"Actual Results May Vary": A Behavioral Review of Eco-Driving for Policy Makers

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EXECUTIVE SUMMARY

This research provides energy and environment policy makers with an up-to-date summary of eco-driving research. Our review of an extensive database of eco-driving studies reveals the fuel and emissions reduction outcomes achieved to date and the conditions under which those reductions were measured or estimated. We summarize the interventions used to achieve those outcomes and consider promising strategies.

The research underscores a clear imperative: we need to understand the behaviors that constitute eco-driving in order to design effective interventions. In short, we seek to inform policy makers of (1) the presently understood savings potential of eco-driving, (2) promising pathways for effective policies, and (3) the need for a behavioral perspective to accurately identify the true savings potential of eco-driving and the most effective policies.

Starting with a broad definition of “eco-driving,” this paper addresses four questions: Why eco-driving? What are eco-driving behaviors? How much do they save? How are they promoted?

Before answering these questions, it is helpful to note that eco-driving is one example of a long- and widely held distinction between technical potential (often assumed to be the best possible performance) and realized performance in the hands of end-users. One common eco-driving reference is the statutory measure of automotive fuel economy for compliance with federal Corporate Average Fuel Economy (CAFE) standards. CAFE is not (nor was it ever intended to be) the best fuel economy any given driver might expect from any given vehicle. Given the central organizing idea of a difference between technical potential and realized performance in the hands of end users, there is far too little eco-driving research that

Key Findings

The most commonly stated function of eco-driving has been increased on-road fuel economy. Other functions, such as emissions reductions and safety, have been substituted or conflated with fuel economy.

There is no consensus on what behaviors constitute eco-driving: definitions differ by functions, forms, and contexts. To aid in systematizing eco-driving classifications, we propose a framework grounded in behavioral theory.

Because definitions vary, so too do estimates of effects. Still, the literature presents a compelling case that drivers can increase their vehicles’ fuel economy compared to established vehicle ratings.

Equally clear, there is much yet to be done to ensure that drivers capture and sustain these improvements. Most eco-driving interventions have focused on driving behaviors. They have largely been limited to training and feedback, with tentative conclusions that feedback is more effective.

The behavioral framework suggested here highlights the need for intervention designs specific to the function, form, and context of eco-driving behaviors.

explicitly adopts a theory of behavior to guide research design and data analysis.

The section on “Why eco-driving?” introduces a central theme of the overall discussion: Answers vary. The two most common answers are increased fuel economy and reduced emissions. There has been little study of interactions between these and related functions such as safety and reduced pollutant emissions other than carbon dioxide. Functions are considered at the level of the individual driver; little consideration has been given to traffic-network level impacts of eco-driving. This variability extends to the second question, “What are eco-driving behaviors?” Definitions and classifications of the behaviors that constitute eco-driving are inconsistent, sometimes contradictory, and never (to date) comprehensive. To support more precise and systematic definition and classification we propose a framework of *function*, *form*, and *context*; the framework emphasizes the importance of understanding eco-driving in terms of what behavior is to be enacted, by whom, in what context, to accomplish what function.

Regardless of the difficulty in comparing or summing results across studies with disparate definitions of eco-driving, it is possible to confidently make two general claims in answering the last two questions addressed in this paper (“How much does it save?” and “How is it promoted?”). First, in addition to the effects of behaviors at the point of vehicle purchase and maintenance, end users of automobiles can reduce energy and emissions intensities while driving their automobiles. Second, there is much more work to be done to support those end users in making and sustaining the maximum practicable and safe improvements. Most studies assess the effectiveness of just one strategy to promote eco-driving. These studies have produced ample evidence that some kind of intervention is typically better than none, but beyond that is difficult to assess since few studies compare interventions. Few studies test hypotheses based on behavioral theory, so the empirical record is difficult to generalize. Rigorous statistical meta-analysis of existing research and additional systematic empirical work, both based on behavioral theory, will garner a greater understanding of which interventions work, for which behaviors, and in which contexts.

There is clear potential to engage people—as buyers, owners, and drivers of automobiles—in energy and emissions reduction policies; there also is much to be done to identify the most promising paths for policy development. In sum, while eco-driving research has developed and deployed sophisticated models of technical systems, such as the vehicles and feedback devices, achieving eco-driving’s full potential requires an equivalent sophistication in our understanding of human behavior. Understanding the behaviors that constitute eco-driving is the crux of the challenge to develop most effective policies that achieve maximum savings potential.

Introduction

Formal policy making in the United States regarding automotive fuel economy starts with federal Corporate Average Fuel Economy (CAFE) standards promulgated in 1975 (to take effect model year 1978). Since then, driver behavior has largely been treated as random error to be eliminated from fuel economy policy and official measurement. CAFE standards are enforced through a process that literally removes the driver from the vehicle: test vehicles are placed on a chassis dynamometer and put through a precise, computer-regulated sequence of speeds over distances known as cycles or schedules. The resulting regulatory measure of fuel economy is translated to real drivers on real roads with this caveat on the Monroney sticker on every new passenger car and light-duty truck sold in the U.S.: "Actual results may vary for many reasons, including driving conditions and how you drive and maintain your vehicle." Additional policies attempt to control other outcomes related to transportation energy consumption and fuel choice, such as climate-forcing emissions. These policies include Low Carbon Fuel Standards (*1*) and carbon cap-and-trade proposals. To the extent they have been made at all, analyses of the potential for energy end-user behavior to affect the outcomes of these policies have been carried out almost solely within a rational actor framework (*2*).

Despite a few exceptions (*3*), official interest in fuel-efficient driving behavior remained generally low in the 1980s; perhaps because reductions in vehicle mass and size as well as changes in drivetrain technology produced large improvements in on-road fuel economy of the light-duty vehicle fleet. Still, estimates of how much on-road fuel economy will vary between drivers of the same vehicle are large; in one "naturalistic" experiment involving matched vehicles, deviation around the mean fuel economy from the 10th to the 90th percentile drivers was -13% to +16% (*4*).

Recent concerns about the contribution of vehicle carbon emissions to climate change, and the critical role of driver behavior in achieving the fuel economy benefits of hybrid vehicles and purported driving ranges of plug-in electric vehicles, has renewed interest in driving behaviors now broadly termed "eco-driving." Psychological theory and research into energy-saving behaviors indicate that fuel saving behaviors are more likely to be adopted by drivers under a set of conditions that include the alignment of attitudes, perceived social norms, and perceived behavioral control, with appropriate driver goals (*5*, *6*, *7*, *8*).

Starting with a broad definition of the term "eco-driving," i.e., vehicle buyer, owner, and driver behavior affecting fuel use and emissions outcomes, this paper reviews the current state of knowledge, guided by four basic questions: Why eco-driving? What are eco-driving behaviors? How much do they save? How are they promoted? Given that most light-duty cars and trucks are sold to private households and that the behavioral contexts are different between drivers of private vs. fleet-owned vehicles, this review will largely focus on privately owned light-duty vehicles.

Why Eco-driving?

First answering the question, “Why eco-driving?” foreshadows the importance of reconciling eco-driving definitions, which we undertake in the next section, “What is eco-driving?” The goals of eco-driving have multiplied with multiplying policy priorities. The impetuses for CAFE standards were concerns for global and domestic U.S. petroleum supply, energy security, and high gasoline prices flowing from global petroleum supply disruptions of the 1970s. Those concerns were almost immediately conflated with vehicular emissions of criteria pollutants: the test procedures that produce the regulated measures of fuel economy were originally designed and implemented as emissions tests. Further, while carbon dioxide (CO_2) and other climate-forcing emissions are more nearly proportional to fuel economy, the small body of literature that explicitly compares the effects of driver behavior on pollutant emissions and fuel economy concludes there is often no single driving behavior to optimize both (*9*).

It will be important to understand which eco-driving behaviors have competing or complementary relationships to which policy goals. Two different answers to the question, “Why eco-driving?” highlight the importance of understanding such differences when comparing eco-driving research and results. First, Dietz, Gardener, Gilligan, Stern, and Vandenbergh (*10*) estimate the effects on emissions of CO_2 of five behaviors they describe as eco-driving: purchase of fuel-efficient vehicles; low rolling resistance tires; routine auto maintenance; driving behavior; and carpooling and trip-chaining. They estimated that these behaviors, if enacted in concert and on a national scale, could reduce total U.S. household sector CO_2 emissions by 9% in ten years. Second, similar behaviors are recognized as a potential source of reductions in transportation energy use. However, estimates of the energy savings range widely: 5% to 20% reductions depending on the driving and experimental context (*11*). Conversely, lack of attention to maintenance practices, route selection, and managing vehicle load (weight and aerodynamics), plus inefficient driving styles (“anti-eco-driving,” if you will), can diminish fuel economy up to 45% (*12*).

The range of these estimates is explained in part by the range of behaviors included in each study’s definition of eco-driving. In contrast to Dietz et al. (*10*) and some other reviews of eco-driving, the emphasis of most empirical research—and thus much of this review—is on driving behaviors, i.e., actions performed by drivers, in-vehicle, in the course of a given trip. The distinction will turn out to be hard to maintain in practice, but this more proscribed view of eco-driving does focus attention on the potential for driving behaviors—exactly those behaviors that are assumed away in official fuel economy measures—to affect energy and emissions outcomes.

What is Eco-driving? What are Eco-driving Behaviors?

From a behavioral perspective, the most important question is, “What is eco-driving?” Answers to our subsequent questions—how much does eco-driving save and how is it (can it be) promoted—depend upon it. In this section, we describe the implications of the following two very different definitions:

> "The characteristics of eco-driving are generally well defined and easily characterized. They involve such things as accelerating moderately…, anticipating traffic flow and signals, thereby avoiding sudden starts and stops; maintaining an even driving pace…, driving at or safely below the speed limit; and eliminating excessive idling." (*11*)

> "…eco-driving enables drivers to maximize the on-road fuel economy of vehicles. Traditionally, eco-driving is limited to driver actions after the purchase of the vehicle…. In this paper, eco-driving is used in its broadest sense: Eco-driving includes those strategic decisions (vehicle selection and maintenance), tactical decisions (route selection and vehicle load), and operational decisions (driver behavior) that improve vehicle fuel economy." (*12*)

Behavioral considerations in defining and classifying eco-driving

Two ways of categorizing behavior will be used to organize this discussion of definitions and classifications. First, a behavior analytic approach defines behavior in terms of *function* (its effect/what it does), *topography* (its observable form/what it looks like), and *context* (who emits what behavior, under what conditions) (*13*). Colloquially, behavior is often described in terms of what it looks like, but in a behavioral analytic approach behaviors are most usefully defined and classified in terms of their functions (*14*) because it is function or consequences that shape and maintain the behavior. Behaviors that serve the same function form a functional response class and may be influenced by the same variables. Thus, an effective definition would be based on function (the consequences of maintaining the behavior), but also specify topography and context. In terms of physical location (a contextual factor), Novak and Pelaez (*13*) distinguish between public events (observable responses occurring outside an individual's skin) and private events (unobservable responses occurring inside the skin). From ecological psychology, behavior-setting theory classifies behaviors according to a broader conceptualization of physical and social context. A behavior setting consists of standing (stable and recurring) patterns of (individual and group) behavior that are synomorphic (matched or corresponding) to particular physical milieu (*15*).

Second, a psychological approach to defining and classifying behaviors would analyze attributes related to behavioral function, topography, and context (rather than classifying based on these three directly). For example, investigations into residential energy conservation often classify energy conservation behavior into two categories of either curtailment or efficiency based on the attributes of monetary cost and frequency of response opportunities (*16*). Curtailment behaviors, such as reduced use of appliances, heating, and air conditioning, are frequent and low-cost. Efficiency behaviors, such as purchase of more efficient appliances, heaters, and air conditioners, are relatively infrequent and more costly. Karlin et al. (*17*) identified seven additional attributes that have been used to distinguish curtailment and efficiency: actions (usage vs. structural); permanence (durability); lifestyle (loss in amenities vs. no change);

cognition (effort required); impact (savings potential); population (anybody can do it vs. a distribution of ability or opportunity across a population); motivation (moral vs. rational).

To the degree that a set of eco-driving responses are part of a class of behavior based on either their function, topography, and context or their relevant attributes, behaviors in such a class can be expected to co-vary and be responsive (or not) to the same interventions. For example, Boyce and Geller (*18*) conducted a behavior analysis of driving patterns and discovered a response class of at-risk driving behaviors that co-varied significantly among 61 drivers. This category consisted of speeding, close following, and off-task behaviors, all of which were correlated with driver age. Similarly, investigations into household energy curtailment and efficiency have yielded distinct profiles of variables that correlate with each (*16, 17*). For example, Karlin et al. (*17*) found demographic characteristics (being male, older, married, a homeowner, and having higher income and education) to be better predictors of efficiency behavior, whereas psychological variables (environmental concern and motivation) better predicted curtailment behavior.

Classifying behaviors based on their psychologically relevant attributes creates an opportunity to differentially apply the most appropriate psychological models of the driver, i.e., the conceptual model of who emits the behavior. Psychological theories span from those that theorize people as individualistic and self-interested to those that "suggest that our behaviours, our attitudes, and even our concepts of self are (at best) socially constructed and (at worst) helplessly mired in a complex 'social logic'" (*19*). Plausibly, across the wide spectrum of eco-driving behaviors, the appropriate conceptual models of vehicle "buyers," "owners," and "drivers" are different. For example, scholars of human behavior as diverse in their approaches as the psychologist Daniel Kahneman (*20*) and the sociologist Anthony Giddens (*21*) posit models of "dual modes of consciousness." Though the details differ, both distinguish between observable behaviors that are the product of high-level, cognitively expensive, deliberative decision making and those that are the product of low-level, cognitively cheap habits, routines, or heuristics. (The relevance of this distinction arises again when we address the fourth question of this review, "How is eco-driving promoted?")

Eco-driving's functions, topographies, and contexts

Function

Policy and personal goals, i.e., functions, of eco-driving vary. Some definitions of eco-driving, e.g., Sivak and Schoettle (*12*), include only fuel savings. Usefully though, Sivak and Schoettle's definition also categorizes fuel saving behaviors according to time. Within their scheme, strategic behaviors may be emitted infrequently but have effects persisting over relatively long periods of time, e.g., vehicle selection and maintenance. Tactical decisions address efficiency trip-by-trip, e.g., route selection and cargo weight. Operational behaviors involve the driver's operation of the vehicle while driving; they may be emitted moment-by-moment.

Multiple eco-driving functions highlight the necessity to understand which functions will ultimately be mapped onto topographical definitions, e.g., what is a driver to do to achieve the desired goal? Alam and McNabola (*22*) specify (and equate) the functions of fuel-savings and CO_2 emissions reduction. While CO_2 emissions and fuel consumption are highly correlated, they are less correlated with other regulated pollutants: carbon monoxide (CO), hydrocarbon (HC), and nitrogen oxides (NO_x) (*23*). Mensing et al. (*9*) articulated a conflict between the most fuel saving and the least polluting driving styles. For example, driving at the lowest possible cruising speed in the highest possible gear uses the least fuel (per unit distance), but this requires high torque engine operations resulting in greater HC and CO emissions (per unit distance).

Some definitions of eco-driving include functions other than energy and emissions, such as safety (*11*). Barkenbus (*11*) contrasts eco-driving with hypermiling*,* which he argues includes unsafe tactics, such as coasting down hills with the engine off and drafting (driving very close behind) larger vehicles. In other words, hypermiling emphasizes fuel saving over safety. However, what is safe or unsafe driving is context-dependent. For example, widely promoted eco-driving behaviors can be unsafe under certain circumstances. Moderate acceleration may be inappropriate when merging onto a highway, as may be driving at speeds considerably lower than the flow of traffic. Seen this way, hypermiling and eco-driving are part of a common functional class of behaviors that are motivated by a desire to save fuel—but a functional class that can be distinguished by other goals for driving. Understanding this, interventions to change driver behaviors may be proactively designed to co-produce multiple desired outcomes.

Finally, policy goals are not necessarily the primary functions that maintain desired behaviors. In other words, the primary reasons people engage in eco-driving may not be to achieve the policy goals. For example, consider the variety of alternative functions (in parentheses) associated with each of the following eco-driving behaviors: purchasing a fuel-efficient vehicle (social status), minimizing the use of one's cabin air conditioner (health and comfort), or driving at a fuel-efficient speed (time management).

Topography

Topographical definitions of eco-driving describe what a driver should do, and therefore are useful in developing behavior change interventions. Unfortunately just as with functional definitions, topographical definitions of eco-driving in academic and popular sources vary widely in terms of the behaviors included. As the two definitions quoted at the top of this section illustrate, eco-driving is sometimes defined broadly to include vehicle purchase and maintenance decisions (*10, 12*) and other times is restricted to a driver's operation of the vehicle (*11*). Behaviors that are widely agreed to be eco-driving are defined inconsistently and may contradict each other. For example, some sources suggest accelerating gently, others accelerating moderately (*11*, *24*), and still others accelerating quickly to cruising speed (*25, 26*). Similarly, maintaining an even speed has been described as having both a positive (*27*) and a negative effect on fuel economy (*26*). Further, terms such as "gently," "moderately," and "quickly" are not defined either in terms of specific physical units, i.e., meters per second squared, or in terms of what a driver is to do: how does a driver know whether she is accelerating gently, moderately or quickly? "Aggressive driving" is sometimes used as a catch-all category for vehicle operations that are the opposite of eco-driving, e.g., "hard acceleration and braking, excessive speed, open windows, etc*.*" (*22*).

In terms of research and policy, imprecise definitions preclude the accurate, reliable measurement required to understand the relationships between interventions, behaviors, and outcomes. Complementary to this review, Dula and Geller (*28*) critique traffic safety research for ambiguous and inconsistent definitions of, ironically, “aggressive driving,” explaining the lack of agreed upon definitions preclude valid and reliable research. In terms of practical applications, imprecise definitions of eco-driving behaviors limit the effectiveness of promotional strategies.

Regardless of whether their scope is narrow or broad, present definitions of eco-driving are not comprehensive. For example, Sivak and Schoettle (*12*) offer a broad conceptualization of eco-driving that ranges from vehicle operations to route selection to vehicle selection, yet leave out important behaviors such as trip-chaining (visiting multiple destinations sequentially instead of making multiple separate trips). Further, we have found no attempts to synthesize an understanding of eco-driving across multiple drivetrain and energy types, i.e., across internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid and electric vehicles (PEVs), and fuel cell electric vehicles (FCVs). This may be understandable for PEVs and FCVs as they have only now started to enter the on-road fleet in small numbers. However, HEVs nationally are approximately 2% of the U.S. on-road fleet. Their importance is even greater than that number suggests because they are generally designed to increase on-road fuel economy compared to ICEVs. In Sivak and Schoettle’s (*12*) scheme, buying an HEV is a strategic behavior that may require different tactical and operational behaviors than an ICEV to maximize on-road fuel economy. In general, HEVs, PEVs, and FCVs may require and allow different tactical and operational behaviors and these behaviors may have a greater influence on their on-road outcomes. Further, as new behaviors become possible in vehicles with both electric traction motors and batteries, those behaviors are capable of being subverted by driver behavior. For example, Kurani et al (*29*) report some drivers of HEVs braking too much in response to feedback showing energy recaptured during braking.

Context

To develop and deploy effective policy, it is crucial to know whose behavior is being targeted, and when and where. In narrow definitions, e.g. Sivak and Schoettle’s (*12*) operational behavior, the context of eco-driving may seem straightforward: the driver (who) performs behaviors, while driving a vehicle (when and where). However, if operation of the cabin air conditioner, heater, windows, and other electronics are included, “who” may include passengers. The context becomes more diverse if eco-driving definitions include other operational, tactical, and strategic behaviors.

Further complicating matters, Alam and McNabola (*22*) identify a potential reductionist fallacy concerning eco-driving. They identified studies suggesting the emissions-reduction and fuel-saving functions of some eco-driving behaviors for an individual driver may not add up to reductions and savings if implemented across a population of drivers. For example, moderate acceleration and low speed under conditions of moderate traffic congestion may result in more vehicles on a given road segment for longer periods of time (*22*). Eco-routing may also have unintended effects, such as a compensatory effect of more aggressive driving if drivers attempt to make up (real or perceived) “lost” time once guided through or away from congestion or other delays (*30*).

The case of HEVs, PEVs, and FCVs illustrates the relationship between function, topography, and context. Even if a shared function is desired, drivers of vehicles powered in part or whole by electric motors may be required or allowed different operational behaviors because the vehicles are themselves a different driving context than are conventional ICEVs: some or all of PEVs’ emissions and fuel use are not created while driving, but while recharging their batteries. Also, there is some evidence that “pulse-and-glide” patterns of repeated acceleration to speed followed by coasting produces higher fuel economy than does steady speed cruising (*11*, *31*). This effect is anecdotally believed to be greater for HEVs than for ICEVs as the internal-combustion engine in an HEV may turn off entirely during the glide phase rather than merely returning to idle. Regenerative braking systems in HEVs and PEVs complicate the functions of braking compared to the unavoidable energy loss from braking in ICEVs because regenerative braking recaptures some kinetic energy during braking, turning it back into electrical potential stored in the battery. In sum, even for shared functions the topographies of eco-driving behaviors may be different across contexts.

A psychological approach to eco-driving: Behavior attributes and models of the driver

Dietz et al. (*10*) classified residential energy conservation based on the attributes of frequency and cost. Dietz et al. classified driving behavior, carpooling, and trip-chaining as *daily* behaviors that are frequent and inexpensive or free; routine automobile maintenance as *maintenance* behavior, which is relatively less frequent and typically associated with some cost; and purchasing a fuel-efficient vehicle or low rolling resistance tires as *equipment* behaviors that are more costly and less frequent.

Sivak and Schoettle’s (*12*) categories of *strategic, tactical, and operational* decisions can also be categorized according to psychological attributes such as frequency and cost. Strategic decisions tend to be emitted less frequently and are more cognitively and economically expensive— and therefore are more likely (though by no means guaranteed) to invoke more complex and deliberative behavioral processes. However, similar to Dietz et al. (*10*), Sivak and Schoettle include both maintenance and equipment behaviors in their category of strategic decisions even though they differ from each other in terms of psychologically relevant attributes: maintenance behavior is less frequent, less cognitively effortful, and less costly than equipment behavior, e.g., buying new tires. Sivak and Schoettle (*12*) do, however, distinguish between major maintenance (keeping engine in tune) and minor maintenance (keeping tires properly inflated)—the former being comparatively more expensive and less frequent.

On the other hand, Dietz et al. (*10*) conflate Sivak and Schoettle’s (*12*) operational decisions (driving behavior) and two behaviors that would fit into tactical decisions (carpooling and trip-chaining) into one category of daily behavior that is frequent and (financially) free. However, as noted previously, tactical decisions are distinct from operational decisions in terms of the durability of their effects on energy use and emissions; functions of tactical decisions are actualized on a trip-by-trip basis, whereas operational decisions affect energy use and emissions continuously while driving. Furthermore, decisions to carpool or trip-chain are likely more deliberative than operational driving behaviors. In sum, current classifications of eco-driving based on psychologically relevant attributes are not sufficiently differentiated to suggest optimal psychological models of the driver that would best support targeted policies.

So, what is eco-driving?

Though not cited in his definition at the top of this section, Barkenbus (*11*) frames his discussion of eco-driving within the function of reducing CO_2 emissions from transportation. His eco-driving definition is strictly limited to topography—what eco-driving looks like. He confines eco-driving behavior to the driver acting in the context of driving. He proposes no behavioral theory. Sivak and Schoettle (*12*) limit the function of eco-driving to increasing on-road fuel economy. They provide only limited description of what any eco-driving behaviors look like. For example, they cite a report stating, “using cruise control improves mileage at highway speeds by about 7%.” They leave unanswered the question, “Use cruise control to do what?” They open the behavioral contexts of eco-driving to vehicle purchase, maintenance, as well as driving. They too offer no behavioral theory of buyers, owners, or drivers.

In sum, claims that “driving behaviors that affect fuel economy are well understood through existing research” (*32*) and “the characteristics of eco-driving are generally well defined and easily characterized” (*11*) are misleading. Approached as a poorly differentiated rubric, eco-driving is doomed to be poorly operationalized because it consists of a variety of topographically discrete behaviors, serving multiple functions, emitted in different contexts by people who may be enacting the role of a vehicle purchaser, owner, or driver. Existing definitions and classifications of eco-driving are not based on a scientific understanding of behavior and therefore are neither explicitly nor systematically based on function, topography, context, or psychologically relevant dimensions. An integrated behavioral approach to defining and classifying eco-driving would guide more effective strategies and policies.

Moving toward such an approach, we reviewed popular and academic sources on eco-driving and identified six categories of eco-driving behavior distinct enough in function, topography, context, and other psychologically relevant dimensions to warrant considering separately when designing suitable interventions. Table 1 presents those six categories of eco-driving behaviors and characterizes each in terms of several relevant variables.

Table 1. Categories of eco-driving behavior and some of their psychologically relevant attributes

Category	Factors	General functions (beyond MPG and CO_2)	Context: When the behavior occurs	Frequency of Opportunities	Cost ($; beyond minimum for fuel/kWh)
Driving	Accelerating, Cruising, Decelerating, Waiting, Parking	Operate the vehicle	En route	Very high	None
Cabin Comfort	HVAC, AUX electronics	Provide comfort, communications, entertainment	En route	Very high	None
Trip Planning	Road type; Road grade; Congestion; Right turns; Trip-chaining; Timing	Get from point A to point B	Pre-trip and en route	High	None (Very low if toll)
Load Management	Cargo weight; Aerodynamics	Be prepared	Pre-trip	High	None
Fueling	Fuel selection; Evaporation during and after fueling; Charging frequency, level, and source	Fuel vehicle	Pre-trip(s)	High	None-low
Maintenance	Oil change and type; Tire inflation; Tire selection; Engine tuning	Maintain vehicle	Regular intervals based on vehicle use	Low-moderate	Low-high

How Much Does Eco-driving Save?

Distinguishing maximum technical potential from observed distributions of effects

Consumers' behavior has long been suspect in the search for explanations of failures to achieve maximum technically achievable effects. McDougall, Claxton, Brent Ritchie, and Anderson (*33*) opine: "…recognize that probable energy savings represents a net impact based on potential savings in a technical sense, reduced to allow for imperfect behavioral response." In a more productive effort to understand the role of end-user behavior in energy outcomes, Stern (*34*) contends:

> "…the impact of any behavioral change that might limit climate change can be expressed by the following equation:
>
> $I = tpn$
>
> Where,
> I is impact;
> t is technical potential, or the reduction in emissions…from the particular action;
> p is the behavioral plasticity…the proportion of people, households, or organizations that could be induced to take the target action; and
> n is the total number of these actors that could possibly take the action."

Generalizing to multiple policy functions, this equation suggests that, generally, total fuel savings and pollutant reductions (I) are equivalent to the technical potential of eco-driving—how much it saves per driver (t), multiplied by the number of drivers who do it (pn). Further, as established in the foregoing section, eco-driving is not a single behavior. Conceptually, this equation applies to each $1 < k \leq n$ eco-driving behaviors.

$$I = \sum_{1}^{n} t_k p_k n_k$$

Using this conceptual model, this section will summarize three recent reviews of the savings potential of eco-driving: Barkenbus (*11*), Sivak and Schoettle (*12*), and Alam and McNabola (*22*). In reviewing these three, it is important to distinguish between savings potential indicated in modeling exercises and vehicle testing on the one hand and human subjects research with recruited participants in real-world field studies or simulated driving situations on the other; prior reviews of eco-driving savings potential tend to treat results of both as equivalent. Modeling and vehicle testing reveal the technical potential of eco-driving, thus inform only one factor in Stern's equation. Human subjects research articulates savings actually achieved with drivers, and therefore includes behavioral plasticity. Unfortunately, the effects of technical potential and behavioral plasticity are rarely parsed: as seen in several studies in Table 1, the independent variable is typically an intervention promoting multiple eco-driving behaviors; the dependent variable is fuel consumption and/or carbon emissions, and driver behavior is the seldom measured and often assumed mediating variable. The following review will clearly differentiate these two types of research and discuss how each can inform effective policy.

Barkenbus (2010)

Barkenbus (*11*) concludes eco-driving can reduce fuel consumption and CO_2 emissions by 10% "on average and over time." He cites four sources; two are online articles reporting real-world eco-driving initiatives. The first is a four-day event sponsored by an automotive manufacturer in which 48 fleet drivers volunteered for eco-driving instruction and hands-on coaching. Drivers were encouraged "to employ smoother braking and accelerating, monitor their RPMs and drive at a moderate speed." Reported effects were increased fuel economy by an average of 24% (*35*). The article reporting this test does not specify whether the four days included baseline measurement or whether additional tests were conducted during or after one-on-one coaching. Though the impact (*I*) is impressive, the details are insufficient to meaningfully inform our understanding of technical potential (*t*) and behavioral plasticity (*p*); the former because the description of targeted behaviors is too vague and was not directly measured, and the latter because we do not know what proportion of the drivers adopted which behaviors.

The second of these online articles reported on a six-month initiative in Denver, CO; 160 city-owned vehicles and 240 citizen-owned vehicles were fitted with a dashboard providing information on fuel costs, carbon emissions, and related driving behaviors (idling, fast starts, and hard braking). Reported result was a 10% reduction in CO_2 emissions per mile (*36*) and 15% improvements in fuel efficiency (*37*). These same reports emphasized a 35% reduction in idling, one citing Denver's former mayor, "Through this program, we demonstrated that by reducing unnecessary idling, we can improve fuel economy, reduce greenhouse gas emissions and generate financial savings" (*37*). On its face, this implies idling has greater behavioral plasticity than hard braking and fast starts. It is difficult to be sure since effects of reducing hard braking and fast starts are not reported. Therefore, we also do not know to what extent each targeted behavior contributed to savings, i.e., technical potential.

The other two sources Barkenbus cites are reviews of multiple eco-driving studies. One is an online conference report from the International Transport Forum and International Energy Agency (*38*). The report reviews 23 studies from more than six countries covering multiple transportation modes. This review reports an average of 5% to 15% improvement in fuel economy immediately after training, 5% improvement in the mid-term (< 3 years), with 10% feasible with continuous feedback. The longer-term estimates are based on only nine of the 23 studies; the report does not specify how many of those nine studies involved continuous feedback. Specific eco-driving behaviors targeted in each study are not specified in the report; again there is little we can say about technical potential and plasticity of specific behaviors.

Finally, Barkenbus (*11*) cites the Driver Energy Conservation Awareness Training (DECAT) program initiated by the U.S. DOE in the late 1970s. Greene (*3*) estimated 10% fuel savings in his review of the program based on other research. Greene based his estimate on five studies, none of which assessed the DECAT program and two of which were based on contrived testing situations and reflect effects of examples of "non-eco-driving", i.e., heavy acceleration, on fuel economy, rather than real-world drivers' modification of their typical acceleration patterns. The other three reports were among seven human subjects studies reviewed in his report, but the average effect (in the most effective study condition) across these studies was 7.2%, not 10%.

Sivak and Schoettle (2012)

Sivak and Schoettle (*12*) synthesized savings estimates across a variety of eco-driving factors within each of their three categories of eco-driving: strategic, tactical, and operational. They conclude that strategic decisions have the greatest technical savings potential, but also conclude practicing the opposite of the eco-driving advice for tactical and operational decisions "can contribute, in total, to about a 45% *reduction in the on-road fuel economy* per driver" for a vehicle officially rated at 36 miles per gallon. [Emphasis added.] That is, they estimate that "anti-eco-driving" behaviors can degrade on-road performance by almost half the regulatory measure of fuel economy.

Sivak and Schoettle (*12*) present the effects of factors related to eco-driving on fuel economy. Each factor encompasses a continuum, including extremes. For example, their estimated 30% improvement in fuel economy from moderating top speeds would only be achieved by drivers who reduce their speed from a baseline of 20% of driving time at 90 mph to about 60 mph. Thus the 30% savings attributed to reducing top speeds would be realized by at most a few drivers on few occasions; *n* in Stern's equation is certainly small for reductions from 90 mph.

Sivak and Schoettle (*12*) identify "aggressivity" as the most influential factor among operational and tactical decisions. As mentioned previously, this term is used inconsistently and imprecisely in the eco-driving literature. Sivak and Schoettle do not define it themselves, but cite two sources to support their claim that it can adversely affect fuel economy by 20% to 30%. One of those sources (*39*) reported vehicle testing in which frequency and intensity of accelerating and braking as well as cruising speed were manipulated: average "savings" of 31% were reported for "moderate" driving. Their other source (*4*) reported 20% variation in fuel economy between the 10th and 90th percentile of drivers in terms of their speed-keeping and accelerating from stop in a field study, but note some of the effect "is expected to result from factors other than the degree of aggressive driving." It may be convenient and even intuitive to group responses together as "aggressivity," but to our reading there is no empirical evidence that all these responses (rate of accelerating from stop, frequency and intensity of accelerating and decelerating, cruising speed, speed-keeping, and using cruise control) co-vary. Sivak and Schoettle (*12*) distinguish driving at very high speeds (impact of -30%) from aggressivity (impact of -20% to -30%), despite their implied definition of the latter encompassing the former—hence, cruising speed may be factored into the impact estimation model twice.

Alam and McNabola (2014)

Alam and McNabola (*22*) recently published a critical review of eco-driving research; they reviewed tactical eco-routing separately from operational eco-driving behaviors. Thus they made a start towards a more differentiated understanding of eco-driving behaviors, i.e., the $1 < k \leq n$ behaviors we've elaborated in Stern's equation, and their relative effectiveness. However, their review of operational eco-driving behaviors does not differentiate between behaviors.

They distinguished between real-world field trials, analytical modeling, and reviews. Lastly, they reviewed network level impacts of eco-driving.

Alam and McNabola (*22*) reviewed 19 studies of eco-driving operational behaviors (nine based on field trial data, six based on reviews, and four based on modeling) with reported fuel economy improvements ranging from 5% to 30%. They noted that results of field studies were typically lower (4.8% to 6.8%) compared to reviews. Findings of modeling studies were mixed as a couple of these (*40*, *41*) examined technical potential at the network level (no field studies have done this) and found an increase in carbon emissions under congested traffic conditions.

Alam and McNabola (*22*) reviewed 10 studies of eco-routing. None were field studies: six were based on modeling and two were reviews. They found a large range of impacts, from 0.35% to 42%, and noted that two reviews gave conflicting accounts: Sivak and Schoettle (*12*) report 15% to 40% impact on efficiency while Klunder et al. (*42*) report 2.1%. Alam and McNabola explain that differences in traffic congestion and road grade between the eco-route compared to the alternative are largely responsible for these ranges. They cite a study that reported drivers increased their speed after feedback on route changes intended to avoid traffic (*30*) and note how some benefits of eco-routing may be reliant upon low penetration of feedback/navigation systems so all traffic is not re-routed at the same time to the same route. In this (possibly unique) case, increasing the incidence of feedback/navigation systems in vehicles (and thus, *n*, the population of drivers capable of taking action based on feedback and navigation advice) and the proportion of the population of drivers of such vehicles, *(p)*, who can be induced to take action might actually have the opposite effect assumed in Stern's conceptual model, i.e., higher population and plasticity leads to worse, rather than better, impacts.

Expanding the scope of the reviewed literature

Alam and McNabola (*22*) provided the most extensive prior review, however, compared to the nine empirical human subjects studies of operational eco-driving behaviors they review, we review 40 here. Our review is summarized in Table 2. Among the 32 studies that measured fuel economy, results of eco-driving interventions averaged about 9% fuel savings. In the behavioral outcomes column, note the inconsistency among eco-driving behavior definitions, the prevalence of cases in which behaviors are not directly measured at all, and how often behaviors are described in terms of their effects on the vehicle—"engine speed," "RPM," "idling," etc.—rather than in terms of driver behaviors, such as accelerating, cruising, decelerating, waiting, parking. That said, we were able to roughly discern the prevalence with which each of these driving behaviors has been measured in the literature. Accelerating is most commonly targeted, following by cruising, decelerating, and then waiting (idling).

Table 2. Human Subjects Operational Eco-driving Research

Source	Field or Lab	Prompt	Measured Outcomes of Eco-driving Interventions		
			Behavior	Fuel Use Reduction	Emissions Reduction
(*43*)	Field	Modeling	Drivers followed eco-driving cars 76% of the time. No increase in passing among drivers following eco-driving cars, except in cases where the eco-driving car had a sticker promoting eco-driving (non-significant)	--	--
(*44*)	Field	Feedback	Positive effect on number of starts where acceleration exceeds 20 km/h in 5 seconds; negative effect on accumulated time to change speeds faster than 20 km/h in 5 seconds and accumulated time of engine on when stopping (idling)	4.3%	--
(*45*)	Lab	Verbal Instruction with or without Feedback	Decreased variability of gas pedal position and mean of over-acceleration beyond that which is optimal given speed in all feedback conditions (lowest with visual + haptic feedback, followed by haptic only, then visual only)	--	Total polluting emissions with feedback: 10% to 12%; verbal instructions only: 5%
(*46*)	Field	Feed-forward	Driving at optimal highway speed	13%	CO$_2$: 12%
(*27*)	Field	Lecture + Coaching	Significant positive effect on gear use with low rpm, maintaining steady speed, coasting, and driving speed limit; non-significant effect on upshifting early (2,000-2,500 rpm) and idling during long stops	5.8%	--
(*47*)	Field	Feedback	--	3.8%	--
(*36*)	Field	Feedback	35% reduction in engine idling; reduced fast accelerations and stops	--	10%
(*24*)	Lab	Goal-setting	Fuel-saving goal compared to fuel-saving + time-saving goal:	Fuel-saving goal: 10%	--

Table 2. Human Subjects Operational Eco-driving Research

Source	Field or Lab	Prompt	Measured Outcomes of Eco-driving Interventions		
			Behavior	Fuel Use Reduction	Emissions Reduction
		(Verbal Instruction)	Lower speed and rpm approaching traffic light; lower gas pedal push and more moderate acceleration through intersection; ns difference in deceleration or braking	fuel-saving + time-saving goal: 2%	
(*48*)	Field	Feedback	Positive effect on an “eco:Index” comprised of four factors: reduced rate and intensity of acceleration and deceleration, early upshifts, and steady, moderate speed. Stronger effect on speed and deceleration.	6%	133kg
(*35*)	Field	Lecture + Coaching	--	24%	--
(*49*)	Lab	Verbal Instruction with or without Feedback	--	Strongest effect for males with efficient acceleration feedback, then instantaneous mileage feedback; feedback presence/ type non-significant for females who had significant improvement in all conditions	
(*3*)	Field	Verbal Instruction	Speed decreased 15%	22%, but 18% controlling for speed	--
(*3*)	Field	“Training” + Feedback	--	-0.2% (piston type gauge) to 5.5% (dial gauge + training)	--
(*3*)	Field	Feedback	--	<1%	--
(*3*)	Field	Verbal Instruction	--	4.8%	--
(*3*)	Field	Feedback	--	3% (non-significant)	--
(*3*)	Field	“Training” + Feedback	--	2.4% to 8.8% depending on feedback type	--
(*3*)	Field	Feedback +	--	-2% to 5.4%	--

Table 2. Human Subjects Operational Eco-driving Research

Source	Field or Lab	Prompt	Measured Outcomes of Eco-driving Interventions		
			Behavior	Fuel Use Reduction	Emissions Reduction
		Verbal Instruction		depending on instruction	
(*50*)	Field	Lecture + Coaching	During coaching: non-significant effect on vehicle speed; 9.13% decrease in engine speed	During coaching: 15.72%	During coaching: CO_2: 12.23%
(*51*)	Field	Feedback	2.4% reduction in median speeds	2.7%	--
(*52*)	Field	Feedback	Significant decrease in proportion of time with high acceleration; 20 other driving pattern factors tested	4% on 1 of 3 routes; non-significant effect on other 2	HC, NO_x, CO significantly reduced in 2 of 3 routes
(*53*)	Field	Feedback	--	No effect	--
(*54*)	Field	Feedback	--	10%	--
(*55*)	Field	Feedback	24% reduction in excessive speed; 38% reduction in excessive engine speed; reduction in extreme accelerations and decelerations	4.8%	Savings of 6.56 g/km of CO_2 emissions
(*56*)	Field	Feedback	Mean decrease in idling 4% to 10% per vehicle per day	--	Average decrease: 1.7 kg of CO_2/vehicle per day
Qian, Chung, & Horiguchi, 2013 as cited by (*22*)	Field	--	--	2.9% to 18.7%	--
(*57*)	Field	Feedback	--	18%	--
(*58*)	Lab	Feedback + Verbal Instruction	Decreased error from optimal pedal position with visual feedback more than two types of haptic feedback; however, steady acceleration was best with haptic force feedback more than haptic stiffness or visual; increased distraction	--	--

Table 2. Human Subjects Operational Eco-driving Research

Source	Field or Lab	Prompt	Measured Outcomes of Eco-driving Interventions		
			Behavior	Fuel Use Reduction	Emissions Reduction
			with visual feedback but greater attention to forward road with haptic feedback compared to no feedback		
(*59*)	Lab	Feedback	Positive effect on optimal acceleration, gear shift timing, decelerate in neutral, and decelerate by downshifting	15.9% (urban) 18.4% (rural)	--
(*60*)	Lab	Feedback	Significant decrease in rpm at gear shift and standard deviation of speed	--	--
(*61*)	Field	Feedback	--	-6.8% to 10.2%	--
(*62*)	Field	Feedback with or without Coaching	Significant decrease in time over speed limit and number of harsh decelerations with feedback; no difference with or without coaching	6.8%; no additional gains with coaching	--
(*63*)	Lab	Feedback	Significant decrease in accelerator pressing and speed	10%	--
(*64*)	Field	Feed-forward	Increase in distance from stopping point when driver releases accelerator	9.5%	--
(*65*)	Field	Feedback	--	3.23%	--
(*66*)	Field	Feedback	Increase in mild acceleration and early upshifts (2,200 rpm)	7.6%	--
(*67*)	Lab	Verbal Instruction with and without Feedback	No change in average speed; reduction in decelerations for instructions and feedback; reductions in extreme acceleration and improvements in shifting during acceleration with feedback	Instructions to drive efficiently without feedback: 9% with feedback: 16%, 23% in urban condition	--
(*68*)	Lab	Feedback	Significantly reduced and stabilized pedal operations; ns difference between adaptive (levelized) and non-adaptive feedback systems	Significant improvement, especially with adaptive feedback	--
(*26*)	Field	Lecture + Coaching	Slight improvements (some statistically significant) in	Lecture + coaching: 2%; lecture,	--

Table 2. Human Subjects Operational Eco-driving Research

Source	Field or Lab	Prompt	Measured Outcomes of Eco-driving Interventions		
			Behavior	Fuel Use Reduction	Emissions Reduction
		with or without Feedback	evenness of speed, acceleration and deceleration as a result of each, training and feedback	coaching, and feedback: 4%	
(*69*)	Field	Lecture + Coaching	--	4.35%	--

Eco-driving reduces fuel use and emissions…by a little to a lot

This literature review indicates drivers can undertake suites of behaviors in the course of driving a given trip to decrease fuel use, i.e., increase on-road fuel economy, and decrease the emissions intensity of their vehicle travel. Most of the research focuses on operational behaviors—some of it better describing the technical potential of either single behaviors or suites of them, other of it incorporating behavioral plasticity but failing to articulate the targeted behaviors. Other than some analytical modeling, very little work has been done to validate the extension of estimated effects from any given study to populations of drivers. Describing those suites of driving behaviors—telling people what to do under what conditions—remains confused. In the next section, we propose that improved feedback to drivers may address this confusion.

Each of the three previously published eco-driving reviews discussed above is based upon qualitative synthesis of findings from disparate studies. Given the variation in findings, an understanding of mediating and moderating variables, including targeted behaviors, and type of intervention is crucial. A systematic research program would most effectively identify these relationships, although sufficient studies currently exist to perform a quantitative meta-analysis that might statistically derive some of the important variables.

How Has Eco-driving Been Promoted? How Could It Be?

In this section, we review strategies used to promote eco-driving and make suggestions about how to leverage these strategies based on the behavioral approach to eco-driving suggested in this paper. This section refers to the 40 studies summarized in Table 2. Most of these are trial or pilot studies where a single strategy was implemented to promote eco-driving—restricted to *driving behaviors*—and its impact measured in terms of driving behavior, fuel economy, and/or emissions. Most common strategies implemented to date can be generally classified as either feedback (information about emitted behavior reflected back to the driver) or training (which we further differentiate as coaching (one-on-one training while driving) or lecture (instruction outside the context of driving). Other strategies include feed-forward (offering information about behavior prior to its occurrence), modeling (confederate drivers demonstrating eco-driving behaviors), and verbal directives to drive efficiently.

Eight studies (reviewed in Table 2) used some type of training or coaching, including lecture-based instruction and/or personalized one-on-one coaching while driving. Only half of these (*26, 27, 35, 69*) measured the effects of the training intervention apart from any other intervention, e.g., feedback, and after rather than during training (*50*). Fuel savings achieved in the first four of these studies ranged (*26, 27, 35, 69*) from 2% to 24%. It is difficult to account for this range because few reports provide details of the training protocol used, including such critical features as the behaviors targeted and the training format (lecture and/or coaching).

The most common strategy to promote eco-driving is in-vehicle feedback; twenty-seven of the studies reviewed in Table 2 used feedback. Sixteen of these provided a fuel-savings outcome for feedback only: average reduction was 5.6%, but ranged from -6.8% to 18.4%. The few studies that compared effects of training and feedback suggest that feedback results in additional effects when added to training (*26*), but training may not result in additional effects above and beyond the effects of feedback (*62*). Similar to the studies of eco-driving training, it is difficult to disentangle what makes feedback effective based on studies that employ different types of feedback among different drivers in different contexts, but studies that have compared multiple types of feedback (*3, 49, 51, 58, 61, 68*) shed some light. Their findings are presented in the next section focusing on feedback as a high leverage strategy to promote eco-driving.

A behavioral plan for the effective promotion of eco-driving

Feedback has been the predominant promotional strategy for operational eco-driving behaviors; the theoretical justification for its prevalence seems sound. Operational eco-driving behaviors are habitual and occur in the context of driving, therefore interventions embedded in that context are a plausible solution. However, this intuition is insufficient to support the development of most effective feedback solutions. Behavioral science must be leveraged to accomplish this task. Very few studies (e.g., *51, 61*) incorporate behavioral theory to guide feedback design and generate hypotheses about what combinations of driver characteristics, specific behaviors, and contextual factors may produce fuel economy increases. This section outlines potential contributions of several behavioral theories to the development of effective eco-driving feedback.

Kluger and DeNisi (*70*) introduced Feedback Intervention Theory (FIT) as a framework for understanding the behavioral mechanisms by which feedback can be effective: “behavior is regulated by comparisons of feedback to goals or standards.” There may be one or more standards to which feedback is compared, including comparisons to self, e.g., past or desired future performance, and comparisons to others, e.g., norms. A discrepancy between feedback and its standard is defined as a feedback-standard gap*.* Only feedback-standard gaps receiving attention will be addressed. Thus, an important aspect of any feedback intervention (FI) is controlling the locus of attention. Once attending to feedback, a person has four options: (1) change behavior, (2) change the standard, (3) reject the feedback, or (4) abandon the standard.

Based on this theory, we suggest that eco-driving feedback should include a salient feedback standard without risking driver distraction. Numeric mileage indicators that offer a single feedback stream of real-time fuel economy or average fuel economy do not have an inherent standard. A driver might or might not recall (or have ever known) the EPA's regulatory fuel economy estimate or any of their own past trip average fuel economy performances to use as an implied standard. Examples of feedback that incorporate a standard include indicator lights that switch color based on comparison of present performance to some "efficient" standard and graphic indicators demarking a desired range for acceleration or braking. The behavioral principle of shaping, i.e., reinforcement of successive approximations of a target behavior, can be leveraged if a feedback standard is easier to accomplish initially and becomes more stringent as the driver's skill increases (*68*).

Regarding the issue of saliency without distraction, haptic feedback is effective and actually increases forward attention to the road according to one study (*58*). In terms of visual feedback, which may be more distracting than haptic feedback, systems involving colored lights, movement, and images rather than numbers or complex graphics, are more likely to be ambient or peripheral displays (*71*) which can be less distracting as they do not require directed attention.

Attributes of feedback that support learning are summarized in Table 3. For example, feedback that reflects a specific driving behavior, e.g., accelerating, is superior for learning new behavior, but it may preclude attention to other behavior not reflected in the feedback. Feedback that reflects an aggregate of responses, say the effect of multiple variables on fuel economy, can promote more diverse and creative behavior change when a motivated driver seeks and tests novel behaviors. The downside is drivers may misunderstand which responses are actually contributing to a change in their performance. Graving, Manser, and Becic (*49*) found that feedback specific to acceleration behavior was more effective for males than instantaneous fuel economy (aggregate) feedback, but females responded comparably to each type (though why this would be remains a topic for further research). Feedback that reflects instantaneous, real-time behavior may be more successful in training new behavior because it can function as immediate reinforcement. In contrast, feedback that reflects accumulated behavior or that is delayed may support goal setting, but it may be temporally too far removed to function as reinforcement of all the relevant behavioral responses.

Feedback that is salient, provides a meaningful and achievable standard, and is otherwise configured to effectively support learning can still fall short if the consequences of closing the feedback-standard gap are not reinforcing. Feedback attributes intended to function as motivating operations (stimuli that influence the effectiveness of consequences as reinforcement; *72*) include "gamification" (including scores and levels), emotional designs (often implemented through graphic representation of caring for animals or growing plants), and message-framing to align feedback with users' values. For example, Kurani et al. (*51*) reported a global average reduction in on-road fuel consumption of 3% in a field test of the effects of feedback to drivers (in which drivers were randomly assigned to one of three feedback screens). However, based on modeling of the field test results, they estimated this effect could have been tripled if each driver had seen the type of feedback that best aligned with their prior goal for driving, e.g., to get around faster, drive safely, save fuel, save money, reduce emissions, or drive less.

Table 3. Feedback Attributes Affecting Learning

Attribute	**Description**
Feedback Standard	Is there a reference point provided to which a motivated user may attempt to align their behavior?
Shaping	Does the standard gradually become more challenging, i.e., does it reinforce successive approximations of ideal behavior?
Behavioral Specificity	Does the feedback reflect a specific driver response or an aggregate of behaviors?
Behavioral Sensitivity	What magnitude of behavior is required for feedback to be affected?
Temporal Granularity	Does feedback convey information about instantaneous behavior or behavior accumulated over a period of time?
Temporal Proximity	Is feedback provided immediately after the relevant behavior or delayed?
Mode of Interface	What is the perceptual mode of interface between the driver and the feedback information (haptic, text, ambient)?

Toward feedback standardization

Eco-driving feedback in conventionally fueled vehicles has typically been restricted to numeric real-time and average fuel economy indicators; even these are not required of vehicle manufacturers. On the other hand, energy displays in hybrid and electric vehicles have been more prevalent, varied, and elaborate; each vehicle manufacturer deploys various metrics and designs to reflect different driver behaviors and vehicle states. The level of variety indicates either a belief in a competitive advantage or, as seems more likely, a lack of a basis for deploying standardized feedback principles. The rapidly increasing prevalence and complexity of in-vehicle displays (for eco-driving or otherwise) and concomitant concern of driver distraction suggest standardization of eco-driving feedback may be coming sooner rather than later. Analogous to other universal iconography displayed in vehicle instrument clusters, such as the glowing fuel pump, headlight indicator, red (blinking and beeping) seat belt reminder, and check engine light, there will be efforts to identify potential measurement and design standards for eco-driving feedback that apply across vehicle drivetrain types and are cross-culturally appropriate. Devising effective eco-driving feedback technology that can be economically deployed in all vehicle types and even simulated through aftermarket free or low-cost technologies, e.g., mobile applications, will increase the population who can eco-drive and may increase the plasticity so that more of those who can, do eco-drive, and thus magnify the impact of eco-driving.

Beyond driving operations

Although the vast majority of eco-driving feedback studies target driving behaviors, some in-vehicle and aftermarket feedback systems include prompts for vehicle maintenance, such as tire air pressure indicators, "maintenance required," and other indicators. Low oil pressure, high coolant temperature, and check engine indicator lights have been included in vehicles for years. Many navigation systems now feature eco-routing, (technically feed-forward, not feedback, as it precedes the targeted behavior). It is easy to imagine feedback for other behaviors, even load management, e.g., prompts to remove unnecessary cargo or racks. The design of feedback intended to affect these behaviors can be subject to a similar process of grounding design in behavioral theory, testing of hypotheses, and subsequent improvement.

Regulations, infrastructure, and incentives change the behavioral context of operational eco-driving, and thus are high leverage strategies also deserving of further attention. Examples include regulations that limit idling; roadway designs that include use of roundabouts and adaptive speed limits; and incentives to scrap less-efficient vehicles and purchase more fuel economical and cleaner vehicles. The latter strategy targets strategic eco-driving behaviors that affect the feasibility and outcomes of subsequent tactical and operational behaviors.

Conclusion

This review of eco-driving addresses four questions within an overall framework that proposes the answers would be improved if behavioral theory guided research design and policy-making. Four questions were asked and answered: Why eco-driving? What is eco-driving? How much does it save? How is it (can it be) promoted? Answers to these questions are prefaced with this observation: Aside from a few select efforts, the creation, deployment, and evaluation of eco-driving research seems to have been carried out without the application of behavioral theory or only implicit assumptions about human behavior.

Why eco-driving?

The most basic answer to this question is because motor vehicle buyers, owners, and drivers might be productively engaged in achieving multiple goals of societal importance. U.S. CAFE standards were prompted by concerns about global and domestic petroleum supply, energy security, and high gasoline prices in the 1970s. CAFE standards were not designed to promote changes in driving behavior—and by design excluded variability across drivers from the official measurement of fuel economy. More recently the question of whether and how to engage consumers and drivers in achieving reductions in CO_2 and other climate-forcing emissions has been raised. Distinctions have been made between eco-driving and hypermiling, the latter carrying connotations of less regard for driving safely. Finally, reducing on-road emissions of criteria pollutants has also been promoted as a goal for eco-driving.

What is eco-driving?

This review demonstrates there is no consensus on a definition or classification of eco-driving behaviors. Across the literature different definitions emphasize ends (functions) or means (topographies) across vehicle purchase, ownership, and driving contexts. As such, eco-driving is operationalized differently across studies because it is taken to consist of a variety of topographically discrete behaviors, serving multiple functions, emitted in different contexts by people who may be enacting the role of a vehicle buyer, owner, or driver. This causes the results of many studies to be non-comparable and many reviews to be simple lists of outcomes rather than analytically rigorous assessments. Existing definitions and classifications of eco-driving are not based on a scientific understanding of behavior and therefore are neither explicitly nor systematically based on function, topography, context, or other psychologically relevant dimensions of behaviors. An integrated behavioral approach to defining and classifying eco-driving is a required foundation for more effective strategies and policies.

How much does eco-driving save?

Vehicle buyers, owners, and drivers can and do make a difference in fuel consumption and emission outcomes and those outcomes can be shaped to increase fuel economy and decrease emissions intensities of individual driver-vehicle combinations. Under many conditions, these will sum to aggregate reductions in fuel consumption and emissions. On one hand, analytical modeling and vehicle testing have revealed much about the technical potential of some eco-driving behaviors and have articulated the influence of some contextual factors. On the other, human subjects research has revealed something about the real-world opportunities for savings and the proportion of drivers who can be induced to adopt eco-driving. These two lines of inquiry must merge to provide a more complete picture of eco-driving's total potential. Engineers and behavioral scientists need to work together in a trans-disciplinary effort to create a comprehensive inventory and classification of eco-driving. This process would be a first step toward accurately assessing the potential effectiveness of eco-driving behaviors. Subsequently, systematic behavioral research is needed to delineate the most promising of these behaviors.

How are eco-driving behaviors to be promoted to the general population?

There is no question there are effective strategies to promote eco-driving. The meaningful questions concern the functional and topographical distinctions of behaviors to establish which have the most potential aggregate savings, when emitted by whom, where, and when. Variation in the operationalization of eco-driving and a near complete absence of behavioral theory inhibits the generalizability of conclusions about the effectiveness of different intervention strategies, e.g., education, training, feedback, goal setting, and incentives, or their possible interactions. As a result, it is difficult to determine the overall savings potential of eco-driving, to distill the relative effectiveness of various eco-driving behaviors, and to develop targeted eco-driving interventions. We suggest a framework for a quantitative meta-analysis capable of discerning the relative effectiveness of different interventions for different behaviors, including, in particular, an in-depth analysis of feedback interventions.

Policy makers have an interest in the distinction between technical potential and real-world outcomes in the hands of a population of users. CAFE standards never denied this, but they did attempt to push the overall technical fuel economy potential of the on-road fleet of vehicles in a desired direction while assuming away driver behaviors that may have aided or impeded progress toward this goal. In this case, key to the distinction between technical potential and realized result is that present CAFE test procedures do not measure maximum technical potential. As a possible goal for feedback design, measurements made for purposes of CAFE conformity are not the best that can be done in any vehicle, merely the best that can be done within the specific context of the test procedures.

Recommendations for policy and policy makers include the careful parsing of eco-driving functions, forms, and contexts when comparing and designing eco-driving interventions. Further, consider safety implications and contextual factors in eco-driving promotional programs. Such multi-function designs, e.g., fuel use reductions and improved safety, guard against the potential excesses of hypermiling. Until a robust research agenda emerges to test the best forms of interventions, feedback can be designed according to established principles and empirical results, i.e., feedback works to some extent and known principles and results can guide the design of good feedback. Suggestions for feedback design include real-time ambient indicator(s) of what a person is to do (rather than what a vehicle is to do), comparison to a driver-salient goal, and a move toward standardization—analogous to fuel, engine, and headlight indicators which have internationally relevant and recognized icons—to allow drivers to more easily enact eco-driving behaviors across different vehicles. Finally, support for research grounded in behavioral theories will allow a basis for generalization and improved intervention design.

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