habits.”

Interviewer: “Do you think if you had the car long-term that you would use a website like that?”

174604 Male: ‘Not on a regular basis. Only when, say, let’s say if I was maybe going on long trips or something like that then I’d be curious, “okay how much gas did I use versus electricity,” things like that. I mean towards the end, maybe until the later part of this month I wasn’t in the website as often as I was in the beginning because there was more of a curiosity keeping track…”

174605 Female: “I think I just got used to it. Yeah, probably looked at the screen more in the beginning.”

Distraction

Participants mentioned two distinct themes within driver distraction. One was a compulsive feedback-watching behavior that distracted them from the primary driving task. The second theme was self-regulation of concentration, where a driver would purposefully choose not to watch the real-time feedback if she felt it was distracting. Distraction is uniquely important to drivers, so the ability of feedback to motivate behavior change with a minimum of distraction is very important, and the study of driver distraction is the subject of a separate body of literature. The conceptual model presented here, however, doesn't have a place for distraction. It is possible that the information presentation style, raw amount of information, or some other attention-relevant metric should be included in the model along with the previously mentioned 'information processing' step. Such a model input could serve both to reduce unexplained variance in an empirical test of the model and to encourage feedback designs that minimize the distraction, which is itself a current strand of research (O Carsten & Brookhuis, 2005).

175001 Male: "I would try to watch what was going on there but I found like it was like talking on a cell phone while I'm driving, you know, and I'm doing that and it was distracting me from the driving..."
175004 Male: "Lucky I didn't get into a wreck. No, actually."
174902 Female: "Just seems dangerous to me."
174904 Female: " I love the fact that it's [...] getting, you know, such amazing gas mileage but you know ultimately it's a car and I'm going to, you know, I'm driving. I'm not staring at the screen the whole time. You know what I mean, like I can't divide my attention that way when I'm driving."

Confusion

Confusion about the information seemed to be due to the large amount of information available on the display, or in other cases to a general lack of understanding of the underlying principles of vehicular operation. Reducing confusion is likely to both increase perceptions of self-efficacy as well as reduce unnecessary distraction.

174702 Female: “I mainly looked at the instruments. I mean, I would go from the energy to the consumption. I’d flip it back and forth to see - try to get the little cars going.”

175001 Male: “And it’s a little misleading to me because everything is moving. Anyway it seems like so I was kind of puzzled.”

Too much effort needed

One theme that applied more to the ex-post web-based information than the real-time information was the effort required to go to the URL and log in. Many participants never viewed the website for that reason, or only viewed it once. Real-time information was the default display in the vehicle, and possibly for that reason, did not strike participants as requiring effort, although the statements about distraction shown in that section could be considered to be an outcome of applied effort.

175301 Male: “Never went there. Oh, I did one time I think. Yeah, initially when you told me. But I’ve been very busy.”

174501 Female: “… it's been a really busy time for me. I would have been checking it probably almost every trip otherwise just to see.”

174601 Male: “I was really looking forward to seeing what's happening and learn more about it, and kind of see the driving pattern style. But yeah, just a matter of time. We didn’t have the 20 minutes to get there and learn.”

Time pressure

A feeling that one must travel quickly due to personal or professional time constraints was an alternative goal that could prevent participants from maintaining an efficient driving style. This was one of the few explicit trade-offs discussed by participants in relation to the feedback or economical driving habits. However, some participants also discussed situations when they drove slowly but arrived at the destination in a normal amount of time. In the conceptual model, beliefs about the value of time would appear among other attitudes as predictors of behavior change.

174702 Male: “I run late sometimes so I kind of hurry myself when I shouldn’t be.”

175101 Male: “…sometimes you know, like I don’t want to be late for work and so I’d go faster…”

174807 Male: "…because of stoplights it's like a couple minute difference… I followed my dad home because we work together. And so we were in separate cars and we literally got home at the same time I was driving totally grandma, like totally slow."

174901 Male: "You get to the destination as fast as some of the people that are pretty heavy footers."

Traffic pressure

In addition to the internal pressure of getting around quickly, respondents who modified their driving style felt strong pressure from other traffic that would pressure them to accelerate faster or maintain higher speeds. Traffic pressure creates both a social norm component relevant to the behavior change factors in the conceptual model, as well as an "external" factor shown in Figure 8 due to the effect of certain traffic conditions to force drivers to move with the flow of traffic.

175101 Male: "…I found some optimal speeds on the highway. Oh and that was the only other experience that was a negative was in trying to get that best mileage. I knew I was going slower a lot of the times than the rest of the traffic, and had to go in the right lane and just, you know, realizing that I'm one of those drivers that always irritated me - but it's different when you're doing it. But yeah you know I would try to not overdo that."

175306 Male: "Okay sometimes I'm in that mode of, "I just want to drive this and maximize the mileage," and so you pull into a stream of traffic and you know you're […] trying to stay off the gas and so you have a slow acceleration up to speed and sometimes people will come up behind, and I honestly have the sense like, well, I don't want them to think that hybrid vehicles are lame, so I'm going to just like pull ahead here, you know, like I don't want to be holding up traffic with a hybrid so I'll make sure I'm not you know…"

174901 Male: "On the freeway you better be going 70 or you'll get run over."

175001 Discussion:
Female: "…at first I was trying to stay under, like in town, 35, because I thought, "oh well…""
Male: "But when you get somebody giving you the finger you just better speed up."
Female: "Yeah, …then I just drove my normal way."

Additional guidance desired

The HMEI could spark an interest in other, related information that participants would then independently seek out answers to or simply ask the interviewer. For such an individual, the raw fuel economy number wasn't adequate information; she was looking for a way to place that information into a broader context. This tendency to seek normative information fits into the conceptual model both in the sense of goal formation, "What fuel economy should I get?" as well as self-efficacy, "Is it possible to get higher fuel economy?"

174701 Female: "But I thought it was useful to at least kind of have an estimate just for comparison, like from day to day. I kind of use it like that, as a comparison, like a workday versus a weekend."

175004 Male: "And the normal cliché about a fully gasoline automobile is what, you cruise at 45 or something […] to get the super mileage. That's what they say. You go faster than that then the wind resistance and so on … but it's all kind of B.S. because they're making assumptions about the gearing. […] So anyway with this car in general you don't know anything about speeds and fuel consumption. People should just know that. Anyway, I mean it should be, and maybe it is for previous people on other websites that you get the best overall lowest cost in travel at […] 53 miles an hour, something like that."

175004 Male: " But then nothing ever tells you what 50 watt-hours does in the minus category of gasoline. How many gallons of fuel […] does that mean do you know? Do you know?"

Differences between real-time and ex-post feedback

As described in the Methods section, the participants were presented with both real-time (OEM Prius display) and ex-post (web-accessible logs) information. Differences in the response to those types of information were observed, as shown in Table 2. To observe the differences between the uses of the information by feedback media, the response counts were normalized to the total unique responses by type of feedback, and shown in Figure 9.

The ex-post information was found to be primarily used for descriptive information as well as guidance or contextual information, although across the 43 households it was often entirely ignored due to the amount of effort required to log in and view the information, and didn't hold the participants' interest for repeated viewings.

Real-time feedback on the other hand, was more associated with factors related to behavior change (a discussion of those factors is in the following section) including reported behavior change, emotional responses to the information, goal setting and achievements, experimentation with the vehicle, and extensions of the feedback or energy-saving concept to other areas in the participant's life. However, real-time feedback was also more associated with confusion and distraction.

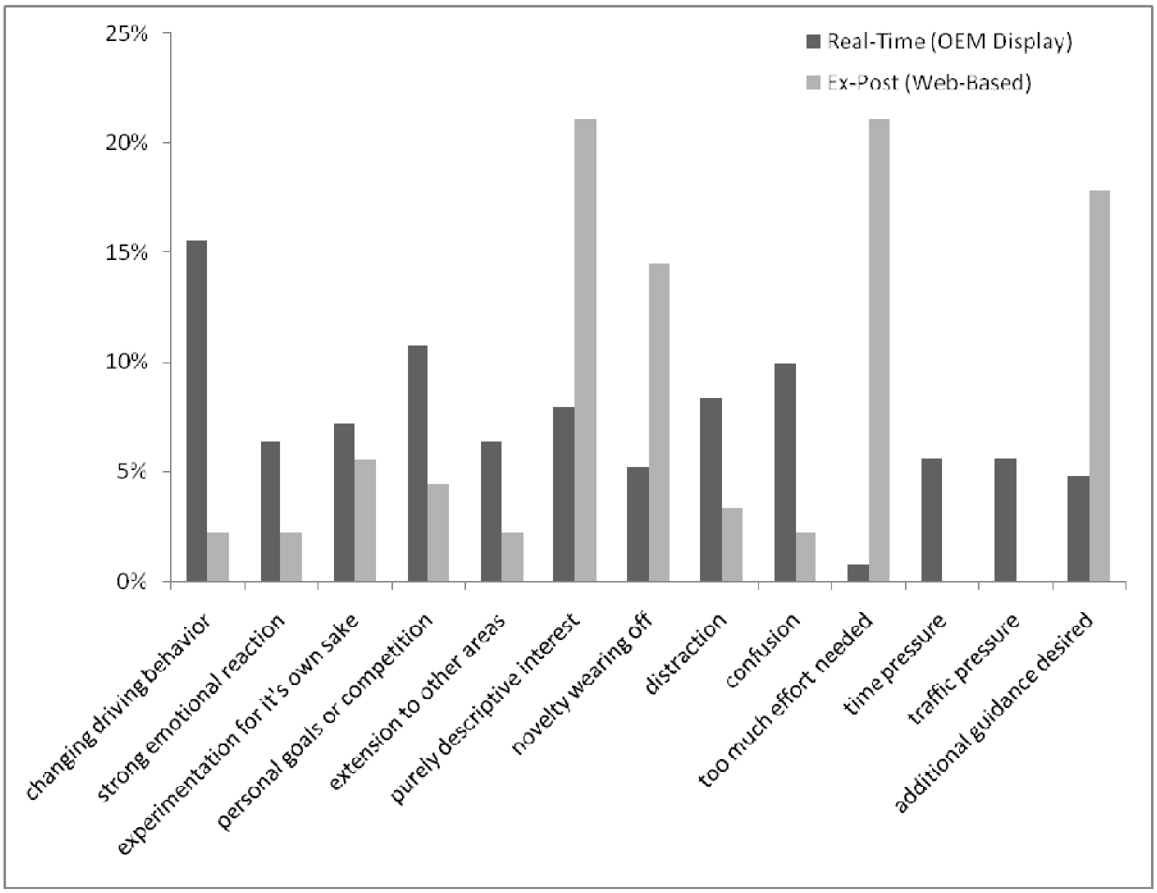


Figure 9: Comparison between real-time and ex-post feedback responses. To observe typical uses of each type of feedback, response counts were normalized by the total unique reposes to each feedback media, such that the theme categories now add up to 100% for each type of feedback, and relative differences can be observed.

Differences between behavior changers and non-changers in response to real-time feedback

The behavioral model presented here based on the TPB and EMGDB suggests that identifiable differences exist between drivers who choose to change their behavior and those who don't, regardless of whether the intention is to perform a behavior or set a goal. Self-reported behavior-changers and non-changers responded differently to real-time feedback and the differences, shown in Figure 10, appear to fit within the theoretical framework, although the causal links between factors in the theoretical model shown in Figure 8 become somewhat vague when observed in the field. However, the longitudinal design of the study and the nature of participant responses (such as experimentation) indicate that the HMEI interacted with psychological factors to generate the reported behavior change over time. The experimental design and results presented in Chapter 5 are additional evidence that the HMEI can cause (rather than simply correlate with) behavior change over time, as the changes in behavior followed the HMEI placement in time – one of the crucial indicators of causality.

As stated previously, comparing the responses of behavior-changers and non-changers shows large differences in the frequency of responses in a variety of themes. These themes can roughly be separated into factors that may have contributed to the initiation of behavior change, and outcomes of the behavior change. The model presented in Figure 8 implies a hypothetical relationship between each factor and the magnitude of the change (e.g. greater perceptions of self-efficacy should lead to greater levels of behavior change and therefore higher fuel economy). However, since this chapter is focused on stated behavior change, estimates of the strength of relationships between responses are left to Chapter 5, in which the relationship between survey responses and the magnitude of observed driving behavior changes is tested in an experimental context similar to the one presented in this chapter. Additionally, even the direction of some relationships, such as how specific perceived social norms or attitudes influence driving behavior, may require further research beyond the scope of this dissertation.

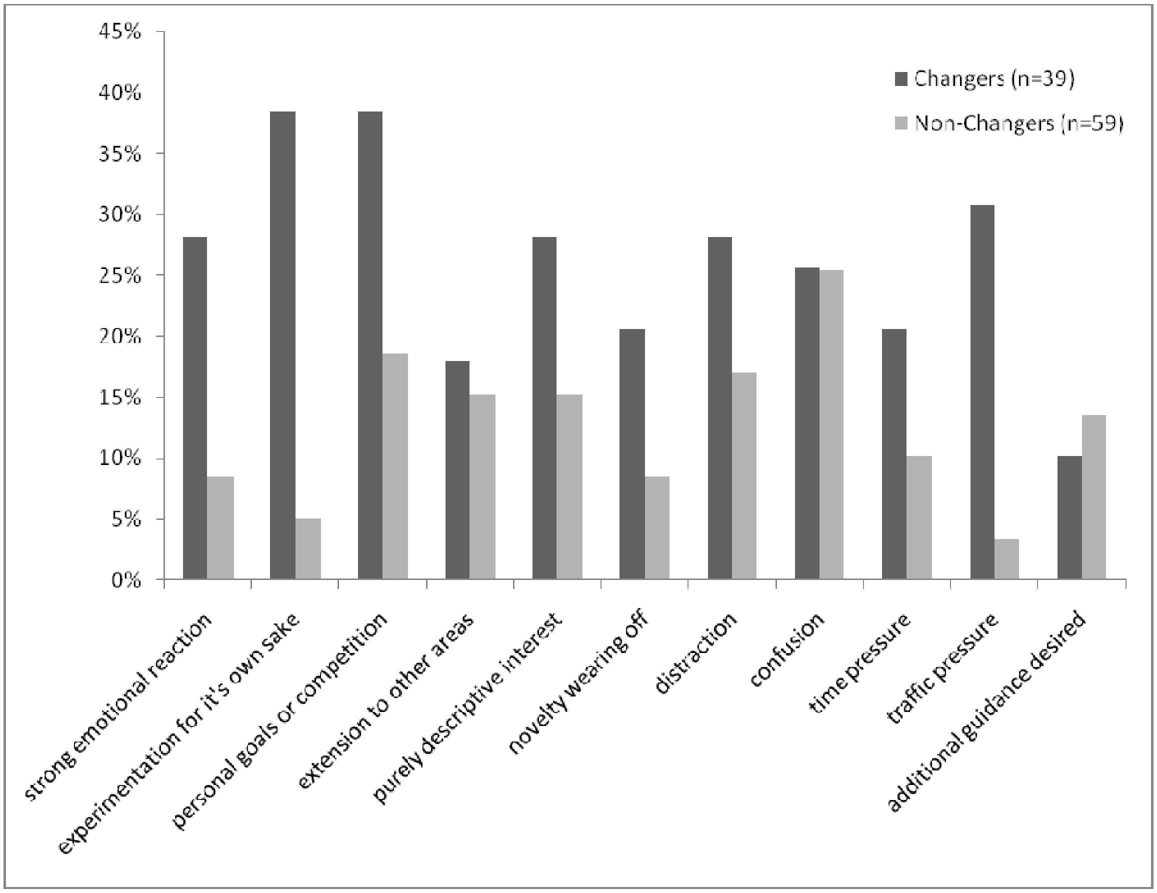


Figure 10: A comparison of response frequency between respondents who self-reported changing their behavior ("Changers") and those that reported not changing or did not discuss the topic ("Non-Changers") shows large differences in a number of themes. The "Changing Driving Behavior" theme is left out since it serves as the group definition in this case.

Factors that may have contributed to the initiation of behavior change

Participants who reported changing their driving behavior to increase fuel economy spoke more frequently of emotional responses, indicating that the feedback activated strongly held beliefs or attitudes. They also reported having goals or trying to achieve outcomes with the car, generally high fuel economy, better fuel economy than another household member, or better fuel economy than the other program participants. Changers spoke of viewing the feedback with purely descriptive interest more frequently than non-changers, indicating either a higher propensity to learn new information, or a predisposition towards information about fuel economy. They also had much higher response rates about experimentation with the vehicle, some of which may simply be behavior change per se, or the propensity to experiment may have led to the behavior change in the first place.

Possible results of behavior change

Some of the emotional responses were in response to the feedback, but it is also apparent that some of the responses were due to the satisfaction of achieving personal goals. Changers spoke more about traffic pressure, probably because they had slowed down on the road and experienced more negative interactions with traffic than normal. In addition, the changers were more likely to mention that they had stopped looking at the information regularly (or at less frequent intervals), possibly because the level of engagement was hard to sustain, or the main reason for the behavior change was experimentation and curiosity rather than the achievement of personal goals. Finally, more of the changers described being distracted on the road by the real-time feedback. As described in the theme section, that response was split between those that continued to use the feedback regardless of distraction, and those that self-regulated their use of the feedback in response to distraction.

Support for behavioral models

One purpose of this paper was to explore if drivers' responses in the realm of energy feedback fit the precepts of the TPB and EMGDB well enough to support their use as predictive models or guides to feedback design. Although there are dozens of behavioral theories that could potentially be analyzed in this way, only the TPB and the EMGDB are discussed at present, both because of their apparent appropriateness to driver behavior change, as well as because of the successful application of the TPB in many fields. The basic concept of the TPB appears to be supported by the responses in this study. The importance of both attitudes (shown through emotional responses to feedback) and perceptions of social norms (traffic and personal interactions), are supported by the participant responses. In addition, the concept of self-efficacy is supported by the propensity of behavior changers to experiment with the vehicle, indicating a basic understanding that their actions would affect the vehicular fuel economy. Finally, the contribution of the EMGDB to the TPB to presume that goals, rather than behaviors, are the focus of individuals is also supported by the evidence. Behavior changers were much more likely to describe creating or attempting to achieve personal goals than non-changers.

Conclusion

Overall, many drivers in this study were strongly influenced by fuel economy feedback. Real-time feedback seemed to have the strongest association with behavior change, although distraction and confusion about the feedback were persistent issues. Ex-post information played a qualitatively different role in participants' experiences, generally as an interesting but not motivating source of information. One important exception to this is that the website was more likely to provide normative or contextual information to the participants, helping them understand the context of their fuel economy, seeing range of possible outcomes, and encouraging goal-setting behavior. The propensity of drivers to look for this type of normative or contextual information may have been less related to the source of the feedback (real-time or ex-post) and more to the lack of available contextual or normative feedback in the OEM Prius display.

Participant responses formed themes that supported the importance of attitudes, social norms, perceptions self-efficacy, and personal goals to driver behavior change. Furthermore, these themes can be mapped into the TPB and EMGDB, and also appear to correlate with self reports of driving behavior change, although the magnitude and statistical significance of the apparent correlation were not tested in this chapter. Participant responses about experimentation and behavioral fatigue indicate that a dynamic model of behavior change would be more realistic. Additionally, driver responses about confusion, a purely descriptive interest in the feedback, and distraction indicate that a model of driving behavior and feedback may merit an additional factor or factors between the outcome fuel economy and the drivers' internal decision-making process that can account for the impact of complexity or distraction potential of the feedback on the drivers' attitudes or perceptions of self-efficacy and resulting behavior change.

Chapter 4: A novel energy economy interface for improved driver behavior: theory-based design and driver responses

Introduction

This chapter describes the design and driver responses to a behavioral theory based human machine energy interface (HMEI) for energy efficient driving behavior. The HMEI was tested by 46 individuals in one-month periods, and the experiment ran for one year. Judging solely by the lack of discussion in the literature, previous feedback experiments have apparently either not used behavioral models or have relied on ad-hoc behavioral models to design the driver feedback. This has resulted in a set of feedback devices that, although apparently effective, are difficult to generalize or improve on due to the lack of an explicit theoretical framework. In particular, the review of research and industry HMEI designs in chapter 2 showed that the lack of a theoretical basis has resulted in many simplistic implementations without the "lessons learned" to apply to future research or implementations. The main purpose of the theory-based HMEI design is to provide an experimental framework that can be used in future work to refine the elements of a broadly effective HMEI.

Design of a theory-based interface

This HMEI design presented in this chapter is based on the conceptual framework of the theory of planned behavior (TPB) and the extended model of goal directed behavior (EMGDB). This interface design allowed me to elicit the response of drivers to feedback that is pertinent to the TPB and EMGDB and to experimentally determine both if and how specific factors such as goals or perceived behavioral control influence driver behavior and energy outcomes. To increase the clarity of the results, we avoided explicitly normative (such as statements of achievement like “good job”, but note that social information, which was included, is also considered normative) and non-emotive information (such as smiley faces or dollar signs) in order to focus specifically on the factors described in the TPB and EMGDB, including goals, social norms, perceived behavioral control, and attitudes. The exception to this rule was that various background colors were used to provide basic information about changes in performance to the driver, and some colors are commonly associated with both emotive and normative information such as green for environmental or go and red for bad or stop. It is also important to note that emotive and explicitly normative feedback may be important in designing optimally effective HMEIs, they are simply beyond the scope of this research. Wherever possible the visual presentation of information was simplified and reduced to avoid unnecessary distraction to the driver. In addition, text was kept to a minimum and numerical information typically accompanied by a simple graphical display. In cases where the numerical information changed rapidly, a 2-3 second average was displayed (as described in Chapter 2), and trailing digits (digits after the decimal point) were truncated in order to improve comprehension since long numbers may require more cognitive effort to read than short numbers, but each additional digit only describes 1/10 of the information in comparison to the preceding decimal number.

HMEI technology

Tablet computers running Adobe Flash in Windows XP were used for the HMEI, providing a programming platform with a flexible graphical interface. The tablets were further modified to enable them to switch on automatically each time the vehicle was started, and were powered through the vehicle 12v system using a custom electrical harness attached to a cigarette lighter port. In order to conserve vehicle battery power, the units were designed to enter a hibernation mode when the vehicle was turned off. A separate data-logger unit placed under the driver-side seat interpreted the raw vehicle OBDII (the standard on-board data port on all post-1996 vehicles) data and relayed it to the tablet using a wireless router. The engineering of the data-logger and the programming of the HMEI was performed by EXControl. Cables were concealed within the vehicle upholstery and dashboard so that the overall appearance of the installation was clean, looking much like a large GPS navigation display.

Use of the novel energy economy measure MPG +

Based on the analysis of energy and fuel economy metrics in Chapter 1, the interface exclusively displayed energy economy rather than fuel economy. The vehicle energy economy (including fuel, kinetic, and potential energy) was converted back into units of gallons of energy (one gallon of gas is equivalent to approximately 33kwh) and displayed as “MPG+” (read MPG plus) to aid in driver comprehension and comparison to standard fuel economy. MPG+ is described in Chapter 1 as MPE, but the term MPG+ is also used in this chapter to refer to the information seen by the driver since that is how it was shown to them in the experiment.

Information layout, personalization, and driver interaction

To aid drivers in observing changes and achieving goals the interface was personalized as much as possible. At the start of a trip, the driver was prompted to sign in by selecting her name on the touch-screen interface. The HMEI then displayed a layout, MPG+ goal, and driving history based on saved driver data. Each HMEI also recorded driver-specified fuel cost and electricity cost on a dollar-per-gallon and cent-per-kwh basis, and this data was shared among all simultaneous users of the same vehicle and was used in calculations of driving cost.

Once a driver selected a name on the introductory screen, the HMEI switched to a display showing driving data in multiple vertical panels, each one with a predefined set of information, as shown in Figure 11. Customization of the layout was programmatically possible, although the set of available panels varied between three participant groups. In the first group a fixed set of three panels was available; for the second group four panels were displayed and two of the panels could be replaced by a limited set of panels, including blanks (panels with no information); for the third group three panels were again shown, although at this time each had multiple options and any of which could be blanked by selecting a blank panel. All groups received a default configuration that included both current and average MPG+ measures, and the complete set of panels available to each group is summarized in Table 3.

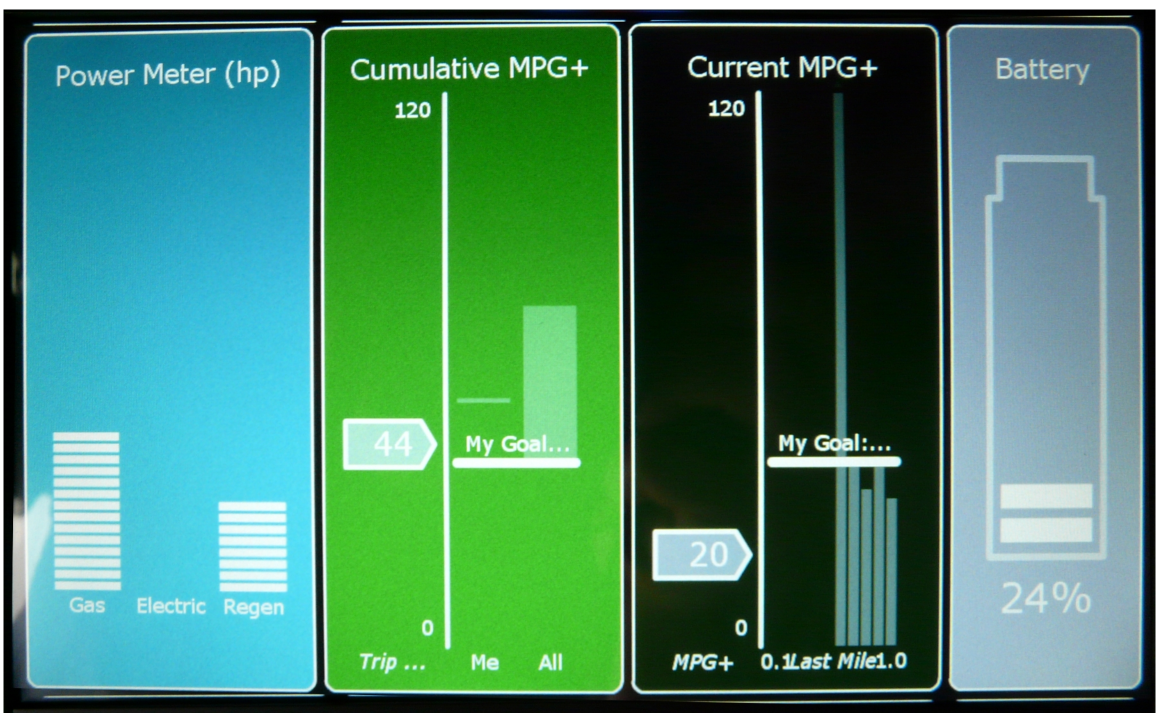


Figure 11: An image of the HMEI used in the study showing one common set of panels.

The driver interaction was limited to the touchscreen display, and in an introductory session users were instructed on how to manipulate the panels and options. Drivers were asked to interact with the HMEI only while the vehicle was stopped to avoid on-road distraction. By touching the screen once the driver controls were activated and primarily consisted of up/down arrows above and below each panel. By pressing an arrow the driver could scroll to the next panel in the set, which was predefined by the researcher. In addition to the panel controls, the first touch would reveal a menu on the far right that included goal and fuel price menu items. In the goal section the driver could specify a MPG+ goal to be used in the display of two of the main panels. In the cost section a driver could specify the gas and electricity cost to be used in trip cost calculations and display.

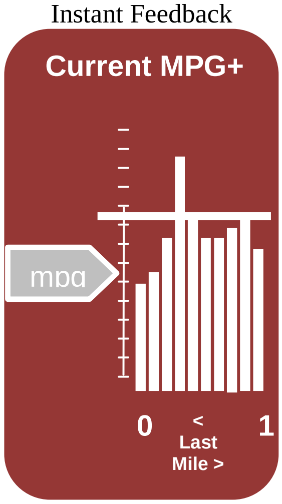
Behavioral factors included in the HMEI design

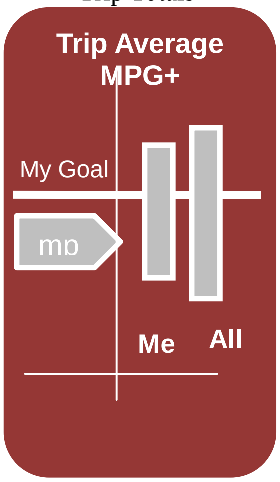
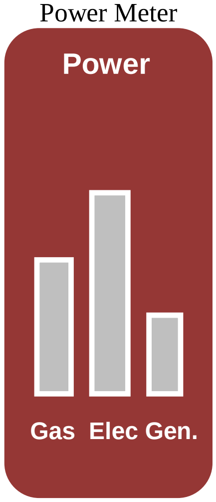
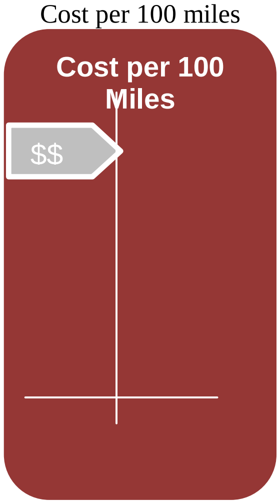
The HMEI design explicitly includes a variety of metrics adapted from the TPB and EMGDB. These metrics include: personal goals, hypothesized to support goal-making and goal-achieving behaviors; peer performance (MPG+ performance of approximately 50 previous drivers functioning as a proxy for social norms under the assumption that drivers will interpret group behavior as a norm), hypothesized to provide normative contextual performance information; multiple temporal periods, hypothesized to increase perceived behavioral control and by which to measure goal achievement; vehicle power broken down by source (gas, electricity and regeneration), hypothesized to influence perceived behavioral control via a greater understanding of vehicle operations; cost information hypothesized to influence cost attitudes and support related goals of reducing expenditure; and CO_2 emissions information hypothesized to influence environmental attitudes and support related goals of reducing emissions. A personal performance history and peer performance metric were both stored as distance-based ranges and only the ranges corresponding to the current trip distance were displayed.

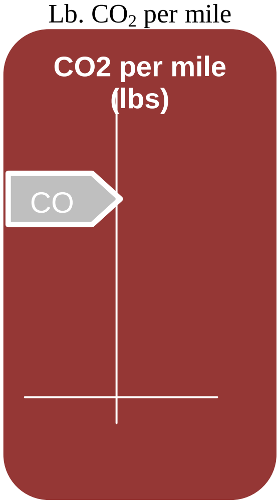
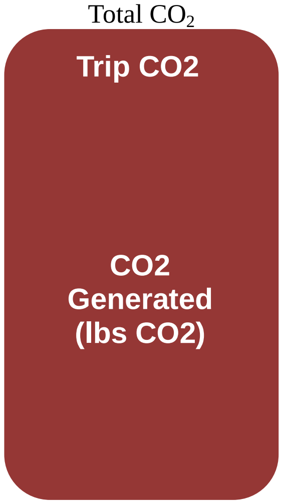
Panel Descriptions

In Table 3 each panel is shown in schematic form and explained. Similar information was provided participants both verbally and in printed form, although the connection between each panel and behavior theory (column 3 of Table 3) was not included in the participant explanations. Text-based panels are not shown.

Table 3: Schematics and descriptions of the experimental HMEI information panels.

Panel, image, (group)	User Explanation (from handout)	Connection to behavior theories
Instant Feedback  (all groups)	This panel shows information about the current rate of energy use or fuel economy, cost, and CO_2 generation. Shows (from left) current MPG+ (combined fuel economy), personal goal, and 1/10th mile averages for the last mile (most recent average is shown on the left). MPG+ is very similar to miles-per-gallon but also includes battery, kinetic, and potential energy (the energy stored in the vehicle’s motion and altitude).	Display of the current MPG+ (energy economy in MPG units) enables drivers to modify their behavior and see instant results, thereby increasing perceptions of behavioral control, and helping them achieve fuel economy goals. The 1/10th mile average bars help display contextual information about the previous mile of behavior or roadway that may encourage goal achievement or a better understanding of the system.

Panel, image, (group)	**User Explanation (from handout)**	**Connection to behavior theories**
Trip Totals  (all groups)	This panel shows information about the trip totals including fuel economy, trip cost, and trip CO_2 generation. Round-Trip average MPG+ fuel economy shows (from left) trip average, personal goal, personal MPG+ history, and other drivers' MPG+ history, where historical comparisons are based on trip distance.	Trip average MPG+ provides users with trip-level outcomes and can compare the trip average directly to the driver goal. Personal historical and Peer ranges are shown to encourage comparisons to similar previous trips, thereby increasing PBC, and to provide a social comparison to encourage goal setting and achievement.
Power Meter  (all groups)	Shows the current gasoline, electric motor, and regenerative power.	The power meter provides the driver with information about vehicle operations, building perceived behavioral control. The meter shows (from left) gasoline power, electric drive power, and power from the regenerative braking system, all scaled to kw. The scale extends from zero to 20kw. The power screen can be used to help achieve goals about driving mode in the PHEV, specifically to maintain the vehicle in all electric operation.
Cost per 100 miles  (group 2,3)	This screen estimates what the next hundred miles would cost if they are driven in the current manner.	This panel is an instantaneous measure of cost that could motivate more financially economical driving behavior. The cost information is hypothesized to influence the behavior of drivers who reported strong attitudes or goals related to cost.

Panel, image, (group)	User Explanation (from handout)	Connection to behavior theories
Total cost  (group 2,3)	Total trip cost including gas and electricity	This panel estimates total trip cost based on driver-defined gas and electricity prices. The panel makes the cost of each trip explicit, potentially motivating more economical driving habits.
Lb. CO_2 per mile  (group 2,3)	This screen shows the current rate of CO_2 generation in pounds per mile.	This panel provides direct CO_2 feedback based on current driving conditions and actions for those interested in reducing environmental impacts. The emissions information is hypothesized to influence the behavior of drivers who reported strong attitudes or goals related to the environment.
Total CO_2  (group 2,3)	This screen estimates total CO_2 generated from both gas and electricity use in the vehicle.	This panel provides a cumulative CO_2 measure for the trip, showing the total (CO_2) environmental impact.

Analysis methodology

The analysis is broken into two chapters due to the complex and varied design of the HMEI, as well as the relatively low sample size of the experiment. The complexity of the design lends itself to qualitative analysis since individual responses to panels or combinations of panels can vary widely, and one purpose of this dissertation is to understand how drivers comprehend different types of feedback, not simply how much they change in response to feedback. The quantitative part of the analysis is treated separately due to the constraints of statistical power. The qualitative analysis is presented here in Chapter 4 and consists of an analysis of driver responses to all available HMEI information recorded in the final interviews. The quantitative part of the analysis, presented in Chapter 5, focuses on the observed changes in energy use due to the introduction of the HMEI and relates those changes to both baseline levels and changes in cognitive factors recorded in a repeated survey.

Participants in the experiment were interviewed after two weeks of exposure to the interface. Interviews were semi-structured in style and broadly addressed the use, charging, and experience of driving a PHEV, with special emphasis on the HMEI. Driving behavior changes during that time are discussed separately in chapter 5. Overall, 46 individuals were interviewed, although only 44 reported driving the vehicle during the HMEI experimental period.

The semi-structured nature of the interviews allowed participants to generally lead the discussion into areas that were of particular interest to them. However, if a participant did not mention her response to the new HMEI, the interviewer prompted her to think about the introduction of the HMEI, if she looked at it, and if she altered her behavior due to the HMEI. At the completion of the study the interview transcripts were processed using the Keyword In Context (KIC) methodology, described in detail in Chapter 3. Four hundred statements about the HMEI were identified using KIC and read in order to identify themes related to the behavioral hypotheses. The statements were first grouped by subject, for instance, goals, and then sub-themes within each subject were identified. In a final pass the statements were re-read to ensure the clarity and consistency of the themes. Below, the overall themes that emerged from these interviews are presented along with representative statements from the participants, identified by an interviewing code and gender. In some cases the statements are cleaned slightly for readability, but the words in all cases are directly from participants, not the researchers. Excerpted text is shown using an ellipsis, and brackets surround text added for clarity.

Results

The theory-based hypotheses posit that goals, average MPG+ information, and real-time MPG+ information presented previously are responsible for the majority of positive driver responses and behavior change. Social comparisons, however did not figure largely in the driver experience, nor did cost or CO_2 information as discussed in the specific sections below. To estimate the frequency of the theoretical factors, user responses were tabulated by category and repeated statements removed such that a list of unique subject-category pairs were generated. These lists were then tallied and are shown together in Figure 12 for an overall view of the driver interest level or response to different features. Descriptions of ecodriving and distraction in response to the HMEI feedback are included in the overview to help frame the information.

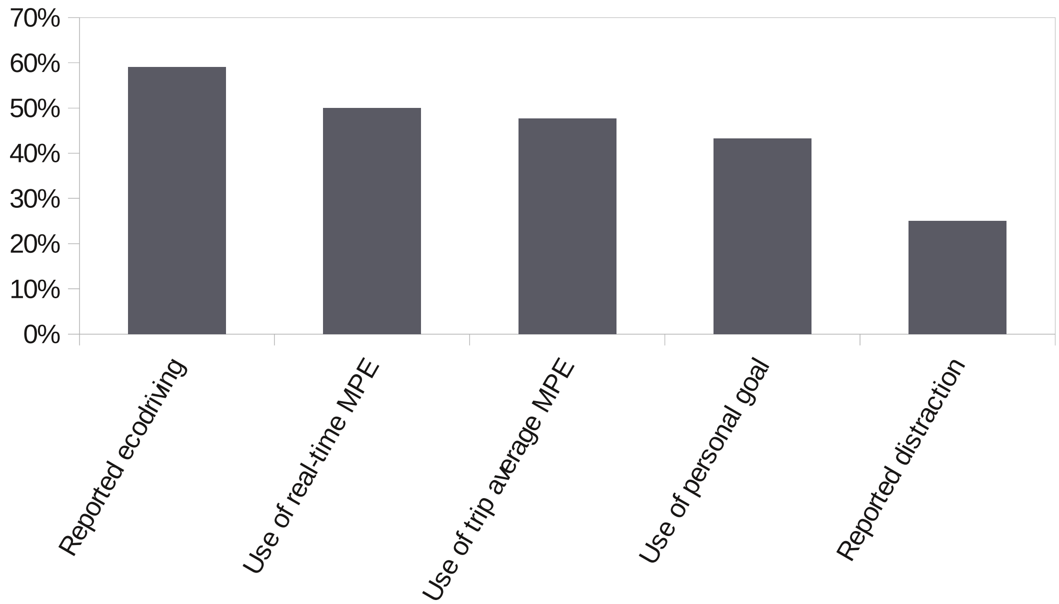


Figure 12: Most frequent driver responses to the HMEI feedback. Responses are shown in percentages based on a total N of 44 individuals. For the behavioral factors (real-time, average, and goal information) only positive responses are included in the tally.

Instant feedback

Overall, the real-time feedback showing current MPG+ and 1/10th mile averages was the most talked about information and resulted in the strongest positive statements of curiosity, excitement, and use. The responses indicate that the use of real-time feedback has three main positive effects: experimentation with new behaviors, motivation for high achievement, and fine control over the vehicle using the feedback as a guide. The use of the real-time feedback for experimentation was important for drivers to develop accurate perceived behavioral control that could later be used to sustain high levels of performance. The real-time MPG+ information therefore directly supports the TPB construct of perceived behavioral control. Driver observations of high MPG+ were also exciting and motivating, an outcome that indicates the importance of short time periods, even if those high MPG+ values are not sustainable. For some drivers, however, the rapidly fluctuating values created confusion and resulted in disengagement. It seems likely that these individuals did not have enough basic knowledge of vehicle operations to make sense of the numbers.

Experimentation and learning

176208 Male: [the HMEI] tells me a lot here about what acceleration does in terms of mileage. I mean, I knew that intellectually, but, again, to have that visual feedback it was really quite striking. It was powerful for me.

176204 Female: Well when I was out on the road, you know, if I varied my speed at all it would cause it [the energy economy] to drop.

176204 Male: The display also surprised me is how bad the gas mileage was at low speeds.

174912 Male: I think at one time I was going downhill in the vehicle; I happened to look at the screen it was like 80 -- I was getting 87 miles to the gallon. It's like that's cool.

175309 Male: I caught myself paying a lot more attention to it to see what happened when I would start up a grade and when I would go downhill. I mean, you take your foot off the gas, when you start braking, right up to the top. You know, you get on a long downhill and, man, it'd show you like you're getting like a 180 miles per gallon. It was kind of fun.

Motivation

176206 Male: I mean, real time feedback on what you're doing and it's like the machines at the gym, you know. When you're on there you can see your heart rate and your, you know, the miles per hour and your calories that you're burning. I mean, it's a great incentive, you know.

175308 Male: I preferred the [instant feedback] because it was constant and it was right now. It gave me current information... it was like, okay, you know, you're down here possibly below 40 what are the conditions and how can you change ... to get that higher?

176303 Female:...sometimes it would be like 170, 180, you know, so that always felt good, but it was brief.

176203 Male: It's funny, because [my family is] watching them, "oh, look at that, it went all the way up to a hundred-something, oh, okay, now it's back here." So they're watching that and really seeing, you know, my driving habits. So, yeah, I think, like I said, that's why I think those visual references really affect people. Because they're making comments, even through they're not driving, they're watching those things and going, "Oh, look at all the green lights up here" ...so I think that really affects how people drive...

Using feedback to control fuel economy

175107 Male: Yeah, but I like it because I could adjust my pressure on the pedal, and you could see the gas mileage go up and you could ... maybe just decrease -- let's say you're doing 67 on the freeway, 68 and get back down to 65 or just below that you could see a dramatic change.

175308 Female: Yeah, because it told you what you were doing right then so you could actually do something about it. I drive in traffic a lot though so for me my patterns were interrupted by people cutting in, and slowing down, and stopping. And I would find that if that guy hadn’t jumped in front of me I would be still coasting, you know, then I wouldn’t have had to step on the gas and change.

176206 Male #2: Well, yeah, I started noticing my efficiency of how to drive it and so, I would change it. And even when I went up a small hill I would decelerate more, because normally, I mean, if I'm driving any other vehicle I'll usually keep it so that my speed is the same, and I'll obviously make the car work harder, whereas when I saw exactly what my numbers were on the Prius I would decelerate when going up even minor hills just to keep my efficiency up, regardless of my speed.

175314 Male: I tried -- any interim acceleration. So, if I was just cruising down the road and I needed to stay at the speed limit, I would try to accelerate slower while I was on the freeway. So, even just from the start, but also getting on the freeway I would, you know, check on traffic, I'd ease into the -- take a long time to get up to speed. So, I did that, too, to try and play with the game.

Extension to other vehicles

175314 Male: ...it did cause me to move my indicator on the mode on the Sequoia from just telling me the temperature outside and what direction I'm driving to, what is my instant gas mileage.

176208 Female: I thought it would be cool to have that in every car so you could kind of watch in the moment.

Confusion

175314 Female: But I could never know what speed was [optimal], You know what I mean? So, it wasn't like I could correlate [his] driving with that. It was just you could see on the freeway versus on the street and that's it.

176204 Female: ...what did I just do that made it go to 170... miles per gallon? What did I just do that made it drop to 20? But I wasn't able to find the pattern I found it a little frustrating. But that's me.

175107 Female: Yeah, if I’m coasting, sure, I’m going to go 180 some miles per gallon, sure, because I’m coasting, you know... so, I don’t know, I didn’t like that part of the screen.

175314 Male: MPG ... didn't seem to be calculating exactly accurate, but it was close enough to get the gist of how well the mileage was doing, because -- I know what it was. If it's miles per gallon and I'm running on 100 percent electric, I should be getting -- it shouldn't calculate because I'm not using any gallons. Right? So, it should be way up off the chart, but it wouldn't be. And so -- So, I noticed that.

Goals, trip averages, and game playing

The goal-line was a common way for drivers to find meaning in the fuel-economy numbers. The line provided a test against which the instantaneous or trip average could be compared, showing a close relationship between the goal and the feedback time period. Numerous drivers customized the goal to be increasingly ambitious or simply to reflect a better sense of their control over fuel economy. Even drivers that simply accepted the default goal value (no explanation of the default was offered by the researcher) responded to it as if it had personal meaning, suggesting that even goals originating from outside the individual can be motivating. In a few cases drivers mentioned reducing the goal setting to reduce the pressure and provide an easier sense of achievement, although these comments were usually made in a humorous context and indicated that such a goal-reduction would be considered “cheating.”

A number of drivers referred to their experience driving with energy feedback as “playing a game,” a statement that may simply indicate they enjoy the experience, or may suggest a true similarity between games and theory-based feedback. Many games share TPB and EMGDB concepts such as multiple levels of performance summaries (in game points, level summaries, and end-of game summaries), goal achievement (high scores and competition), and personalization (personal scores and lists of named high scores).

Goal achievement using the average panel

175308 Male: I would only look at it towards the end of my trip, saying, okay, this is what it was for my trip. It wasn't as needed, not necessarily needed but you just didn’t look at it as much because it was what it was. And so you really didn’t change how you were driving versus when you were looking at the [current MPG+]...

176204 Female: I'm not going to ... reach that goal so maybe I should get it down here so I'm in the green. No, that's cheating. So we just left it there and then, you know, you pay attention to the overall.

Playing fuel economy games with the average

175308 Male: Yeah. Like a little game in a sense. You say, okay, how can we drive to get it up to 70 miles per gallon or whatever.

176206 Male #2: It was a game for me. I started seeing it. I just wanted to get -- Because then I had your cumulative MPG plus and I just tried to get that as high as I could. I mean, I don't remember the exact number, but I think I got it up to 50 something at one point.

175309 Male: We just have competitions every week. [My co-worker would] say what's your miles per gallon? I said, you know, I'll tell you the next time I fill it up, and I haven't filled it up in 10 days. He'd go, “dang it.”

Social comparisons

The distance-based peer fuel economy range, which showed a bar indicating the range of MPG+ from the 5th to the 95th percentiles of previous drivers at similar trip distances, received little attention by drivers, possibly because of the oversimplified labeling system used to designate the meaning of the bars on the screen. Some drivers specifically referred to the social information as not being useful, indicating that the peer comparison is not a clear motivating factor. One problem with the social comparison could be that it was a display of the range (5th -95th percentiles) of previous MPG+ scores at the distance of the current trip. This range was so broad that it may have been too difficult for drivers to form a relevant goal, for instance to achieve a trip MPG+ near the top of the range, suggesting that a mean value, or some more moderate range could be more motivating.

Personal and peer distance-based comparisons

176207 Male: I did like the facts that you had combined our scores against all the other users of the other cars that you have going. That I thought was interesting just comparing different driving styles.

175308 Male: You saw a range of what everybody else was [getting], but that really wasn't as useful because for me it was just saying, okay, there's the range but you don’t know what they were getting. And you really can't do anything about it so it was just like you can only worry about yourself and just, okay, what can I get.

175107 Female: Yeah, or if I'm stopped somewhere, you know, I could see it and get an idea what's going on, but as far as the other screen, was it -- all -- you know, everybody else and then me, it's like, well, what -- that doesn't make any difference. I don't know why that even was there.

176205 Male 1: But for me I guess, you know, at the beginning I just drove it kind of normally until later on I guess I got interested to find out if I could like meet my goal and kind of be the one to use the least amount of gas or something like that. So I started to I guess drive in a way to save the most amount of gas, but I guess [at] sort of a point it wasn't really, how do you say it, ideal or it wasn't really efficient. So I pretty much resumed back to my normal driving habit.

Power information

Unlike the energy economy panels, the power panel showed the magnitudes of the current energy use of the gas engine, electric motor, and regenerative braking scaled to horsepower. When the vehicle used less than 10kw of total power, the screen would be bright blue, and it would decrease in brightness as more power was used. This power limit was chosen because it corresponds to the built-in limit of the 2008 Prius electric drive power, and thereby indicated the potential for all electric drive, although whether or not the vehicle actually maintained all electric drive was also a function of the control system and battery levels, not only the driver.

This panel had a mixed influence on drivers depending on their area of focus. One beneficial effect of the power information was that it helped some drivers understand basic vehicle operations and allow them to make sense of an otherwise hidden internal control system. For other drivers the panel was used as a predefined all-electric driving goal, although the limited situations in which all-electric driving was possible was a source of frustration. For others, the regenerative braking was understood to be a positive result, causing confusion about what driving style would result in the lowest energy use.

Learning about vehicle operations

174507 Male 2: ...it really helped when I had the second phase where you were showing us, you know, what was going on. And so it was kind of interesting, sometimes when I thought it was just running on battery it was running on gas. But I like to get it so that the thing would, you know, come up to the stop, and then I'll just kind of shut down and then take off real slow, see if I could hold that battery, run it the whole way.

Frustration with the implied goal of all electric driving

175310 Female: Okay. So if it was a longer stretch and not start/stop/start, which I have a lot of start/stop from here to work, if it was a longer stretch, like, if I hit all the lights right going down Walnut, I stay in the black [high power] until I get to that first, probably, light which is a couple blocks turning left onto Winding, and then I can keep it in the bright blue [low power] for a long time if I don't have to stop. And then I get irritated when I have to stop, I'm like "God bless America, now I'm going to be in the black."

Counter-intuitive interpretations

175310 Male: Well, no, I just knew at some point I'm going to get into the blue, so let's just get there as quickly as possible.

CO_2 information

CO_2 information was fascinating to a subset of drivers, possibly because they are particularly sensitive to climate change issues. However, the most common theme that came up in statements about the CO_2 information is that although they were surprised by the large amount of CO_2 that the test vehicle was emitting, none of the drivers interviewed had a context in which to understand the reported CO_2 values. This suggests that although CO_2 is a household term, individuals don't have enough basic knowledge about CO_2 (such as a carbon footprint or possibly more detailed knowledge) to understand CO_2 feedback in numeric form. Unlike the responses to other panels, the motivational impact of the CO_2 information seemed to be consistent at the household level (all household members tended to have the same response), indicating that environmental values tend to be shared closely (or they are at least professed to be shared) among household members. This indicates that CO_2, if placed within a clear context, has the potential to provide the basis for a more motivating social comparison than fuel economy; in particular, peer or household emissions could provide the needed context for a CO_2 reduction goal.

176207 Female: It was interesting to see, okay, that's how many pounds of CO2 you put out, but I have no frame of reference as to what that equates to.
176207 Male: [I] didn't have any real usage for the CO_2 output because I don't know comparatively what that is.
176208 Female: That surprised me, how much carbon we were putting out in just short trips.
176208 Male: And again, thinking down the line that the technology will continue to improve, you know, marketing is going to be a part of this. And come on, folks, we've got to clean up our act here or we're just going to extinguish ourselves. So, I don't have -- I don't have a good context to put the values in, but I was still struck by the values that I saw on that screen. And so that -- Yeah, that, by itself, I think is important feedback, and with -- with more -- You know, I would seek out more information, and see, all right, let's provide the context for this value in addition to just looking at the value itself, the absolute value.
176208 Male: Okay. You've just -- There it is. Ten pounds of CO_2, you schmuck.
176206 Male #2: I'm really not familiar with how much CO_2 a regular car puts out, so I wasn't too familiar with that.
176206 Male: And it seemed high, I mean, given the -- you know, that it's a hybrid. So, that was the only thought I had and then I immediately just put it out of my mind, because I don't like to think about the poison, you know, that we add into the environment. I thought it was really high, so I wondered what it is for regular cars. I said, oh, my God.
174809 Female: But it was nice to see that you were saving or not -- I think we were surprised at how much CO_2 you produce, huh?

Cost information

Cost information was interesting to a small proportion of the drivers that had access to these panels, and for them it was useful for motivating behavior change. However, for most drivers the trip cost information was seen as useful for budgeting but didn't motivate energy savings. Indeed, some drivers were pleasantly surprised by how inexpensive trips were, indicating that in some situations accurate cost information may actually discourage conservation behaviors.

175312 Male: Well, it's interesting to see, like as you're driving to see what type of gas mileage you're getting and also the screen that shows you how much you've spent is also useful.
176207 Female:... yeah, it's very expensive to sit and idle.
176207 Female: Generally I'm so busy I'm pushing to get from one appointment to the next, but, you know, it's like there was just times I left a little bit early for work and I could just kind of relax and watch those costs go down a little bit. It was fascinating to watch. I could see if you were on a real conscious level you could save money doing that.
176206 Male #2: I was like, oh, my God. Look at this. Look at my inefficiency at getting from point A to point B, as far as money goes. But as far as time went, I saved time, but I definitely enjoyed seeing the hard evidence right in front of me of how I was driving and how that affected my cost.
174912 Female: I remember seeing that, so that’s not a lot, and I said, wow, a whole dollar to do all this stuff. That’s pretty good.
174809 Female: And you know, sometimes you don’t even look at the dollar amount because you have to buy it anyway, and so, you know.

Screen colors

During the course of the experiment two different screen color styles were used, eliciting widely different responses from drivers. In the first case three different bright colors were used to signify low, medium, and high performance. The colors were red, orange, and green, respectively, to make use of the symbolism of a traffic light or environmental “greeness” to indicate that higher MPG+ scores were better than low scores. This color style created a highly visible “flash” as the panel transitioned from one region to another, for instance when changing from a low MPG+ to a medium MPG+ the current panel would suddenly jump from a bright red background to a bright orange background. Many drivers responded negatively to the flashing colors in the first set. The color change was too strong and distracting to the eye. In addition it created the feeling of discontinuous rapid fluctuation rather than control.

In the second color style each panel was instead assigned a gradient from dark to light tones of the same color, so for instance the Current MPG+ screen would transition from a very dark, nearly black green background at low MPG+ scores to a deep shade of green at medium scores to a bright green at high scores. This gradient provided an ambient sense of change, but did not “flash” at the driver like the first style. In contrast to the multi-color style, drivers responded positively to the single color gradient of the second style. The continuous nature of the transition provided an easy reference to the driver, but did not overwhelm the driver's concentration with unnecessary information about the points of transition.

One overwhelming finding of the interviews was the propensity of drivers to use the screen color information, rather than numerical values or geometric descriptions to describe driving performance. Phrases such as “in the blue” or “in the green” were commonly used in almost every household as shorthand describing all electric or high energy economy driving. Although comparing numerical and color-based information wasn't a specific aim of this study, the trend was organic and clear. The responses suggest that color-coded information could be very important in creating a quick-reference to driving performance that has low cognitive load and is usable for drivers without strong numeric sense or quantitative context by which to compare feedback numbers. In addition, the way color information is presented can have important consequences for the user experience.

Preference for a color gradient rather than changing colors

176303 Female: I'm frequently looking at it. I did like the way it lit up bright when you reached the goal, because that was just something, you know, that I could kind of be aware of without really watching it while I'm driving.

175312 Male: It's really just in my, like peripheral. I don't like stare at that while I'm driving, obviously, but, like I'll see it get a lighter color green and that means that I'm having a better fuel economy, so that's just kind of there.

174910 Male 2: I don’t know. I just, I kind of understood it after a while because he kind of explained it and then, after using it for a while, I understood it. I can’t think of anything to change. I was, it was, I noticed it changes colors, you know, the better gas mileage you get. It’s nice. Light green and everything. And then, when you’re not doing so good, it’s all black. So that was kind of fun.

175314 Male: I don’t like the flashing colors. Those -- when the glare, you can't really see the colors. All you can see, it's going on and off and I couldn't remember what yellow meant, or red meant, or green meant. And so I was like, well, I'm just looking at the line going up and down.

175107 Female:...and then I did not like the second screen where it shows you how much gas it’s [using. It was] annoying just because it was always flashing or doing something .

Motivating symbolism of the color information

175310 Female: I wanted to be in the blue, I did. I know, that is pathetic, I'm 43, I wanted to be in the blue.

176204 Female: Well even our daughter was a passenger and she got into it, she would tell me what color I was...

176206 Female: I would like more the color to be green and red instead of blue and red.

Distraction

Many drivers reported that the HMEI was distracting, although the extent of the issue seemed to vary by individual. Much like the responses to the OEM Prius display in chapter 3, drivers reported that the HMEI took attention away from the road, but also that they practiced a certain amount of self-regulation by deciding not to watch the HMEI if it seemed too distracting.

One important difference between the HMEI and other sources of in-vehicle distraction is that the HMEI may promote safer driving habits. Drivers who paid attention to the HMEI and changed their behavior reported increasing following distances and driving at lower speeds, two behaviors that normally reduce the propensity to have driving accidents (Carsten et al. 2008; Young, Birrell, & Stanton, 2011). However, these self reports may be inaccurate, and understanding how the new behaviors and distraction combine to either increase or reduce road safety requires further research.

One possible solution to the distraction issue is to transmit information in ways that use less driver attention and visual time, such as relying more on color and sound. In addition, placing the HMEI in a "heads up" position near the top-center of the dashboard could reduce the time spent looking away from the road.

Finally, it is clear that some drivers were overwhelmed by the complexity of the feedback presented. A general solution to this problem that would reduce the amount of attention required by the HMEI would be to show only a small amount of information at a time, possibly following the even-based methodology developed in chapter 2.

176204 Male: I think it was good is that they didn't have that display in the beginning because you had to get used to the car first, because it is distracting... since it does flash those colors around, you know, initially it does distract you, until you get used to it.

175107 Female: It was just distracting, and then it's like, what, every tenth of a mile how much I was getting and it goes up and down and up and down and it changes colors. It changes colors. I'm going, oh, look, it's black, oh, yea, you know, oh, God, I'm doing something wrong, and it -- you know, it's just not something I felt was comfortable.

176204 Female: And you've got to scan everything when you're in traffic, especially, front and back, and so you drive, you operate your car a little bit on remote. And I have not learned, I guess, on remote I'm not as efficient as I am when I'm paying attention to that little screen. Out in the country, you're on these roads, yeah, you have to scan, you're watching for the dog or the car pulling out, but you got a little more attention span that you can give to the efficiency.

174809 Male: I would just say no, I'm not going to even look at the screen. I'm just going to drive the car.

Ergonomic issues

Other issues mentioned by drivers were primarily ergonomic. In particular, many drivers mentioned that they would prefer the feedback to be “heads up”, that is, right in front of them on the dash rather than on the center console since information on the center console requires a driver to turn her head to read it. However, some individuals adapted to the center position by glancing at the HMEI when looking right at the right side-mirror, and in this way making the HMEI a part of the normal driving routine.

Conclusion

Design of the experimental HMEI was inspired by behavioral theories including the theory of planned behavior and the extended model of goal directed behavior. Overall, the HMEI design elements were successful in displaying contextually and behaviorally relevant energy data as well as inspiring the driver to use the HMEI as a tool to gain control over energy use. Response to the feedback varied with the individual, but a number of themes were commonly repeated by many drivers. In particular, real-time feedback was used as a tool for experimentation and learning, goals were compared with trip averages to both motivate behavior, and trip average scores were used as a kind of high-score in competitive or game situations.

Real-time energy economy – including a combination of fuel, kinetic, and potential energy - was the primary metric for experimentation and learning, as drivers reported learning about the impact of their behavioral choices in the moment. However, for some people this measure did not impart a sense of control; for this group the real-time measure merely “showed them what the car was doing,” suggesting that some individuals require additional sources of knowledge or motivation before they will make use of the instantaneous information.

Having a personal goal integrated in the feedback system was especially important to the driver experience. The goal provided a metric by which to judge the otherwise non-normative information on the feedback display. In this way the goal and the trip average metric worked in tandem to encourage ecodriving. Many individuals customized the goal to suit their level of effort or drive-cycle, and generally goal achievement was met by positive feelings. The importance of a customizable goal wasn't directly tested, but driver responses suggest that customization provides additional motivation over a pre-set goal, especially for high-achievers.

Personal and social comparisons in the Trip Average MPG+ panel were rarely used by drivers. For a few drivers, this comparative information provided a new source of goals as hypothesized during the design process. However, the presentation of the high-low range of scores appears to have been too challenging, as the natural goal was the top score, a value that only 5% of trips ever reached. A better design could have shown the mean scores or a range from 25th to the 75th percentile scores, values that could motivate drivers without being too challenging. In addition, the extra information was tough for many drivers to digest and was often simply ignored. To be effective, the presentation and labeling would have to be improved.

The TPB and EMGBD hypotheses that goal, real-time, and trip-average feedback would motivate behavior change are clearly supported by driver responses. Much less clear, however, is how social information might influence driver behavior. Only a small minority of drivers found the social information useful, an indication that the information was not clearly presented, a poor metric (the range) was chosen, or that social information was simply not as critical to the driver experience as the other available information.

The most important contribution of the theory is from the EMGDB: the inclusion of a personal goal which could be easily compared to the trip average fuel economy was an important factor in driver motivation and to my knowledge has not been implemented in any commercial HMEI system. This simple addition reinforced driver motivation to ecodrive and allowed drivers to set more aggressive goals as they became more proficient. Perhaps the most interesting feature of a personal goal is that it is relatively simple to implement and could be easily and widely applied to any commercial HMEI system.

Chapter 5: Comprehending consumption: driver feedback, attitude change, and ecodriving

Introduction

In this chapter I present the results of a year-long study on driver feedback, attitudes, and behavior change. Underlying the design of the experiment is the conceptual framework of the Theory of Planned Behavior and Extended Model of Goal Directed Behavior, two related behavior change models that emphasize the contributions of attitudes, social norms, perceived control, and goals to behavior and behavior change. Although behavior change theories were used to design the experimental instruments and intervention, the analysis is exploratory in order to maintain the broadest possible view of the experimental effects. Given that contextual factors (such as traffic density or trip drivecycle) are known to be important in the application of behavior theories as well as in many transportation applications, it is currently unclear how those contextual factors might interact with behavior and therefore an exploratory analysis is particularly important.

Background

This chapter draws on two distinct areas of literature: fuel economy feedback and behavior change. In this section I present a brief overview of the fuel economy feedback (HMEI) literature. A more complete evaluation of the effectiveness of fuel economy feedback and an analysis of behavioral theory for driving behavior was presented in Chapter 2.

Fuel economy feedback research

Fuel economy feedback research is a field that seems to manifest itself according to such geopolitical events as oil embargoes; oil spills or other shortages; fuel price fluctuations from demand, production, or refining capacity; concern over global warming or concern over energy security. However, even with the importance of so many different reasons for conserving fuel changing over time, the behavioral results of past experiments have been fairly stable. In the past couple of decades technological advances in sensing, computing, and vehicle design have made inexpensive computation and display a possibility and have contributed to a recent resurgence of interest in the topic, both among researchers and consumers. The other reasons for a resurgence in interest are of course the current popular subjects of climate change and energy security.

In the following paragraphs I group HMEI designs by behavioral complexity, that is, by the types of behaviorally relevant information that the HMEIs display. Simple HMEI feedback comes in many forms. Examples include HMEI designs that primarily display real time fuel economy (MPG or l/km) in formats ranging from text displays to bar charts to dial gauges, two common examples of which are shown in Figure 13. Early designs include vacuum-based gauges (Greene, 1986), while more recent incarnations include digital displays based on vehicle OBD II CAN bus data (Barth & Boriboonsomsin,

Figure 13: Top: A 1995 BMW dashboard Vacuum-based MPG Gauge (bottom center).Bottom: a scangauge digital readout.

2009). Digital displays have the advantage of easily providing running trip or lifetime averages, but in other respects the real-time information and display have been available for about 40 years (Greene, 1986).These HMEI designs do not make an overt attempt to influence other areas of knowledge or attitude, but rather assume that drivers have appropriate attitudes, ecodriving knowledge, behavioral and social norms that would motivate them to increase their fuel economy, or that such factors are irrelevant. The opposite effect is certainly a possibility. For example, real-time feedback is a popular tool in car-racing circles for a race called the ¼ mile drag, in which racers attempt to drive ¼ mile in the shortest possible period. In fact, many 3rd party vehicle interfaces are designed for such racing situations and include fuel economy as an optional piece of information. In the case of the ¼ mile drag, the feedback information indirectly encourages higher rates of energy use by enabling drivers to achieve higher rates of acceleration. So in one context, drag racing, feedback encourages increased energy use, but in another, ecodriving, it is presumed to reduce energy use. The reason why these two situations are different is clearly not due to any built-in effect of feedback itself, but to the personal and social factors surrounding each activity that give meaning to the information on a case-by-case or even person-by-person basis.

Examples of more sophisticated devices include various levels of contextually aware feedback in which the HMEI presents advice or feedback that is dependent on the driving situation, as understood by available sensors and algorithms (Ganti, Pham, Ahmadi, Nangia, & Abdelzaher, 2010; Syed & Filev, 2008; van der Voort, 2001). These devices take a more serious approach towards the driving context and focus on solving the technical issues associated with understanding or predicting driver needs with various attempts to provide timely advice to drivers that is not contrary to the driving situation or safety. However, in general they do not approach the larger theoretical issue associated with behavior change: designing information to influence particular psychological factors.

A final set of reports and news articles, unfortunately not available as peer-reviewed papers, concern the recent attempts by the automotive industry to apply behaviorally sophisticated, if ad-hoc, HMEI designs, some of which are currently available in production vehicles, such as the Ford Fusion Hybrid HMEI shown in Figure 14. Notable reports come from Ford, Nissan, Toyota, and Honda, all of which are invested in highly efficient hybrid and electric vehicle production (Abuelsamid, 2010; Ando, Nishihori, & Ochi, 2010; Satou, Shitamatsu, Sugimoto, & Kamata, 2010). These systems are generally integrated with navigation, provide real-time fuel economy feedback, social and goal-related information such as fuel economy rankings or “prizes” for achievement, and contextual feedback such as trip distance-based ratings. However,

Figure 14: Ford Fusion Hybrid EcoGuide. Image from the Ford Fusion official website: http://www.ford.com/cars/fusion/

possibly due to the closed and competitive nature of the automotive industry, the effectiveness of these designs have not been vetted in a peer-review type setting, and detailed designs are difficult to come by.

Description of the experiment

In the following sections I present the methodology and results of an HMEI experiment performed in California's Yolo, Solano, and Sacramento Counties from September 2009 to September 2010 with 24 households and 42 individual drivers. The experiment was conducted as a part of the larger UC Davis Plug-in Hybrid Electric Vehicle (PHEV) Demonstration in which households in place of their own vehicles as a part of their normal routine (Kurani et al., 2010). The households that participated in this experiment were selected from the pool of respondents for the PHEV demo, and were not selected based on any additional characteristics beyond those required by the PHEV Demo, which included an available place to charge the PHEV and relatively high vehicle insurance coverage. The respondents included a demographically wide range of individuals, from middle to high income, young to retired, and single occupant to family households.

Individuals in the feedback experiment generally followed a four-week plan, although some individuals had longer use of the PHEV for various reasons. At the beginning of the first two weeks the subjects completed an online behavioral survey, and then completed a slightly modified version of that same survey (now including questions about the study vehicle) after two weeks (phase 1) and again after four weeks (phase 2). Each vehicle was outfitted with a custom 7” by 5” HMEI, described in Chapter 4, that was mounted directly over the OEM center console screen. During phase 1 the HMEI showed only the PHEV battery state of charge, simulating information that an OEM

PHEV or EV would have. At the beginning of phase 2, the HMEI energy information was activated, revealing a variety of energy economy, cost, and emissions information. The subjects were given a pamphlet describing the meaning of each information panel, although no ecodriving information or encouragement was given to the subjects.

The HMEI recorded detailed vehicle operations from the OBDII port (On-Board Data Port, standard in US vehicles since 1996) as well as GPS coordinates, the driver identity, and the selected information panels in the cases where drivers were allowed to select from a variety of information panels. In addition, vehicle operations were recorded using the V2Green fleet management system. The data redundancy turned out to be extremely useful, as a bug in the HMEI meant that only short trip data was properly recorded onboard. In the analysis presented below, trip-level driver identity and selected panel data were matched to 1 hertz driving data recorded from the V2Green system.

The study HMEI panels and driver operations are described in detail in Chapter 4. One important note is that the HMEI used real-time energy economy rather than fuel economy. The reasons for this are described thoroughly in Chapter 1 and summarized here. One notable reason for using energy economy is that the study vehicles used both gasoline and electricity as primary energy sources, and miles-per-gallon is not a meaningful measure for vehicles with part (or all) electric operation. To combine gasoline and electric fuel sources, a thermodynamic equivalency was made based on gasoline and battery energy. Gasoline and battery energy were converted to joules (using the lower heating value of gasoline) and then into miles-per-gallon of gasoline equivalent (MPGe) which was represented to drivers as MPG+ (“miles-per-gallon plus”) to present a simple and accurate measure of energy consumption, avoid confusion over too much new terminology, and generally skirt the issue of energy equivalency since the subjects came from a wide variety of backgrounds and few had technical educations.

Methodology

To best explore the data without assumptions that could bias or otherwise frame the results, model-based exploratory analysis was used wherever possible. The concept behind model-based analysis is to structure data according to latent characteristics available within the data itself (Fraley, 1998). Much like a basic model-fitting process, model-based analysis uses measures of model fit to determine not only the appropriate parameters to include in a model as in traditional model fitting, but to determine how to segment non-linear factors into categories that each have a uniform influence on the dependent variable, and how (or whether) to cluster individuals into groups. This methodology is used in three distinct ways in this analysis: in the determination of cognitive factors (as shown in Table 4); in the determination of distinct trip types, a contextual factor that can have a non-linear effect on energy use; and in the determination of behavioral subgroups, i.e., whether there are identifiable groups who respond differently to the energy feedback in ways that can be explained by the behavioral model.

Cognitive factors

A survey instrument was designed to measure fuel-economy related attitudes, social norms, perceived behavioral control, goals, and personality factors. Approximately six questions related to each of these five constructs tested different aspects of each. The survey questions were generated specifically for this experiment and refined with pilot subjects before the experiment began. For a complete list of survey questions used in the analysis please refer to Table 4. The survey was given in three waves: before the initiation of the experiment (wave 0), once after the baseline driving period (wave 1), and a final time at the conclusion of the experiment (wave 2). Changes between waves 0 and 1 are attributed to the experimental context of the PHEV and observation in general, and changes between waves 1 and 2 are attributed to the introduction of the HMEI. Wave 1 is therefore used as the baseline cognitive measure, and the difference between waves 1 and 2 as the experimental effect.

The 35 cognitive survey items shown in Table 4 were created to reflect factors hypothesized to be important in driver behavior change based on existing theories applied to the driving context, in particular the TPB and the EMGDB. However, the structure implied by those theories may not fit the response patterns or be meaningful to fuel economy. A principal component analysis (PCA) was performed to determine the revealed structure of the responses. The PCA was used to find orthogonal (uncorrelated) cognitive factors, and to reduce the dimensionality of the data, e.g. to result in a handful of meaningful components, each one a linear combination of similar original responses. The number of final PCA factors was selected using multiple heuristics: by performing a traditional scree-plot analysis, by selecting components with eigenvalues greater than one, and by searching for meaning in the rotated components. In this case the scree-plot method resulted in four PCA components, whereas the eigenvalue method indicated that there were 12 components. However, as many of the eigenvalues were only slightly higher than unity, they can likely be dismissed without major repercussions for the integrity of the analysis. Four components, accounting for 38% of total variance, were selected as the final set and rotated for interpretation and analysis using the varimax method. The components and factor loadings are shown in Table 4.

Table 4: Principal Components Analysis of Cognitive Factors Summary and Interpretation. Dark shading indicates strong loadings between the survey item and the rotated component. Factor interpretations are shown at the bottom of the table.

	Survey Question	Rotated Component (RC) Loadings			
		RC # 1	**RC # 2**	**RC # 3**	**RC # 4**
Attitudes	Driving fast is fun	0.03	0.58	-0.31	0.36
	Saving gas makes me happy	-0.17	-0.28	0.58	0
	Driving efficiently is unsafe	-0.14	0.29	-0.31	-0.25
	Using gas lets me do what I need to do	-0.36	0.3	0.29	0.18
	Saving gas is important	-0.01	-0.33	0.57	0.05
	Saving time is more important than saving gas	0.24	0.7	0.03	-0.05
	When driving it is best to "go with the flow"	0.01	0.55	0.03	0.06
	Most people save gas by driving efficiently	-0.1	-0.07	0.38	-0.08
	I don't care if other drivers think I'm slow	0.17	-0.53	0.19	0.01
	It is important to drive at or below the posted speed limit	0.15	-0.47	0.22	0.03
	I have had bad experiences with other drivers getting mad at me	0.15	-0.11	0.17	-0.21
	[My friend] thinks that I waste gas	0.09	0.21	-0.33	-0.47
Knowledge and Perceived Behavioral Control	I like to know all about my car	0.1	0	0.4	0.44
	I like to master new technologies	0.04	0.04	0.25	0.57
	How I drive can change my fuel economy	0.13	0.06	-0.03	0.55
	I know how to drive efficiently	-0.04	-0.07	0.17	0.65
	I already drive as efficiently as I can	0.06	0.03	0.72	0.1
	My fuel economy is a result of factors beyond my personal control	0.1	0.08	0.1	-0.48
	How I drive is determined by roads and traffic	-0.13	0.15	0.01	0.41
	I could make an % improvement in my primary vehicle fuel economy by changing my driving style.	0.57	0.35	0.07	-0.35
	I could make an % improvement in my PHEV fuel economy by changing my driving style.	0.62	0.28	0.11	-0.41
	Difference between highest and lowest perceived trip average mpg (calculated)	-0.09	-0.07	-0.32	0.42
	Average of all confidence statements (calculated)	-0.18	0.01	0.53	0.17
Personality	I'm not about to change my driving habits	0.17	0.4	0.02	-0.02
	I'm a perfectionist	-0.7	-0.06	0.04	0
	I like to be the person in a group who has the right answer	-0.37	0.26	0.14	0.5
	I don't care if I win in competitions	0.43	-0.52	0.05	-0.17
	I'll try something a second or third time to get it right	-0.48	-0.3	0.2	0.4
	I usually leave things at "good enough"	0.53	0.2	-0.36	0.02
Goals	Goal to "Get around faster"	0	0.74	-0.17	0.07
	Goal to "Generate less carbon dioxide from driving"	0.23	-0.52	-0.21	0.17
	Goal to "Drive less overall"	-0.16	-0.47	0	0.05
	Goal to "Save gas"	-0.46	0.08	0.25	-0.12
	Goal to "Save money related to driving"	-0.17	0.2	0.45	0.06
	Goal to "Drive more safely"	0.57	-0.17	-0.04	-0.01
	Interpretations:	Satisfied & Safety Concious	Fast & In a Hurry	Gas and money Saving	Expertise

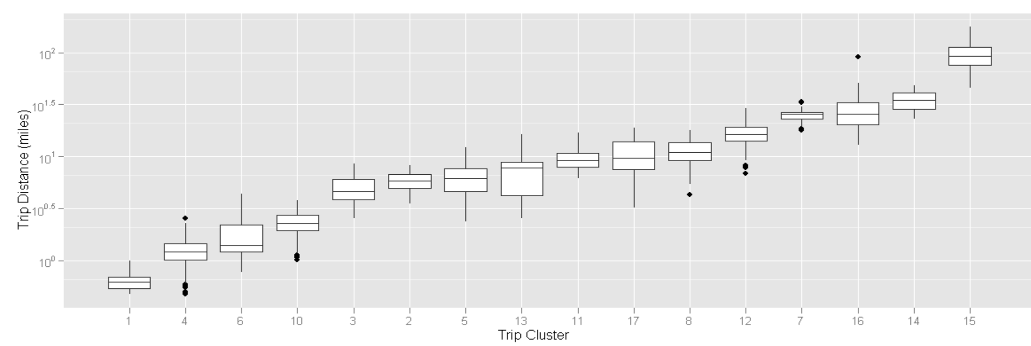
Contextual vs. behavioral factors

The driving context can have a profound effect on fuel economy that is largely beyond the control of the driver, given a particular trip and vehicle choice. These contextual factors can include the type of roads used, frequency of stops, road speeds, and other network, regulatory, traffic, or land-use details. Studies of fuel economy technology generally include mechanical models of the vehicle which can explain minute differences in fuel economy from accelerations and decelerations, essentially presenting a mechanical, rather than psychological, explanation for energy use. In contrast, this study presents an examination of driver behavior, not fuel economy technology. In order to determine what changes in energy use are due to driver choices it is essential to use a model of fuel economy that clearly separates contextual factors (those that are exogenous to the measured driver behavior) and factors that are influenced by driver behavior. These definitions are somewhat flexible depending on the definition of driver behavior, so it is important to have a clear definition of driver behavior before attempting to measure behavior change. Although driver behavior can be interpreted in a broad manner that could include vehicle purchase choices, trip-making choices, or even voting habits (related to transportation infrastructure funding), this chapter focuses specifically on driver behavior in the vehicle, assuming vehicle type and origin-destination habits are fixed. Weather, traffic, and trip-level factors such as drive-cycle are considered contextual factors that are by nature exogenous to in-vehicle behavior and are therefore included as explanatory model terms to reduce unexplained fuel economy variance and increase the precision of the behavior change estimate. Although it is not the focus of the model, the driving context remains critical to a small or medium sample size study of fuel economy, such as this one, since no two different trips can be compared without including contextual factors such as drive-cycle, altitude gain, or vehicle type to reduce the variance in fuel economy between trips. In a study with a very large sample size, no contextual factors would be needed since the statistical power of the model would be much higher and the large variance between trip types would eventually average out.

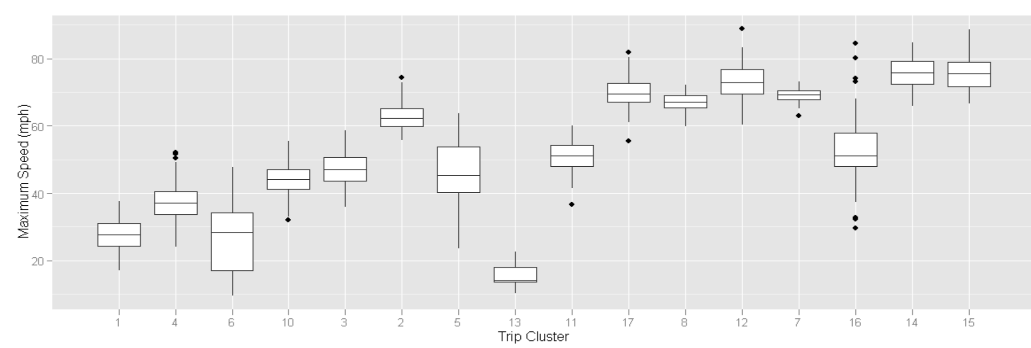
Trip types

Trip-level factors such as trip speed, drive cycle, and traffic levels are some of the most important contextual (non-behavioral) fuel economy factors. To reduce trip type variance, a form of model-based clustering is used to determine what distinct trip types exist in the observed travel data. Model-based clustering uses a probabilistic assignment algorithm to test the amount of variance explained by different numbers of clusters, in this case trip types. When the amount of variance explained by the next cluster does not outweigh the additional parameters according to an information criterion, the final cluster is rejected, and the routine is complete at the penultimate cluster set. The trip clustering analysis was performed using the R package Mclust, which uses the Baysian Information Criterion (BIC), a well-known information criterion that is used to penalize the addition of parameters (or in this case, trip type cluster). Trip distance, maximum speed reached, and stops/mile were used as the clustering variables. The results of the clustering resulted in 18 distinct trip types described in Figure 15 A-D by their clustering dimensions, as well as fuel economy.

A.



B.



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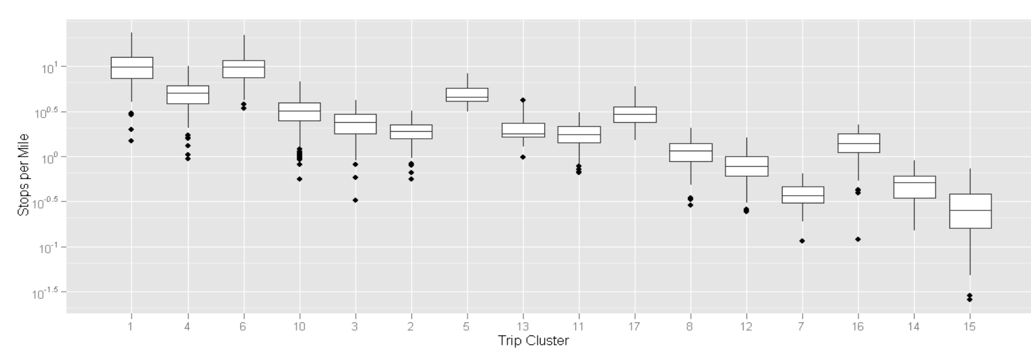

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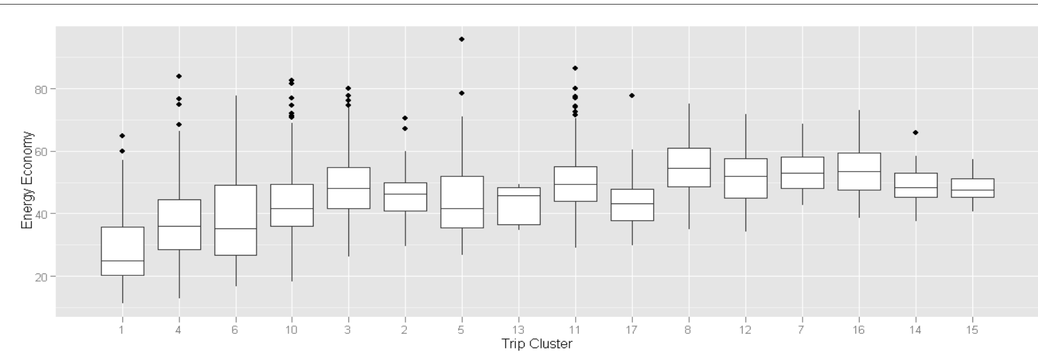

Figure 15: Trip type cluster descriptions. Trip types are organized by increasing trip distance for ease of comprehension. A wide variation in trip characteristics can be seen in both the number of stops per mile and trip speeds, even in adjacent distance categories. Overall energy economy of the trips (not used in clustering) is shown in the bottom plot, and displays a nonlinear relationship to distance, although the general trend is an increasing energy economy with distance.

Summary of the behavioral model

The models used here to estimate changes in fuel economy due to behavior change combine the statistical methods of mixed effects models, mixture models, and growth models. Each model includes a mixture of multiple distributions of related mixed-effects sub-models, each sub-model containing identical parameters related to vehicle operations and contextual effects, subject-level random intercepts to account for repeated measures, and latent group-level growth parameters related to the change in fuel economy over time due to the introduction of fuel economy information.

To estimate the effects of both the HMEI and cognitive factors, which are linked explanatory variables since it is hypothesized that the interface causally interacts with cognitive factors to produce outcome behavior change, two related models were created. The first model includes an interface dummy variable and antecedent phase 1 cognitive factors to account for pre-existing cognitive factors. This model is used to determine the overall impact of the interface and the change in driving behavior over time due to its presence. The second model removes the interface variable completely and introduces a cognitive term representing the change in cognitive components from the first to the second phases of the experiment. This model is used to test the hypothesis that changes in cognitive factors are the direct determinants of driving behavior. With larger sample sizes it would be possible to combine these two models in a structural equations model (SEM) to test the effects of the interface and cognitive factors simultaneously; the current sample of 23 drivers is too small for such a complex SEM model.

The R package flexmix was used to perform the Finite Mixtures optimization and group assignments and found three distinct latent groups based on the survey responses.

The R package nlme (non-linear mixed effects) was used to then fit the mixed-effects models based on the latent group definitions found from flexmix.

Statistical background

Mixed effects modeling

Because this study recorded real-world driving behavior among many individuals, the data represent unbalanced repeated measures. Thus a linear mixed effect model was used to assess the relationships in the data (Hedeker, 2004; Vonesh & Carter, 1992). In this context the mixed effect model is synonymous with a hierarchical or multilevel linear model that accounts for variance within the measures of an individual driver while simultaneously testing an experimental effect. By defining the individual as a random effect, each individual is associated with a unique intercept, and the individual deviations are measured relative to this intercept (a process also called centering). Without individual intercepts the experimental effect could have an erroneously significant p-value since the assumption of the simple linear model is that every observation is independent (and contributes a degree of freedom), whereas the assumption of the mixed effects model is that every between-subject center is independent, but within-subject observations are not independent. Due to this restriction the model contains fewer true degrees of freedom, and parameter estimate p-values will be higher (and therefore less significant) than in the case of a simple linear model. As an example a model of the experimental effect with a random subject intercept yields a similar coefficient for the experimental effect, but a p-value more than an order of magnitude larger (less significant) than the linear model with no control for repeated measures, as shown in Table 5.

Table 5: A P-value Inflation Example. All other parameters have been removed for clarity. Although the parameter estimates of feedback are similar between the two model types, the linear regression model shows a p-value that is 20 times lower than the mixed effects model.

Linear mixed-effects model:
Call:
Fixed effects: MPGe ~ phase + speed.traffic + day.part + log(miles) + stops + trip type + temp.cold + I(ratio_batt_j^2)
Random effects:
Formula: ~1 | alias
Coefficients:

	Value	Std. Error	t-value	p-value
(Intercept)	31.3	5.3	5.8	<0.0001
Feedback On	0.98	0.29	3.3	7e-04

….

Linear regression model:
Call:
lm(formula = MPGe ~ phase + speed.traffic + day.part + log(miles) +
stops + trip type + temp.cold + I(ratio_batt_j^2), data = tripdata)
Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	29.1	5.5	5.2	1.33e-07
Feedback On	1.2	0.29	4.2	3e-05

...

Growth mixture models

One challenge faced by many researchers is the presence of unidentified subgroups of individuals, sometimes referred to as latent clusters or latent groups. Much as mixed effects models are important for properly defining a model with known subgroups (in this case, individuals), finite mixture models were developed to identify latent groups that are not explicitly recorded in the data, but can be estimated from measured variables (Leisch, 2004). The Mixture Models concept is that a given distribution may actually be composed of multiple related distributions, that is, multiple related groups of individuals that are better described by distinct group-level model coefficients. Given a fixed number of presumed latent groups, mixture modeling software estimates the group assignments that generate the lowest BIC for the model. Variable coefficients can be selected to remain constant between groups, or vary with the groups, again much like mixed-effects models. To estimate the number of distinct groups of individuals (and group assignments) in this dataset I ran a mixture model optimization for each number of latent groups from 1 to 5 (although a 5 groups solution could not be fit due to a lack of degrees of freedom), and recorded both the Akaike Information Criterion (AIC) and the BIC. The model with the overall best combination of low AIC and BIC is presumed to be the most accurate representation of the data and therefore the proper number of latent groups, in this case three.

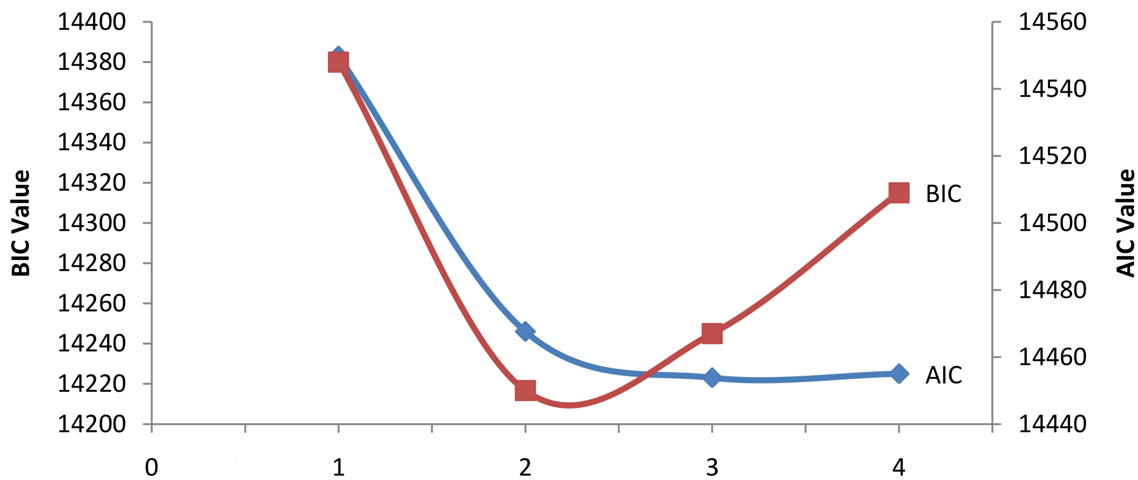

Figure 16: Finite Mixture Model analysis of latent groups. Either two or three groups should be chosen for this model due to the AIC and BIC minimums. The BIC is characteristically more conservative in groups due to a higher marginal parameter penalty than the AIC. In this case, the minimum AIC at 3 groups is chosen to preserve group identities rather than force distinct clusters into heterogeneous groups.

Adding to the exploratory power of the finite mixture model is the concept of a growth model. The purpose of a growth model is that the researcher is interested in determining how one factor leads to changes in a second factor over time, potentially among numerous (possibly latent) groups (Hedeker, 2004).

Distinction between simultaneous and ex-post clustering

The purpose of estimating a mixture model is that when lumping all subjects into one aggregate group, it is possible to miss differences that could radically alter the interpretation of the study (Hedeker, 2004). For instance, it is plausible that half of the group would increase their fuel economy and half would decrease it by the same amount. The aggregate result could be that there was no discernible change, since the mean change would be zero. However, this result could hide the reality of the experiment which was that there were two groups with different outcomes. This situation is distinct from a random distribution of behavior with mean zero, in which half of the population would be expected to decrease their MPG and half to increase it. If the group segmentation is ex-post, made after the model is defined, the results may meaninglessly segregate the subjects (for instance, based on random variation) rather than a true grouping (based on individual characteristics) and discover two "groups" when the observed difference is simply random error. To avoid this problem the behavioral subgroups are determined simultaneously with the model using the mixture-model methodology and based on the coefficients of phase 1 cognitive survey results and changes in survey responses between phase 1 and phase 2. This increases the likelihood that any observed differences in between-group performance is due to actual between-group identity differences, not random error.

Data and model details

Numerous steps were taken to ensure the accuracy of the model results, and allow the model to run without error. Of central importance, the dependent variable, energy economy (MPGe or MPGGE), was normalized by truncating trip distance at 0.75km (approximately 0.5 miles). This was done because of irregular and non-normal fuel economy at extremely short distances due primarily to driveway idling. Multiple energy feedback screens were available to subjects (as described in Chapter 4), although the model does not necessarily account for the different screen designs.

In addition, only individuals with trips in both phases of the experiment (interface-off and interface-on) are included. Each independent continuous variable was checked for linearity with the dependent variable (energy economy), and linearized where necessary. Most critically, the proportion of battery energy used for the trip was squared to linearize its relationship with energy economy. The final data include 23 individuals and 2024 trips.

The model used for Finite Mixture analysis was designed using mainly theoretical considerations, with modifications based on model necessities such as parameter reduction and interpretation. The theoretical considerations primarily consisted of including only trip-level factors that provide the behavioral context (such as trip type), while including a single form of psychological independent variable to explain behavior. This method insured that enough contextual information was included to test the hypothesis of behavior change without including so much contextual information that behavior change effects were washed out (such as in a mechanical vehicle model). The final model parameters are shown with descriptions in Table 6.

Table 6: Description of model parameters. Selected descriptive statistics for the factors and average MPGe are available in Figure 17.

Parameter	Description
MPGe	Miles per Gallon Equivalent energy economy dependent variable. Gasoline energy and electricity are combined into one energy measure using the lower heating value of gasoline.
Satisfied and Safety Conscious	The driver-specific PCA score from factor 1 as described in Table 4.
Fast and In a Hurry	The driver-specific PCA score from factor 2 as described in Table 4.
Gas and Money Saving	The driver-specific PCA score from factor 3 as described in Table 4.
Expertise	The driver-specific PCA score from factor 4 as described in Table 4.
Traffic speed	Regional traffic speeds matched to the trip hour.
Cold start	A 0-1 dummy variable that equals 1 when the vehicle-measured ambient air temperature is lower than 20C, defined to account for cold-starts.
Battery energy ratio squared	The squared ratio of battery energy to total energy. The purpose of this variable is to absorb PHEV-related variance.
trip type	Trip type categorical variable, displayed in order of increasing mean trip distance.
Absolute time	Common time parameter to absorb variance related to the passage of time or exogenous events over the 1-year study period.
Day	Time relative to each participant, in days since the interface is activated

Results

Latent group interpretations

The three latent groups determined using the finite mixtures algorithm are interpreted below using group-level boxplots of the pre-HMEI cognitive factors, the changes in the factors during the experiment, as well as group fuel economy before and after the HMEI deployment, as shown in Figure 17. The three latent groups are defined as Savers, Speedsters, and Techies as shown in Table 7.

Table 7: Group Definitions

Group	**Size (drivers)**	**Group Description**	**Group Name**	**Average Change**	**Final change (MPGe)**
1	4	Before the introduction of the HMEI group 1 had the highest average MPGe and had high scores associated with the Gas and Money Saving component, and low Expertise scores. However, the group steadily decreased their MPGe during the HMEI phase, showing decreases in both Gas and Money Saving scores, as well as fast and in a hurry scores.	Savers	-2.6	-6.8
2	9	Group 2 is defined primarily by high pre-HMEI scores on the Fast and in a Hurry component and the lowest group average MPGe fuel economy. After the introduction of the HMEI the group made some increases in Expertise scores, and made moderate, although not statistically significant improvements in average MPGe.	Speedsters	1.0	2.0
3	10	Group 3 began the experiment with high Expertise scores and low Satisfied and Safety Conscious scores. The group made large and steady improvements in MPGe fuel economy over the course of the HMEI placement, and showed increases in both Satisfied and Safety Conscious and Gas and Money Saving scores.	Techies	4.4	10.2

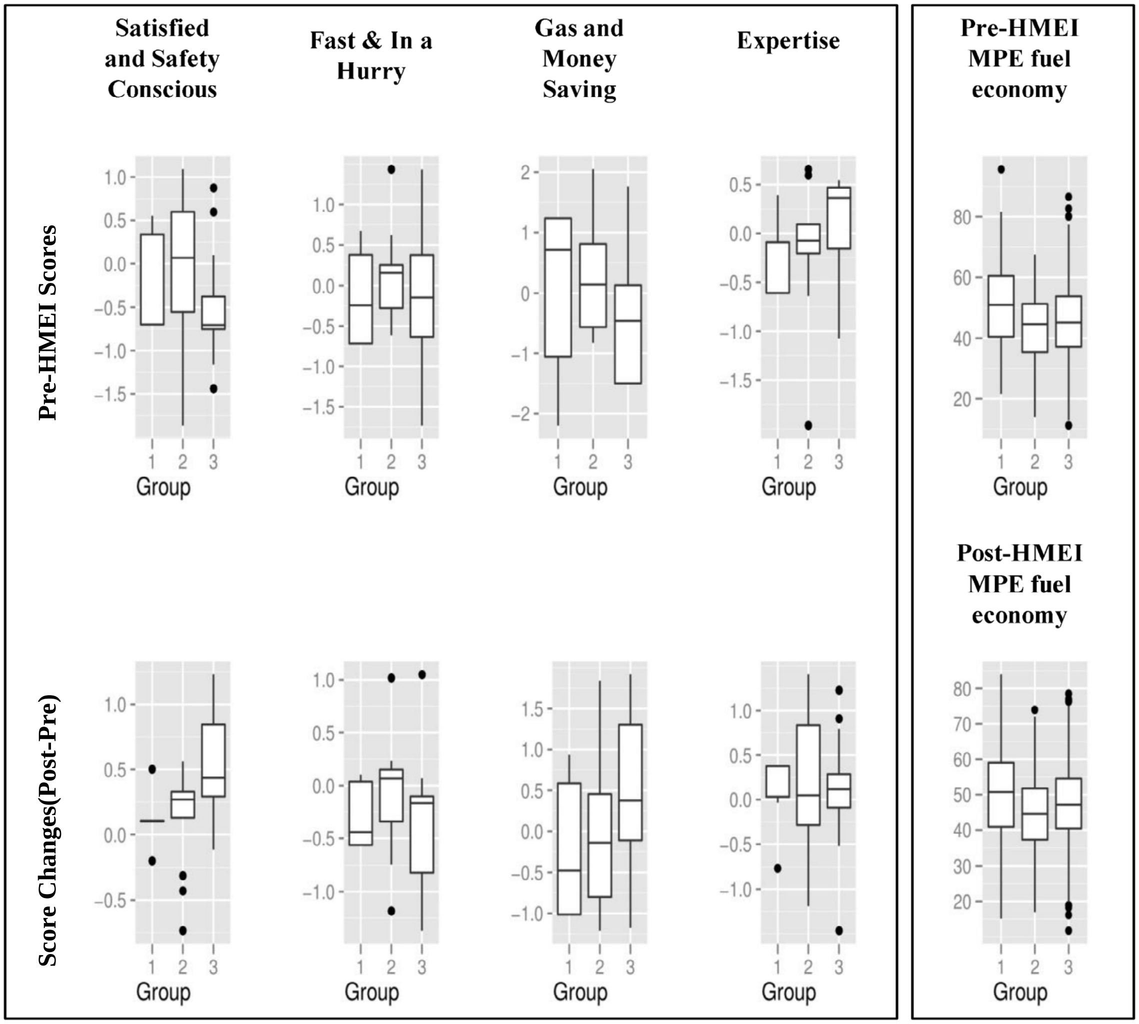

Figure 17: Box Plots showing inter-group differences.

Cognitive factor and interface growth mixture model

The growth model shown in Table 8 and Figure 18 describe the pattern of change in MPGe over time due to the introduction of the HMEI . Initial (pre-HMEI) cognitive factors and purely contextual variables including cold-start and trip type parameters are held constant between the latent-cluster sub-models and are shown at the beginning of the output in the table. Following those common parameters in Table 7 are the latent group specific parameters showing numerous statistically significant differences in all tested parameters relating to the effect of the interface over time.

The pre-HMEI cognitive components, however, are not significant predictors of average MPGe in this model. This may suggest that the latent groups, which were defined in tandem with the cognitive model, explain enough of the preliminary behavioral variance to reduce the explanatory power of the pre-HMEI cognitive factors.

Statistically significant group-level intercepts indicate that the three groups have fairly well defined intra-group baseline driving behavior, although it should be noted that the effect of the cognitive factors and trip context need to be included to estimate the group means. It is interesting to note that the Savers have the highest baseline driving fuel economy (the effect of cognitive factors excepted). Referring to Table 8, one can see that group 3 has the highest initial scores on competitiveness, again indicating that the competitive personality factors are counterbalancing the speeding behavior during the experiment.

At the bottom of the table are the growth parameter coefficients that describe the change in driving behavior over time during phase 2 and reveal the average group behavior, as shown in Figure 18. Techies and Speedsters showed a positive growth in fuel economy over time, although Speedster growth coefficients are not statistically significant.

Surprisingly, the Savers showed a marked decrease in fuel economy during phase 2. The MPGe boxplot means in Figure 17 show that the Savers also had the highest phase 1 fuel economy. There are a number of possible explanations for this counterintuitive effect of the HMEI on the Savers group. One possible explanation is that the group was already displaying ecodriving behavior in phase 1, and became tired of the effort in phase 2, coinciding with the introduction of the HMEI. Another possible explanation is that the

Savers are focused on reducing gasoline and monetary expenditures, and when they were finally presented with the HMEI feedback they primarily perceived the high fuel economy of the experimental PHEV vehicle, rather than the incremental benefit of ecodriving. Under this interpretation, the Savers are so satisfied with their fuel economy that they relax their former habitual ecodriving practices. A small increase in Satisfied and Safety Conscious and a decrease in Gas and Money Saving support the latter interpretation since they indicate a decrease in motivation to ecodrive due to the high native fuel economy of the experimental PHEV vehicle. Under this interpretation the group's behavior change is dependent on their perception of high or low fuel economy relative to their primary vehicles, and is therefore a vehicle specific effect.

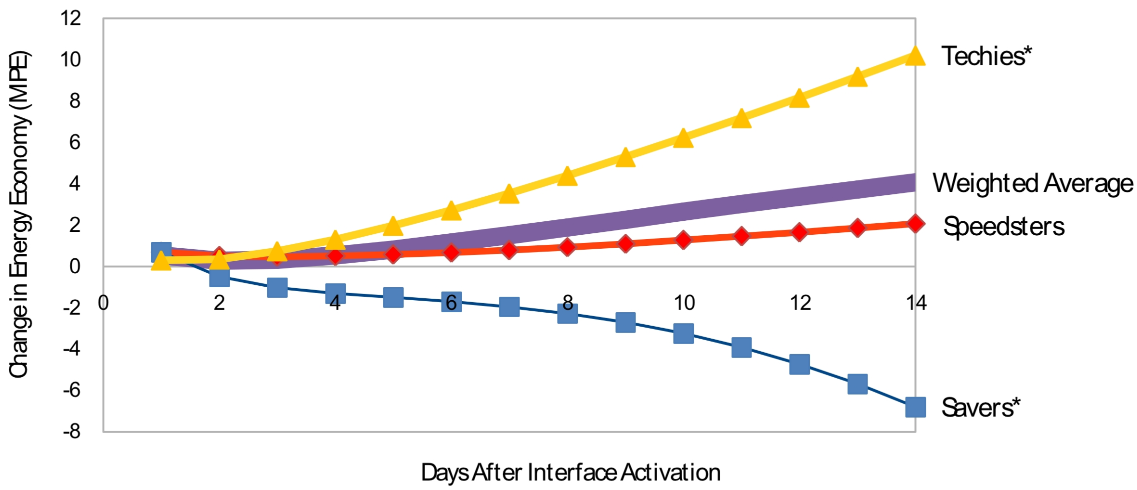

Figure 18: Estimated changes in MPGGE over time as compared to the baseline driving case with significant growth terms indicated by stars (*) and relative group sizes indicated by line weight. Parameters were estimated in the growth mixture model.

Table 8: Growth Mixture Model of Energy Economy due to Energy Feedback

Growth Model

Dependent Variable : MPGe Energy Economy

Term		**Value**	**Std.Error**	**t-value**	**p-value**	
(Intercept)		22.2	5.6	4	<.001	Intercepts
Speedsters		-4.5	1.8	-2.5	0.02	
Techies		-3.2	1.7	-1.9	0.08	
Satisfied and Safety Conscious		-0.7	0.82	-0.9	0.41	Preliminary Cognitive Factors
Fast and In a Hurry		-0.9	0.85	-1.1	0.30	
Gas and Money Saving		-0.7	0.58	-1.2	0.24	
Expertise		1.7	1.0	1.6	0.12	
cold start		-2.8	0.48	-5.8	<.001	Contextual Efficiency Factors
traffic speed		0	0.07	0.2	0.87	
absolute time		0	0.04	0.5	0.59	
battery energy ratio squared		193	4.1	47.5	<.001	
trip type 4		8.4	0.77	10.9	<.001	<- Shorter to longer trips ->
trip type 6		1.3	1.2	1	0.30	
trip type 10		13.8	0.76	18.2	<.001	
trip type 3		18.9	0.74	25.5	<.001	
trip type 2		20.6	0.98	21	<.001	
trip type 5		16.1	0.99	16.2	<.001	
trip type 13		17.1	1.8	9.6	<.001	
trip type 11		23.4	0.83	28.2	<.001	
trip type 17		19.8	1.1	17.4	<.001	
trip type 8		26.1	0.86	30.5	<.001	
trip type 12		26.2	0.84	31.1	<.001	
trip type 7		28.9	1.1	27.1	<.001	
trip type 16		27.3	1.4	20	<.001	
trip type 14		27.3	1.3	21.1	<.001	
trip type 15		26.7	1.2	22.3	<.001	
HMEI Offset	Savers	6.9	2.5	2.7	0.01	HMEI Effect Growth Parameters
	Speedsters	1.7	1.5	1.1	0.27	
	Techies	2.3	1.6	1.4	0.15	
Linear day term	Savers	2.8	1.2	2.4	0.02	
	Speedsters	0.4	0.85	0.4	0.65	
	Techies	1.5	0.51	3	3.E-03	
Squared day term (increasing effect with time)	Savers	-0.1	0.03	-2.4	0.02	
	Speedsters	0	0.03	-0.2	0.82	
	Techies	0	0.01	-3.6	3.E-04	
Square-root day term (decreasing effect with time)	Savers	-8.9	3.4	-2.6	0.01	
	Speedsters	-1.4	2.2	-0.6	0.53	
	Techies	-3.5	1.7	-2	0.04	

Cognitive change and behavior model

The cognitive change model shown in Table 9 is structured very similarly to the growth model, although with one key difference. Rather than include growth factors to determine how individuals changed their behaviors over time due to the availability of the HMEI, terms are included that represent the change in cognitive factors between the wave 2 and wave 3 surveys in order to test the relationship between behavior change and cognitive factor change.

The model presented in Table 9 indicates that, as predicted by behavior change theories, the cognitive factors did play a role in energy economy changes between the pre and post feedback experimental conditions. However, the real-world size of the effect cannot be directly estimated from the parameter value in the model since the value is based on the PCA data transformation, and is not a directly interpretable unit. For instance the effect of one unit change in Expertise could easily be quantified, but it is unclear what that unit represents. Each latent group shows a distinct pattern of change in cognitive factors related to behavior change, and statistical significance of many of the coefficients for cognitive factors indicate that changes in these cognitive factors correlate with changes in driving behavior and may be causal (although the causal relationship is not tested statistically). Assuming that driver psychology is directly responsible for driving style, the HMEI is not interpreted as the proximal cause of the change in driving behavior, but as the cause of changes in cognitive factors that then directly influence driving behavior. Alternatively, the HMEI could cause changes in certain cognitive factors and behavior change, and the new behavioral condition could cause changes in other cognitive factors.

The effect of pre-HMEI cognitive factors on average fuel economy are sensible according to their analogs in behavior theory. Both the Satisfied and Safety Conscious and Fast and in a Hurry terms are negatively and significantly related to baseline MPGe, which is reasonable since the Satisfied factor suggests little desire to exert extra effort, and the Fast factor is related to aggressive driving practices. The Gas and Money Saving and Expertise are both positively related to baseline MPGe, which is also sensible since the Saving factor indicates a desire to ecodrive, and Expertise relates directly to the TPB concept of perceived self efficacy, which is hypothesized to be an important contributing factor in behavioral decisions.

Increases in Satisfied and Safety Conscious are negatively related to MPGe, although the term is insignificant for the Savers group. Interestingly, the parameter coefficient is more than twice as large for Speedsters than for Techies, indicating that Speedsters' behavior is more sensitive to the factor.

The model shows a similar story for increases in the Fast and in a Hurry factor, of which all three group parameters are significant and negatively related to MPGe. In this case the Savers are by far the most sensitive to changes in this factor.

Increases in the Gas and Money Saving term, however, are positive for Savers, as expected, but negative for Speedsters. This could indicate a reverse-causality situation, where we may be observing a motivating factor in the case of the Savers, and a response to low or decreasing MPGe in the case of the Speedsters. In particular, the default personal goal built into the HMEI was defined as the average MPGe for a prior set of drivers. If the Speedsters, who had the lowest group average MPGe, tended to achieve fuel economies lower than the default goal, they may have created a new personal goal to conserve in response.

Increases in Expertise were significant for the Savers group and were positive as expected from the TPB. The non-significant results for the other two groups could indicate that without a goal to save, the additional expertise acquired through use of the HMEI doesn't translate into a behavioral choice to ecodrive, supporting the close relationship between goals and behavior postulated in the EMGDB.

Table 9: Cognitive Change and Behavior Model results. Sets of parameters are outlined.

Cognitive Factor Model

Dependent Variable : MPGe Energy Economy

Term		**Value**	**Std.Error**	**t-value**	**p-value**	
(Intercept)		18.9	4.8	4.0	<.001	Intercepts
Speedsters		-2.2	9.4	-0.24	0.81	
Techies		0.21	9.3	0.02	0.98	
Satisfied and Safety Conscious		-0.93	0.29	-3.2	<.001	Preliminary Cognitive Factors
Fast and In a Hurry		-2.8	0.44	-6.4	<.001	
Gas and Money Saving		0.50	0.54	0.93	0.35	
Expertise		1.3	0.60	2.21	0.03	
cold start		-2.5	0.48	-5.3	<.001	Contextual Efficiency Factors
traffic speed		0.04	0.07	0.54	0.59	
absolute time		0.02	0.02	0.83	0.41	
battery energy ratio squared		193	4.0	47.9	<.001	
trip type 4		8.1	0.76	10.6	<.001	<- Shorter to longer trips ->
trip type 6		0.82	1.2	0.66	0.51	
trip type 10		13.8	0.74	18.5	<.001	
trip type 3		19.2	0.73	26.3	<.001	
trip type 2		21.1	0.96	22.1	<.001	
trip type 5		16.2	0.99	16.3	<.001	
trip type 13		17.1	1.8	9.6	<.001	
trip type 11		23.2	0.80	29.1	<.001	
trip type 17		20.0	1.1	18.1	<.001	
trip type 8		26.4	0.83	31.7	<.001	
trip type 12		26.3	0.82	32.2	<.001	
trip type 7		29.0	1.0	28.6	<.001	
trip type 16		27.3	1.3	20.3	<.001	
trip type 14		27.5	1.3	21.7	<.001	
trip type 15		26.8	1.2	22.6	<.001	
Change in Satisfied and Safety Concious	Savers	-2.8	3.0	-0.95	0.34	Cognitive Factors
	Speedsters	-7.7	2.1	-3.7	2.E-04	
	Techies	-3.1	1.2	-2.7	0.01	
Change in Fast and in a Hurry	Savers	-15.1	3.0	-5.0	7.E-07	
	Speedsters	-4.2	0.66	-6.3	3.E-10	
	Techies	-1.5	0.74	-2.0	0.05	
Change in Gas and Money Saving	Savers	8.0	1.9	4.3	2.E-05	
	Speedsters	-2.0	0.29	-6.9	4.E-12	
	Techies	1.1	0.80	1.4	0.15	
Change in Expertise	Savers	5.5	2.2	2.5	0.01	
	Speedsters	-0.38	0.41	-0.93	0.35	
	Techies	-0.61	0.52	-1.2	0.24	

Conclusions

The results of this study have a number of important implications for understanding the effects of driving behavior in the HMEI context. The most important results are: 1) there are multiple types of people who can be differentiated by their cognitive factors and who have substantially different responses to the HMEI; 2) the majority of participants increased their MPGe for the duration of their exposure to the HMEI over the two-week period with feedback compared to their two-week period without feedback; 3) cognitive factors are shown to change based on exposure to the HMEI – an indication that driver attitudes, perceived control, goals, and even reported personality indicators are flexible constructs that are influenced by HMEI feedback; and 4) Reductions in complacency and perceptions of time pressure and increases in both an interest in saving gas and money or increased vehicle expertise are all associated with increased fuel economy when encouraged by an HMEI.

The results of the growth model show that drivers made changes to their driving behavior and MPGe over the course of the experiment, and that the changes increased with time, positively for the Techies and Speedsters and negatively for the Savers. The majority of subjects increased their MPGe and the largest group, Techies, increased their average by 10 MPGe (22% increase over their baseline) over the course of the feedback. However, none of the groups had stabilized their behavior after the two-week course, indicating that understanding long-term changes in behavior will require a longer experiment. In addition, the cognitive model showed that initial cognitive factor levels are predictive of baseline MPGe, supporting the behavior change model described in Chapters 3 and 4.

The results of the cognitive factor model indicate that cognitive factors changed during the experiment in a way that correlated with changes in MPGe. In addition, the effects are largely consistent both within the model and with hypotheses generated from the TPB and EMGDB. However, it is difficult to understand if some of the changes in cognitive factors caused or were caused by changes in behavior, in particular in the case of the Gas and Money Saving factor. The mixed directionality of the coefficient implies that the factor either has different meanings for different groups or that the effect of the HMEI is cognitively distinct for different groups. In either case, it is clear that the HMEI had a direct influence on both cognitive factors and behavior. Exactly how cognitive factors and behavior interact in a causal sense is still unclear.

The complex cognitive factor results indicate that a more sophisticated behavioral interpretation may be required to improve on theory-based feedback. Standard behavioral theories such as the TPB predict that independent factors contribute to behavior, but this study found that there are additional relationships between these factors that comprise behavioral constructs, in this case the four constructs of Satisfied and Safety Conscious, Fast and in a Hurry, Gas and Money Saving, and Expertise. Although it is possible that the effects of these constructs are specific to the driving behavior context, these constructs will improve the sophistication of the conceptual basis of future behavior research since they indicate that traditional behavioral factors actually act together in specific ways.

The Savers group appears to have a negative response to the HMEI. Their outcome may largely be explained by an effort to drive carefully in phase 1 as reflected by their high average phase 1 MPGe. This early effort, counter to the design of the experiment, could have created a potential for behavioral exhaustion in phase 2 when they slowly decreased their fuel economy over time from their phase 1 average. Alternatively, the group may have achieved their goal to save money and gas simply by participating in the experiment since they were able to drive a highly fuel-efficient PHEV, reducing their desire to have an additional impact through driving behavior. A future experimental design could take two different approaches to this issue. The first would be to use the subject's own vehicle in the experiment. This would mitigate the experimental effect in phase 1 in which individuals were experiencing a new vehicle for the first time, as well as remove the jump in fuel economy that most drivers experienced. The second design would be to randomize the order of the HMEI deployment, allowing half of the drivers to begin the experiment with the HMEI activated, and therefore canceling out the effect of precocious phase 1 drivers. However, the latter design would potentially create a post-HMEI effect, and as little is known of the strength of the learning effect in this context, the design may underestimate the HMEI effect for the drivers that receive the HMEI first.

Conclusion: Towards a better HMEI, and the possible future role of behavioral HMEIs in transportation and beyond.

This dissertation was a first step in using behavior change theories to provide drivers with fuel economy feedback. Chapter 1 discussed an important contribution to the literature, which is to focus on energy economy, rather than gasoline economy for real-time driver feedback. Much of the work in Chapters 2 and 3 was focused on developing the concept of a theory-based HMEI with the specific aim of creating a starting point for future theory-based work in the field. The main sources of hypotheses were the theory of planned behavior and a related model, the extended model of goal directed behavior. Each model made important theoretical and practical contributions to the final experimental HMEI design shown in Chapter 4. Chapter 5 tested the effect of the experimental device within the context of the UC Davis PHEV demonstration and extended previous analyses by developing a more sophisticated statistical model capable of separating latent groups of individuals, determining the effect of time, and investigating the importance of attitudes, goals, and other cognitive factors.

This look at driver feedback went far beyond the typical field test by examining the premise of feedback itself, and testing the psychological mechanisms that generate both the desire and the ability within individuals to change behavior.

From a theoretical standpoint major findings include the theoretical importance of personal goals, social information, and carefully integrated average information. Of particular importance is the driving context, and theoretical considerations generated a variety of solutions for driver comprehension that can be applied in future designs.

From an application standpoint the HMEI design presented in Chapter 4 successfully integrated numerous behavior-theoretic factors into a practical user interface. One addition of primary importance is the idea of presenting information to the driver, rather than the car. A touchscreen interface allowed each driver to receive personalized goals, feedback, and summaries. The use of color also turned out to have a strong effect on drivers, and indicates that the use of color should be carefully considered in order to effectively support the feedback without creating a sense of fluctuation. The HMEI design can be compared to the most common sophisticated commercial HMEI, that of the early-model years Toyota Prius discussed in Chapter 3. Although interview methodologies differed, preventing a direct comparison of effectiveness, many more individuals (40% in the OEM case versus 60% in the custom HMEI case) reported changing their behavior in response to the custom HMEI than to the OEM Prius interface, and the focus on energy economy and personal goals may be largely responsible for the difference.

Finally, the analysis of driver behavior presented in Chapter 5 both supports the findings of previous researchers in total magnitude and adds greatly to the nuance of the system dynamics both in a temporal and in a cognitive sense. The changes due to the HMEI increased continuously for the entire two week duration of the experiment, raising the question about what the equilibrium effect would be. Using the literature review in Chapter 2 as a guide, the HMEI effect is likely to be sustained given the additional motivational effect of trip average summaries and especially user goals. Possibly the most important finding in Chapter 5, however, is the close relationship between changes in driver cognitive factors (in particular, goals, attitudes, and perceived behavioral control) and changes in behavior. The finding supports the use of the TPB and the EMGDB, but more generally suggests two main lessons.

The first lesson is that energy use is inextricably bound to flexible thought processes that can be influenced through the application of appropriate feedback. Rather than repeating the simplistic mantra that more information is better, feedback designers would be well served to focus feedback on driver goals, attitudes and perceived behavioral control, and let the driver's own emergent motivation create the ultimate positive change in behavior. This means choosing relevant metrics and placing them in human-centric contexts, for instance by employing personalized feedback and socially important metrics.

The second lesson is that goals and norms are sorely lacking in energy feedback. Goals and norms provide the context by which individuals can comprehend the consequences of their own actions. Goals are flexible constructs that come from the individuals themselves and should be shown in relation to performance in a way that matches drivers' own thought processes about different temporal periods. Norms are external to the individual and can be built into the feedback to provide contextual cues for each type of information, guiding users towards an understanding of their own behavior.

Energy feedback is a potentially powerful way for individuals to achieve their own goals, and for designers and policy-makers to help frame and encourage socially relevant goals. Current implementations are becoming much more sophisticated, but a theoretical basis can bring important additions to even the best HMEIs in the field.

The effect of feedback on driver thought processes indicates a larger role for feedback in policy. The complexity of energy information and the lack of context that individuals have about the environmental implications of energy use in transportation are a real problem for grassroots support for legislation. By educating individuals about energy use and encouraging the formation and achievement of goals, feedback can endow individuals with a real (and correct) sense of personal ability and responsibility over environmental impacts that may translate into future support for environmental legislation.

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Appendix

Source material for figure 6

Title	Author	period (days)	Effect (reduction)	Sample size	HMI design
Real Time Advisory System for Fuel Economy Improvement in a Hybrid Electric Vehicle	Syed and Filev, 2008	1	10.00%	1	“accelerator pedal position advisory”
The effect of eco-driving system towards sustainable driving behavior	Lee, 2010	1	0.00%	14	A 3 icon color display showing poor, neutral, and eco indicators
Driver Energy Conservation Awareness Training: Review and Recommendations for a National Program	Greene, 1986 /Chang et al. 1976	1	5.40%	1	Vacuum-based mpg meter
Driver Energy Conservation Awareness Training: Review and Recommendations for a National Program	Greene, 1986 /Banowetz and Bintz, 1977 (US DOT)	1	3.00%	140	Vacuum-based mpg meter
Driver Energy Conservation Awareness Training: Review and Recommendations for a National Program	Greene, 1986 /Bendix, 1981	1	2.20%	1	Vacuum-based mpg meter
Driver Energy Conservation Awareness Training: Review and Recommendations for a National Program	Greene, 1986 /Bendix, 1981	1	8.80%	1	Vacuum-based mpg meter
Development of the On-Board Eco-driving Support System	Satou et al. 2010	1	18.00%	1	intricate onboard+web. Raltime feedback+Fuel usedXdistance metric and rankings.
Enviance Denver case study	https://www.drivingchange.org/	1	0.00%	214	web only
FEST - A New Driver Support Tool that Reduces Fuel Consumption and Emissions	Voort, 2001	2.5	6.00%	12	“existing” - presumably realtime mpg?
FEST - A New Driver Support Tool that Reduces Fuel Consumption and Emissions	Voort, 2001	2.5	11.00%	12	HMI gives driver advice based on vehicle operations

Title	Author	period (days)	Effect (reduction)	Sample size	HMI design
Eco-Driving: Pilot Evaluation of Driving Behavior Changes Among U.S. Drivers	Boriboonsomsin, Vu, and Barth 2010	14	3.75%	20	realtime mpg+throttle+ lb. Co2/mile. Trip summary stats. (Eco-Way by Earthrise Technology / OBDII connection)
Auditory and haptic systems for in-car speed management – A comparative real life study	Adell et al. 2008	28	0.00%	127	device shows roadway speed limit and beeps when speed limit reached
The effects of an acceleration advisory tool in vehicles for reduced fuel consumption and emissions	Larsson and Ericsson, 2009	42	0.00%	20	Haptic Feedback
Development of a System to Promote Eco-Driving and Safe Driving	Ando, 2010	126	4.30%	50	Complex web and mobile phone feedback comprising scores and logs. "To promote the eco-driving is a very hard work"
Long-term effects of training in economical driving: Fuel consumption,accidents, driver acceleration behavior and technical feedback	Wahlberg, 2007	365	4.00%	350	Real-time and average consumption (km/l) text display