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The many reasons your mileage may vary: Toward a unifying typology of eco-driving behaviors

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ABSTRACT

The role of vehicle driver behavior has been ignored in prior energy and environmental policy making. Laboratory procedures that produce the fuel economy estimates posted on every new car sold in the US are designed to preclude the effects of differences between drivers. Yet, every vehicle states the caveat, "Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle." Eco-driving as means of strategically taking advantage of this variability has been inconsistently defined in conceptual analyses and variously operationalized in empirical analyses. The present research clarifies, synthesizes, and expands on prior definitions of eco-driving to develop a comprehensive and precise definition and typology of eco-driving behaviors. The resultant typology includes six mutually exclusive classes of behavior: *driving, cabin comfort, trip planning, load management, fueling,* and *maintenance.* This typology establishes a basis for systematic research to determine energy and climate impacts and develop effective policies and interventions for different types of eco-driving.

1. Introduction

Driver behavior has been treated as random error in models of motor vehicle fuel economy and related policy making. An early exception was research prompted by the spikes in oil prices in the late 1970s (Greene, 1986). Fuel-efficient driving behavior fell back under the radar in the 1980s, perhaps because technical changes in vehicle drivetrain technology prompted by the then new Corporate Average Fuel Economy (CAFE) standards and downward shifts in vehicle mass and size produced large improvements in on-road fuel economy. Recent concern about the depletion of fossil fuels and contribution of vehicle carbon emissions to climate change, as well as the critical role of driver behavior in achieving the fuel economy benefits of new hybrid and electric vehicles, has renewed interest in what is now most frequently called *eco-driving* (see CIECA, 2007, for other terms).

Eco-driving is part of what Dietz et al. (2009) call a *behavioral wedge*, referring to "the adoption and use of available technologies in US homes and nonbusiness travel by means of behaviorally oriented policies and interventions" in order to "appreciably reduce energy consumption… with low or zero cost or attractive returns on investment, and without appreciable changes in lifestyle" (p. 18452–18453). Dietz et al. identified five behaviors related to personal vehicular transportation that would reduce US household sector emissions by 9% in ten years if implemented on a national scale: purchase of fuel-efficient vehicles; low rolling resistance tires; routine auto maintenance; driving behavior; and carpooling

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and trip-chaining. Of these behaviors, purchase of fuel-efficient vehicles can have the most profound effect; however, given the selection of a vehicle, lack of attention to maintenance practices, route selection, and managing vehicle load, in addition to inefficient driving styles, can diminish fuel economy up to 45% (Sivak and Schoettle, 2012). Clearly, there are suites of behaviors available to drivers to reduce the energy and emissions intensities and totals of their vehicle travel.

2. What is Eco-driving?

From a behavioral perspective, this is the most important question. The answer is (or should be) foundational to questions regarding the savings potential of eco-driving and how best to promote it. One can only effectively understand any behavior once it is operationally defined so that it can be measured consistently and analyzed systematically. In the field of behavior analysis, two main ways of defining behavior are acknowledged; behavior may be defined in terms of its topography (its observable form/what it looks like) or in terms of its function (its effect/what it does; Cooper et al., 2013).

2.1. Topography

Topographical definitions of eco-driving specify what a driver should do, and therefore are useful in developing interventions. A satisfactory topographical definition of eco-driving should be precise and consistent in order to avoid confusion and develop a parsimonious and reliable account of the behaviors that constitute eco-driving. It should be comprehensive so that the full potential of eco-driving is understood. Current definitions of eco-driving do not sufficiently meet these criteria.

2.1.1. Consistent

Definitions of eco-driving in academic and popular sources vary widely in terms of the behaviors included; they are typically restricted to a driver's operation of the vehicle (Barkenbus, 2010), but sometimes inclusive of vehicle purchase and maintenance decisions (e.g., Sivak and Schoettle, 2012). Even eco-driving behaviors related to vehicle operations (i.e., driving) that are widely agreed-upon are defined inconsistently. In some cases, definitions seem to contradict each other; for example, sources recommend accelerating gently (AA, 2014), accelerating moderately (Barkenbus, 2010; Dogan et al., 2011), and accelerating to quickly reach cruising speed (Birrell et al., 2014; Wahlberg, 2007). Similarly, evenness of speed has been treated as having both a positive and a negative effect on fuel savings (Beusen et al., 2009; Wahlberg, 2007, respectively).

Some of the confusion about what constitutes eco-driving, topographically, is likely because the answer varies from one vehicle to another. For example, Energy and Environmental Analysis, Inc. (2001) discussed how the relationship between "aggressive" driving and fuel economy is dependent on a given vehicle's horsepower/curb weight (HP/WT) ratio—the more powerful the vehicle the less it is penalized in terms of fuel economy for driving styles characterized by high rates of acceleration and braking and high maximum speed relative to average speed. In vehicles with low fuel economy, there is little room for improvement gained from widely promoted eco-driving behaviors. Sivak and Schoettle (2012) pointed out that driving a vehicle rated as achieving on average 11 mpg (21 L/100 km) in accordance with all eco-driving practices would result in no fuel savings.

2.1.2. Comprehensive

Regardless of whether the scope is narrowly restricted to vehicle operations or more inclusive, existing definitions of eco-driving are not comprehensive, i.e., they do not include all the possibilities within a given category of eco-driving behavior, such as vehicle operations. Sivak and Schoettle (2012) 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) and do not consider eco-driving in the context of hybrids (HEVs), plug-in hybrids (PHEV) and electric vehicles (EVs)—the latter two together referred to as 'PEVs'. This focus on internal combustion engine vehicles (ICEVs) is typical of eco-driving research despite the fact that many driver behaviors have a relatively greater influence on efficiency outcomes for PEVs (e.g., AA, 2014, October 9).

HEVs and PEVs are exceptions to some eco-driving rules that apply generally to ICEVs. For example, repeating a cycle of heavy acceleration to top speed then coasting ('pulse and glide') can allow a HEV to run on battery power for longer periods without engaging the engine (MetroMPG, 2006, January 15), amounting to greater fuel savings compared to moderate acceleration and even speed which are widely promoted as eco-driving for ICEVs (e.g., Barkenbus, 2010). Regenerative braking systems in PEVs present a unique opportunity for re-capturing some energy lost in braking, a behavior not available to ICEV drivers.

2.1.3. Precise

"Aggressive driving" is sometimes used as a catch-all for vehicle operations that are not eco-driving; e.g., "aggressive driving behavior such as hard acceleration and braking, excessive speed, open windows, etc." (Alam and McNabola, 2014). Conversely, eco-driving proponents often recommend accelerating "moderately" without further operationalization (e.g., Barkenbus, 2010). In terms of research, imprecise definitions preclude accurate and reliable measurement, which is required to understand the relationships between interventions, behaviors, and impact. Complementary to this assessment, Dula and Geller (2003) critiqued traffic safety research for ambiguous and inconsistent definitions of, ironically, "aggressive" driving, explaining how it precludes valid and reliable research.

2.1.4. Positive actions

In current definitions of eco-driving, behaviors are often targeted for decrease (e.g., acceleration, braking, idling, speeding, and "aggressivity"). While this is perfectly acceptable, care should be taken to define eco-driving in terms of positive, actionable behavior (e.g., "obey speed limits" is preferable to "don't speed"; "turn off the engine if you think you will be stopped for at least one minute" is preferable to "avoid idling"). Recommendations should specify what the driver should *do* rather than what they should *not do* in order to pass the "dead man's test" of behavior, a basic rule of thumb in psychology which holds that, "if a dead man can do it, it ain't behavior, and if a dead man can't do it, then it is behavior" (Lindsley, 1965 as cited by Malott and Suarez, 2005, p. 9). This lighthearted rule concerns the serious importance of focusing on what a person actually *does* when defining a target behavior for intervention. Technically, low rates of behavior can be reinforced (e.g., accelerating a no more than half throttle), but absent behavior cannot be (e.g., refraining from accelerating).

2.2. Function

The defining function of eco-driving seems relatively straightforward compared to its topography, yet sources are inconsistent. Some definitions of eco-driving specify only a fuel-savings function (e.g., Sivak and Schoettle, 2012). Others specify (and implicitly equate) fuel-savings and carbon dioxide (CO_2) emissions reduction (e.g., Alam and McNabola, 2014). While CO_2 emissions and fuel consumption are highly correlated, they are less correlated with other harmful vehicle emissions: carbon monoxide (CO), hydrocarbon (HC), and mono-nitrogen oxides (NO_x; e.g., Ericsson, 2001). Mensing et al. (2014) articulated a conflict between the most economic driving style and the most ecologic driving style. For example, driving at the lowest possible cruising speed in the highest possible gear is most fuel efficient, but this requires high torque engine operations that result in greater HC and CO emissions.

Some definitions of eco-driving include the function of improved safety (e.g., Barkenbus, 2010). Barkenbus contrasts eco-driving with *hypermiling*, which includes unsafe tactics, such as coasting down hills with the engine off and drafting (following closely behind other vehicles, especially trucks). In other words, hypermiling emphasizes only a fuel-saving function, therefore safety may be compromised. CIECA (2007) discusses a list of eight eco-driving behaviors that could conflict with safety. Those engaged in eco-driving interventions and policy-making should recognize that all fuel-saving behaviors, safe and unsafe, belong to the same functional class of behavior and thus can tend to be correlated; this acknowledgement will promote thoughtful interventions that proactively discourage unsafe fuel-saving behaviors. Put more bluntly, it is not safe to include safety in the definition of eco-driving because it releases advocates and program designers of the responsibility to proactively plan for the fact that unsafe fuel-saving behaviors will be reinforced any time fuel-saving in general is reinforced.

None of these functions are necessarily prominent behavioral functions of the behaviors under consideration. That is, the primary "reasons" people engage in eco-driving behaviors may not be to save fuel and reduce emissions, just as the primary reasons people engage in *non*-eco-driving behaviors is not to maximize fuel waste and emissions. For example, consider the various possible functions associated with purchasing a fuel-efficient vehicle (e.g., achieving social status), using the cabin air conditioner (e.g., improving comfort), and turning the engine off instead of idling (e.g., reducing noise). In the field of behavior analysis, behavior is most usefully defined and classified in terms of its prominent behavioral function because it is the function, or consequences, that shape and maintain the behavior.

3. Present research

Claims of some researchers that "driving behaviors that affect fuel economy are well understood through existing research" (Gonder et al., 2011, p. 11) and "the characteristics of eco-driving are generally well defined and easily characterized" (Barkenbus, 2010, p. 763) are misleading. Previous definitions and categorizations of eco-driving are not based on a scientific understanding of behavior and therefore are neither explicitly nor systematically based on behavioral function or topography. Issues with past treatments include conflicting and incomplete consideration of behavioral functions and imprecise, inconsistent, and incomplete behavioral topographies. As a result of this unsound foundation, it has been difficult to determine the overall savings potential of eco-driving and to distill the relative effectiveness of various interventions on different eco-driving behaviors.

Approached as a broad and variable rubric, eco-driving is doomed to be poorly understood because it consists of a variety of topographically distinct behaviors with a variety of functions. A behavioral approach to defining and classifying eco-driving should be based first and foremost on behavioral functions. Behaviors that serve the same function (a functional response class) are influenced by the same set of variables; to the degree that a set of eco-driving behaviors are part of a common functional response class, we can expect them to co-vary, correlate with a distinct profile of demographic, psychological, and contextual variables, and be responsive (or not) to the same types of interventions. For example, Boyce and Geller (2002) conducted a behavior analysis of driving patterns and discovered a response class of at-risk driving (speeding, close following, and off-task behaviors) that co-varied significantly among 61 drivers and was predicted by age.

The present analysis begins to develop a typology of eco-driving behaviors based on behavioral functions by synthesizing, clarifying, re-framing, and elaborating upon currently existing definitions and categorizations. This more comprehensive typology will enable a better account of the savings potential associated with eco-driving. The typology will also inform the development of targeted interventions and policies across the entire range of eco-driving behaviors.

4. Methodology

We performed content analysis of eco-driving definitions in iterative stages based on the qualitative content analysis method described in Hesse-Biber and Leavy (2010; p. 235; see Fig. 1). We first reviewed the literature and focused on synthesizing existing eco-driving definitions in peer-reviewed academic journal articles (e.g., Barkenbus, 2010; Birrell et al., 2014; Sivak and Schoettle, 2012), resulting in an initial classification scheme. We chose peer-reviewed academic sources as our foundation because they are the most reliable source for rigorous scientific analyses.

We assessed the resultant classification in light of additional data collected from two sources: popular media and consultations with experts. Our sampling strategy for searching popular media for eco-driving definitions was to focus on the first three non-sponsored links in a Google search of each of three terms: (1) “eco-driving”; (2) “driving to save fuel”; and (3) “driving to reduce emissions” (Eartheasy, n.d.; ECOWILL, n.d.; Energy-efficient Driving, 2015, July 2; Leech and Planet Green, 2011, December 6; AA, 2014, October 9; US Department of Energy, n.d.-a; US Environmental Protection Agency, n.d.). We consulted with experts (including co-authors) in hybrid and plug-in electric vehicles (PHEVs) because these vehicle types are underrepresented in the eco-driving literature. We then refined and revised our initial classification scheme based on new behaviors and definitions identified in popular media sources and feedback from experts.

We present each major class of behavior, and sub-classes within each, in terms of their defining functions and topographies. Any calculations provided regarding how the vehicle should be operated (e.g., speed, gears, RPM) to achieve fuel savings are synthesized from our sources. We did not favor, pick, or choose among calculations, nor did we make any new calculations. We remind the reader that our purpose was not to empirically validate the fuel savings potential of these behaviors, but rather to inventory and organize them from a behavioral perspective. Our goal is to provide a framework to support more systematic investigations of fuel savings potential and inform the development of behavioral strategies to promote eco-driving.

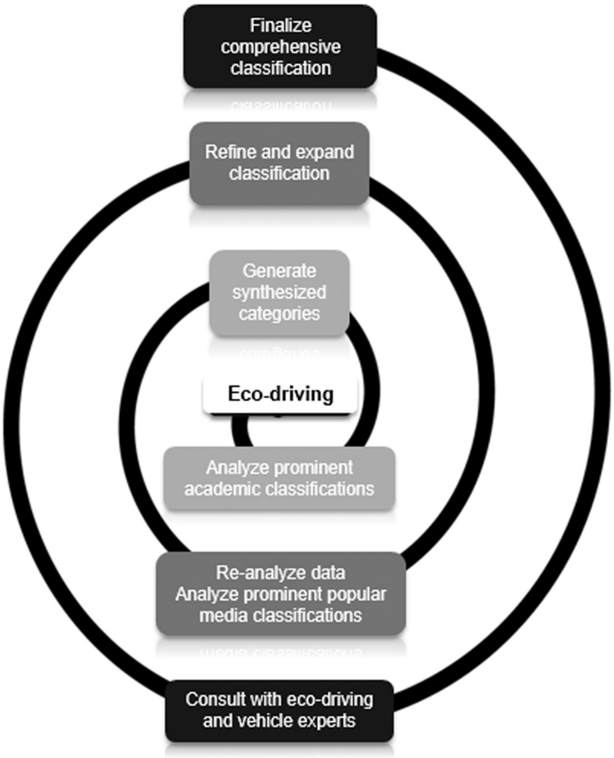

Fig. 1. Iterative classification method based on content analysis of academic, popular, and professional sources. Adapted from Hesse-Biber and Leavy (2010).

5. Results

First, we define eco-driving as exactly those behaviors overlooked in EPA fuel economy estimates posted on every new vehicle, encompassed in the accompanying statement: "Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle". This excludes vehicle selection decisions (Sivak and Schoettle, 2012) and creative commuting solutions such as carpooling, car-sharing, and ride-sharing. We identified six classes of eco-driving: *driving, cabin comfort, trip planning, load management, fueling,* and *maintenance.*

5.1. Driving

This class of behavior aligns closely with Sivak and Schoettle's (2012) category of operational decisions, although we exclude use of air conditioner (included in *cabin comfort*) and re-frame the behaviors they categorized as speed/rpm, use of cruise control, aggressivity, and idling. The function of driving behaviors is straightforward: driving; i.e., operating the vehicle to control direction and speed. We subdivide driving behaviors into what we view as the major functions of driving: accelerating, cruising, decelerating, parking, waiting, and driving mode selection when available. Within these classes, we specify the topography of eco-driving behaviors—typically involving driver manipulation of pedals, gears, and other controls (e.g., cruise control, steering wheel, mode selection), as well as spatial regulation (i.e., maintaining distance from other vehicles and anticipating road conditions, traffic, and signals).

5.1.1. Accelerating

Most eco-driving sources include acceleration as an important factor, but there is a lack of operationalization and clarity. A general rule noted is simply to minimize acceleration (Energy-efficient Driving, 2015, July 2); however, in order to reach a desired speed—the function of accelerating—there are more and less efficient ways to go about it. Recommendations often seem to conflate the speed and steadiness of acceleration, which comes across as vague and confusing; e.g., sources recommend accelerating gently (AA, 2014, October 9), moderately (Barkenbus, 2010), and quickly to reach cruising speed (Birrell et al., 2014). We synthesized information from our sources to better operationalize these behaviors in terms of driver use of pedals and gears.

5.1.1.1. Pedals and gears. Birrell et al. (2014) recommends accelerating smoothly, with no more than half throttle. "Smoothly" is not operationalized, but this notion is consistent with other studies that measure standard deviation of accelerator pedal as an indicator of eco-driving (e.g., Azzi et al., 2011). "Half throttle" can generally be taken as a guide to depress the pedal no more than halfway. Ericsson's (2001) analysis implies one should avoid extreme acceleration, acceleration with strong power demand, acceleration with moderate power demand, and engine speeds over 3500 RPM. The first three are clearly operationalized in the research but at a level too technical to distill into general verbal rules for drivers to follow. The latter (engine speed >3500 RPM) is clearly operationalized in a way that a driver can easily assess, but is specific to ICEVs. When designing a drive cycle optimized for fuel economy, Gonder et al. (2011) set the acceleration rate at 3 mph/s (or 1.3 ms/s).

Shifting up to higher gears early is widely recommended in both academic and popular literature; sources recommend shifting up in the range of 2000–2500 RPM (Barkenbus, 2010; Birrell et al., 2014; ECOWILL, n.d.; AA, 2014, October 9). Birrell et al. further recommends using block gear changes "when appropriate", especially on the highway (Energy-efficient Driving, 2015, July 2). Ericsson (2001) found that late changing from 2nd to 3rd gear in particular predicts greater fuel use and emissions. AA notes that efficient shifting is so influential that all manual transmission vehicles are likely to have a gear shifting indicator (GSI) in future; in Europe, the GSI has been mandatory on all new cars since 2009. Miller-Wilson (n.d.) recommends intentional upshifts with automatic transmissions, by accelerating quickly to top speed (relating also to accelerating—pedal behaviors above).

In conclusion, sources provide some general rules about efficient accelerating: accelerate evenly (minimizing average deviation of pedal position), at no more than half throttle, around 3 mph/s (1.3 ms/s) and under 3500 RPM, and constantly until reaching desired speed, upshifting at 2000–2500 RPM for manual transmissions. However, as one of our experts (T. Stillwater, personal communication, January 15, 2015) notes, for a given vehicle "there is an optimal acceleration for the road segment you are driving and the speed you want to reach. Anything that diverges from that is less efficient."

5.1.2. Cruising

Where the function of accelerating is to accrue speed, the function of cruising is to maintain speed. Efficient cruising is typically addressed by recommending a cruising speed. Academic and popular sources offer two main approaches to efficient cruising speed. Most sources generally recommend driving at the speed limit or safely below it (Barkenbus, 2010; Birrell et al., 2014; Eartheasy, n.d.; AA, 2014, October 9; US Department of Energy, n.d.-a). Other studies articulate optimal speed or speed range; which is dependent on the vehicle.

Ericsson (2001) found that both emissions and fuel consumption are negatively correlated with percent of time traveling 31–44 mph (14–20 ms). El-Shawarby et al. (2005) analyzed vehicle fuel-consumption and emission rates per-unit distance and identified an optimal speed range of 37–56 mph (17–25 ms), with considerable increase outside this optimum range. When designing a drive cycle optimized for fuel economy, Gonder et al. (2011) set cruising speed at 40 mph (18 ms).

The optimal cruising speeds for ICEVs and HEVs typically fall within these ranges, but it is much lower for PEVs. Further, different energy use factors differentially contribute to total energy use at different speeds; e.g., ancillary loads, like climate control, use more energy at lower speeds. Below, we further define the topography of efficient cruising in terms of driver behaviors with respect to gears, pedals, cruise control, and spatial regulation.

5.1.2.1. Gears. ECOWILL (n.d.) recommends cruising at low RPM. RPM is a factor of speed and gear. Ericsson (2001) found that time driving at moderate engine speeds in 2nd and 3rd gear (for particular vehicles tested) was negatively related to fuel consumption and vehicle emissions. Energy-efficiency Driving (2015, July 2) notes that optimal efficiency occurs when cruising with the transmission in the highest gear. In a manual transmission, gear selection is especially important; the highest gear possible that enables a fuel-efficient cruising speed is recommended. US Department of Energy (n.d.-a) recommends the use of overdrive gears to save fuel and reduce engine wear; overdrive allows the engine to operate at lower RPM. While newer vehicles have electronic overdrive that does not require specific activation by the driver (it turns on based on power demand), older vehicles may have a knob or button incorporated into the gearshift that the driver must use to turn on overdrive (Overdrive: Mechanics, 2015, July 16). Overdrive is only available, and efficient, at certain cruising speeds (e.g., above 40–45 mph or 18–20 ms), which are specified in vehicle manuals, and should be avoided under circumstances of high power demand as it could strain the engine (e.g., towing or climbing a hill; Overdrive: Mechanics).

5.1.2.2. Pedals and cruise control. Ericsson (2001) found that speed oscillation is positively correlated with fuel and emissions. Minimizing speed oscillation is consistently recommended as eco-driving, though it is variously phrased; e.g., maintain constant speed, uniform throttle positions (Birrell et al., 2014), drive smoothly (AA, 2014, October 9), keep an even driving pace (Barkenbus, 2010), drive steadily (Eartheasy, n.d.). In a similar vein, the use of cruise control is widely promoted as eco-driving (Barkenbus, 2010; Eartheasy; ECOWILL, n.d.; US Department of Energy, n.d.-a; Sivak and Schoettle, 2012). According to AA, cruise control is appropriate on rural roads, highways, and in some traffic situations in cities.

An exception to the steady speed rule is a technique called ‘pulse and glide’ or ‘burn and coast’. This technique involves a repetitious cycle of quick acceleration to a speed above desired cruising speed and then coasting down to a speed below desired cruising speed. This can be dangerous (and illegal) in a conventional ICEV if the engine is shut off or the vehicle put in neutral while coasting. Driver assistance technologies have made this technique possible for ICEVs, though it is automated; the only behavior that may be required is refraining from pedal pressing at some range of speed (e.g., BMW ECO PRO mode), at which point the system takes over. Some hybrid vehicles, like the Prius, will remain operable though the gas engine automatically turns off when coasting below certain speeds (e.g., 40 mph or 18 ms), thus the driver can more safely engage in pulse and glide. MetroMPG (2006, January 15) cautions that this technique can cause undue wear and tear on vehicle systems when implemented on open highway driving, but gains could be achieved without this risk in situations where the driver must frequently accelerate and decelerate anyway, e.g., urban and suburban roads.

5.1.2.3. Spatial regulation. Energy-efficient Driving (2015, July 2) generally advises to “drive in such a way so as to minimize acceleration and braking, and maximize coasting time.” One means of achieving this is to monitor and regulate the distance between your vehicle and the vehicle in front of you. Van der Voort et al. (2001) defines a metric called time to collision (TTC) as following distance divided by speed difference and observed that efficient drivers had fewer small TTC values. ECOWILL (n.d.) provides some specific recommendations for following distance: keep a distance equivalent of around 3 s to the vehicle driving ahead and let off the accelerator when traffic slows to keep this safety distance without braking.

Related to following distance, many sources encourage anticipating traffic flow and signals in order to cruise efficiently, avoiding unnecessary braking, stopping, and accelerating back to cruising speed (Barkenbus, 2010; Birrell et al., 2014; ECOWILL, n.d.; AA, 2014, October 9). Regarding timing traffic signals, Energy-efficient Driving (2015, July 2) describes how a driver can let off the accelerator or even brake far enough in advance when approaching a red light in order to arrive at the intersection at maximum speed after the light changes to green, also accounting for the time it takes traffic stopped at the signal to move through. It is noted, however, that this could have adverse effects at the traffic network level and it does not work when signal lights are triggered by traffic rather than timed. There are also important relationships between speed and spatial regulation. Specifically, driving at posted speeds should allow for best signal timing and moderate speeds offer more freedom to accelerate, coast, or decelerate as needed; additionally, more energy is lost in braking at high speeds (Energy-efficient Driving).

Accelerating slightly when approaching an uphill road segment to maintain speed while minimizing accelerating during the grade change is efficient cruising via spatial regulation, as is letting off the accelerator on downhill segments, leveraging momentum to maintain speed (i.e., coasting); coasting in neutral or with the engine off is often illegal and AA (2014, October 9) notes that it will not save fuel in modern vehicles anyway. In sum, spatial regulation is a function of speed and pedal use. It can involve acceleration and deceleration, but when defining eco-driving in terms of behavioral functions for the driver, if spatial regulation functions to maintain speed (and avoid stopping), it is cruising; thus, though the vehicle accelerates and decelerates in the process, the driver is cruising.

In conclusion, efficient cruising largely involves a critical interaction between spatial regulation, speed choice, and gear. More specifically, efficient cruising involves minimizing deviations in trajectory (steering straight and lane-keeping) and speed (by either a steady foot on the accelerator pedal or cruise control), and driving at an efficient speed (determined by vehicle model and constrained by speed limits, road and weather conditions), with an efficient gear choice (highest gear and overdrive when appropriate).

5.1.3. Decelerating

The function of decelerating is either to reduce cruising speed or to stop. Efficient decelerating involves pedals and gears. A straightforward goal for efficient deceleration is to minimize braking (Birrell et al., 2014). Of course, in order to accomplish this the driver must *do* other things (positive, actionable behavior).

5.1.3.1. Pedals and gears. Birrell et al. (2014) and AA (2014, October 9) recommend letting off the accelerator in time, without downshifting, thus using engine braking to roll to a stop or lower speed. When overdrive is engaged and can be manually turned off, one can also employ engine braking when going downhill to slow or maintain speed (Overdrive: Mechanics, 2015, July 16).

5.1.3.2. Regenerative braking. Drivers of PHEVs are able to recover some energy lost while decelerating through the use of regenerative braking. For safety and performance purposes regenerative braking systems always work in conjunction with traditional hydraulic brakes and depending on driver brake input, vehicle design, and conditions, the two systems can be blended together. In general, hydraulic brakes begin to activate during conditions of moderate braking and will be the only source of braking during emergency stops, at low speeds (5 mph or 2 ms and below) and cases where the battery is full. Maximizing the amount of energy regenerated requires minimizing the use of the hydraulic brakes, which is typically achieved through steady braking at light to moderate stopping power.

5.1.4. Waiting

Waiting is comprised of opportunities to idle or to replace idling with more efficient options. Implications of idling are straightforward: every vehicle achieves 0 mpg (or L/100 km) when idling, therefore a general rule is to minimize idling (Barkenbus, 2010; Ericsson, 2001; Sivak and Schoettle, 2012; US Department of Energy, n.d.-a; consumerenergycenter.org; aut.howstuffworks.com; Energy-efficient driving, 2015, July 2; Eartheasy, n.d.). As discussed previously, some idling is avoidable by accelerating, cruising, and decelerating efficiently. This section focuses on how to wait efficiently in cases where the vehicle is stationary, such as upon starting and parking, during passenger and cargo loading, in drive-thru establishments, and during traffic delays. Efficient waiting mainly involves gears and the ignition.

5.1.4.1. Gears and ignition. AA (2014, October 9) advises to not start the engine until you are ready to depart. In other words, start moving as soon as the engine is running smoothly. They recommend scraping ice instead of idling the vehicle to warm up in the winter and note moving warms up car better than idling anyway. Michigan Clean Cities (michigancleancities.org/eco-driving) recommends conservative use of remote starters to minimize idling before trip departure.

Energy-efficient Driving (2015, July 2) advises to shift into neutral when idling cannot be avoided to minimize fuel waste. More commonly, however, sources advise shutting off the engine when stopped mid-tour. AA (2014, October 9) recommends the following as a general guide:

> For a warm car in daylight conditions in mild weather, turning the engine off for a wait of around a minute or more will probably save fuel/CO_2 – assuming it's safe to be without indicators and you can live with the interruption to the radio and heating/ventilation system. A cold engine, cold weather, or additional electrical loads will all extend the period you'd have to be stationary to get a benefit from switching off.

Opportunities to turn the engine off rather than idle include walking into stores instead of using drive-thrus (michigancleancities), waiting for trains or picking up kids (michigancleancities), traffic jams and long traffic lights. Times when it may not be appropriate include when at the back of the traffic jam where you may need to maneuver and avoid the risk of a rear end collision (Energy-efficient Driving, 2015, July 2). Diesel vehicles should not be turned off during periods of diesel particulate filter (DPF) regeneration (AA, 2014, October 9). Vehicles with automatic start-stop systems do this job for the driver; they will turn off the engine when the vehicle is idling for some amount of time, then turn it back on upon power demand; it will not turn off the engine in cases when vehicle charge, weather, or electrical loads would make it inefficient to do so (AA).

5.1.5. Driving mode selection

Some vehicles allow users to select specific driving modes, e.g., via a button on the dashboard. These modes typically alter the energy use of the vehicle. Selectable driving modes vary among manufacturers but are generalized here in four main categories.

5.1.5.1. Normal mode. This is the default mode for vehicle operation and represents the as-tested configuration for emission and fuel use testing.

5.1.5.2. Economy mode. The selection of an economy driving mode will change vehicle features to reduce energy consumption or to support eco-driving techniques. The distinction being that the latter strategy is *passive* and relies on consumers to engage with new information provided by the vehicle to reduce their energy consumption (feedback about efficiency of driving behavior, such as ambient indicator lights that illuminate different colors to signal efficiency versus inefficient driving). *Active* economy modes make changes directly to vehicle operations, including gear shifting at lower RPMs, preventing or holding off downshifting, decreasing vehicle top speed or acceleration rate, remapping of the throttle pedal to allow for smoother acceleration, limiting the rate of acceleration, activation of aerodynamic features such as the closing of front grill shutters or lowering of the vehicle ride height, changes in the cruise control system, engaging of cylinder de-activation systems and reducing the energy consumption of cabin comfort systems.

5.1.5.3. Increased performance mode. Some vehicles allow users to select driving modes which provide better vehicle performance at the expense of additional energy consumption. Examples of changes made with the selection of a performance mode include: holding gear shifts to higher RPMs, increasing vehicle top speed, increasing rate of acceleration, disengaging of cylinder deactivation systems, and for hybrid or plug-in hybrid vehicles the selection of a performance mode may result in the use of the gas engine (for additional power) while battery power is still remaining.

5.1.5.4. Fuel management modes. Some vehicles that have the ability to store two fuel sources on-board might provide consumers with the option to control which fuel they use at any given time, since, depending on the vehicle configuration and conditions it might be more efficient to use one of the fuels over another. For plug-in hybrid vehicles there are currently three modes of operation which affect which fuel(s), and the relative quantity of those fuels used to propel the vehicle.

5.1.5.4.1. EV mode. For plug-in hybrids with limited electric drivetrain power, the selection of EV mode will optimize driving dynamics to use only, or as much electricity as possible as allowed by the vehicle design, to propel the vehicle and reduce gasoline use while the vehicle is operating in EV mode.

5.1.5.4.2. Blended mode. This mode will optimize the use of both fuels to create either improved fuel economy for a trip which is beyond the electric only range of the PHEV or provide additional vehicle acceleration, power, or higher top speed.

5.1.5.4.3. Hold EV range. This mode allows users to defer the use of electricity for a later point in the trip or other trip completely. Holding EV range could be advantageous under a number of scenarios such as if you will be driving beyond the EV only range of the PHEV, will need additional power to climb hills, or are not sure about the next time you can charge your PHEV. Users of PHEVs describe their use of "holding electricity" as a strategy to make the most efficient use of electricity as possible, which is often when idling in traffic and in city driving.

The strategy for use of these driving modes depends on the specific PHEV, however, their effective use relies on advanced trip planning techniques and assumptions about distance until next charging opportunity. In general, if the trip exceeds the available range and depletes the battery before the next charging attempt, keeping the vehicle within electric mode could result in higher fuel consumption. Economy mode inherently provides (active economy mode) or supports (passive economy mode) greater savings or efficiencies, performance mode can decrease efficiency, fuel management provides greater control over the fuel used in a dual fuel vehicle and could provide savings or increased performance depending on the context.

5.1.6. Parking

US Department of Energy (n.d.-a) recommends parking in a warmer place (i.e., garage) in cold weather so the engine does not begin as cold. In warm weather, using a sun shade or parking in the shade keeps the vehicle cooler to reduce need for air conditioning (Eartheasy, n.d.). Parking in the shade also minimizes evaporation of gasoline. Parking facing out can save idling time when departing and being skilled in parallel parking can reduce time searching for other options (Leech and Planet Green, 2011, December 6). Finally, turning off air conditioning, heating, and auxiliary electronics before shutting off the engine to decreases engine load when you start the next trip (Leech and Planet Green; Eartheasy; Energy-efficient Driving, 2015, July 2).

5.2. Cabin comfort

As previously mentioned, Sivak and Schoettle (2012) considered use of air conditioning in their category of operational behavior along with driving behavior. We separate it from driving behavior into a class with a unique set of functions we term cabin comfort. Cabin comfort involves regulation of comfort and use of electronics for entertainment and communications. Unlike driving behaviors, cabin comfort behaviors do not make the vehicle operate (stop and go), and they are accessible to vehicle passengers as well as drivers.

5.2.1. Comfort, entertainment, and communications

Using air conditioning requires up to 3.7 kW of extra power (Energy-efficient Driving, 2015, July 2), therefore conservative use of air conditioning is recommended as eco-driving (e.g., California Energy Commission, 2014; Sivak and Schoettle, 2012), especially in older vehicles (Eartheasy, n.d.) and hybrid and plug-in electric vehicles (US Department of Energy, n.d.-a). Rolling the windows down for ventilation and cooling is a more efficient alternative at low speeds, but air conditioning is more efficient at high speeds as an alternative to windows down, which increases aerodynamic drag. AA (2014, October 9) recommends rolling down windows instead of using the defroster.

In ICEVs, cabin heating slows down the engine warming process and uses more fuel (Energy-efficient Driving, 2015, July 2). Depending on the vehicle design, cabin heating in a PHEV may be supplied through waste heat from the ICE. As such, depending on the driver's climate selection the ICE could be engaged even while energy is remaining in the battery and the vehicle would otherwise be operating in EV mode. To minimize the use of the PHEV's ICE for cabin heat a variety of options may be used to maintain cabin comfort without using the cabin heater such as electrically heated seats and steering wheels, electric front window defroster, or electric heat pump system.

Other accessories also add load to the engine, increasing fuel consumption. Conserving use of these features, such as heated seats and windscreens, demister blowers, headlights, entertainment equipment (stereo, video player) and anything plugged into cigarette lighters (phone and tablet chargers, navigation systems, etc.) is recommended (AA, 2014, October 9; Eartheasy, n.d). Like heating and air conditioning, these other accessories affect fuel economy on all vehicles, but can have a greater effect on hybrid and electric vehicles (US Department of Energy, n.d.-a).

5.3. Trip planning

There are a variety of eco-driving behaviors regarding how, where, and when to drive. We classify these behaviors as trip planning. We organize them into *how, where*, and *when* but there is a great deal of overlap among them. For example, *trip-chaining* (combining multiple trips) may involve another strategy, *trip-timing*; e.g., planning *when* you travel, as when one times errands in order to pick up kids from school on the way home.

5.3.1. How you drive

Eco-routing (Ahn and Rakha, 2013) refers to selecting routes with less congestion, roads types amenable to steady fuel efficient speeds (above 45 mph or 20 ms according to Energy-efficient Driving, 2015, July 2), and flatter roads instead of those with steep grades. Planning routes with more right turns and *planning unfamiliar journeys* to prevent getting lost are additional suggestions along these lines found on websites (AA, 2014, October 9; Eartheasy, n.d.). These behaviors concern planning trips based on *how* you reach a destination.

5.3.2. Where you drive

Trip planning also includes *trip-chaining*, which refers to linking together multiple locations in a single tour rather than making multiple single trips. While eco-routing is typically defined as the most efficient way to get from point A to point B (Ahn and Rakha, 2013), trip-chaining can be described as the most efficient way to get to points A, B, and C. In addition to cutting down on distance traveled, trip-chaining shifts trips so that more driving is done while the engine is warmed up.

5.3.3. When you drive

One of our expert interviewees mentioned planning travel times for optimal wind speed and direction, although this seems beyond the scope of what is generally applicable to most trips for most drivers. Although avoiding traffic via eco-routing is mentioned, timing trips to avoid traffic was surprisingly not mentioned in any of our main sources, but it has obvious and significant implications. Planning trips according to weather has substantial potential for savings. Ambient temperature can have an impact on overall efficiency, energy use, and emissions for ICEVs, hybrids, and PEVs. Cold weather extends the time it takes for the engine to come to normal operating temperature and the engine will cool down quicker as well. Fuel savings and emission reductions from hybrids and plug-in hybrids operating on gasoline are, in part, due to the stopping of the engine at times when it is not needed for propulsion or to maintain vehicle systems. However, these start/stop ICE systems are programed to operate while the engine is at normal operating temperature. Further, in extreme hot or cold environments PHEVs may automatically engage the gasoline engine to maintain an appropriate temperature for the battery. This is referred to engine running due to temperature (ERDTT). In all vehicle types, heating and air conditioning are more easily conserved in moderate weather. Eartheasy (n.d.) recommends the use of a block heater one or two hours before driving in temperatures −20 °C or below to reduce fuel consumption by up to 10%.

5.4. Load management

5.4.1. Minimize weight

In sum, load management is about traveling prepared while minimizing *weight* and maximizing *aerodynamics*. Minimizing or removing excess cargo weight is commonly recommended as eco-driving (AA, 2014, October 9; Eartheasy, n.d.; Sivak and Schoettle, 2012). An extra 100 lbs can increase fuel costs by 2% (US Department of Energy, n.d.-a). This could involve traveling lighter on a journey, removing shuttled items or personal items accumulated over time, and reducing equipment load such as carrying a half size spare tire. Another strategy mentioned is driving with less fuel (lighter load) and filling up more (Energy-efficient Driving, 2015, July 2).

5.4.2. Maximize aerodynamics

Necessary cargo should be stored inside the vehicle whenever possible as hauling cargo in roof racks and boxes adds wind resistance, increasing fuel consumption (AA, 2014, October 9; California Energy Commission, 2014; Eartheasy, n.d.; US Department of Energy, n.d.-a). Using rear racks is sacrificing aerodynamics less compared to roof racks when exterior cargo is unavoidable—or even strapping things under the vehicle. When cargo is hauled on the roof, using low profile and aerodynamic racks and cargo holds, and packing roof racks tight and low help reduce wind resistance (AA; MetroMPG, 2007, March 10). When not in use, roof racks and boxes and bicycle and ski racks should be removed. Further, removing other common unnecessary accessories, such as “brush guards, wind deflectors (or ‘spoilers’, when designed for downforce and not enhanced flow separation), running boards, [and] push bars . . . will improve fuel economy by reducing both weight and aerodynamic drag” (Energy-efficient Driving, 2015, July 2).

5.5. Fueling

5.5.1. ICEVs, including hybrids

Efficient fueling can entail using the proper grade/octane of gasoline or renewable fuels, biofuels and ethanol blends, when the vehicle allows (e.g., Eartheasy, n.d.; US Environmental Protection Agency, n.d.; US Department of Energy, n.d.-b). It also involves considerations of fuel evaporation. Fuel evaporation can be minimized by refraining from topping off and make sure the gas cap is intact and on tightly (Car Care, 2012, March 7). Energy-efficient Driving (2015, July 2) further recommends fueling at night and parking in the shade to prevent evaporation.

5.5.2. PEVs

Emissions from PEVs are shaped by the source of the electricity used to charge the vehicle. The electrical grid is a complex and dynamic system where the type of feedstock and quantity of that feedstock changes according to the utility, wholesale electricity market, electricity demand, regulations, and resource availability, which for renewables such as wind and solar is dictated by the time of day. Individual’s actions to change the source of electricity and emission content are possible through the participation in special green electricity programs, installation of home solar panels, or through the use of controlled charging software which, using price signals or other information from the utility, can delay, start, or pause vehicle charging based on user preferences.

5.6. Maintenance

5.6.1. Wheels and tires

Investing in low rolling resistance tires (Sivak and Schoettle, 2012), keeping wheels aligned (Energy-efficient Driving, 2015, July 2), and keeping tires properly inflated (US Environmental Protection Agency, n.d.) are recommended as eco-driving. Sivak and Schoettle contend that tires with 25% greater rolling resistance can decrease fuel economy by 4%, and four tires underinflated by 5 psi can result in 1.5% decrease in fuel economy. Sources generally recommend checking tire inflation once per month and before long or high speed trips (AA, 2014, October 9; ECOWILL, n.d.).

5.6.2. Engine

Sources also widely recommend regularly servicing a vehicle’s engine to maintain efficiency, including engine air filter, spark plug, engine oil, and addressing any other diagnosed malfunctions in the engine and related sensors, especially the oxygen sensor (Energy-efficient Driving, 2015, July 2). Services should be performed according to manufacturer instructions and scheduling (Eartheasy, n.d.; AA, 2014, October 9). A poorly tuned engine can use up to 50% more fuel and produce up to 50% more emissions than one that is running properly (Energy-efficient Driving). Eartheasy recommends regular visual checks of the air filter along with consultation of the vehicle owner’s manual and notes that dirty filters can decrease fuel economy by up to 10%. Usually, engine oil should be changed every 3000–5000 miles; clean oil results in better fuel economy (Eartheasy). It is also important to use the proper grade of engine oil (AA), with lower viscosity oil moving through the engine easier and using less gas (Eartheasy; Energy-efficient Driving); specifications for proper engine oil can be found in a vehicle owner’s manual.

6. Discussion

The goal of this study was to make significant progress toward a behavioral typology of eco-driving by synthesizing, clarifying, and re-framing previous definitions. Our typology is based on the concept of behavioral function—the consequences that serve to shape and maintain behavior. We frame eco-driving as behaviors a driver can do—not what “a dead man can do”, e.g., minimize accelerating. Our analyses yielded six main categories of eco-driving behavior: driving, cabin comfort, trip planning, load management, fueling, and maintenance. We further divided driving behavior into accelerating, cruising, decelerating, waiting, driving mode selection, and parking.

Our typology includes behaviors that are not often considered in research on eco-driving. Researchers and policy makers should consider all six categories of eco-driving and develop targeted strategies based on the unique functions, topographies, and contexts of each category (Table 1). For example, Trip Planning and Load Management behaviors that occur pre-trip could be targeted by prompts and advice upon starting one’s vehicle. This is already done with on-board navigation systems and apps that can suggest eco-routing, but one could also imagine notifications at outset of trips when sensors detect unnecessary cargo weight or vehicle accessories for the given trip (e.g., roof racks used for leisure activities on the way to work).

Table 1
Eco-driving typology by function, topography, and context.

Type of eco-driving	Function: Why	Topography: What	Context: Who, when, where
Driving	Operate the vehicle	Accelerating; cruising; decelerating; waiting; parking	Driver, en route, in-vehicle
Cabin comfort	Comfort, communications, entertainment	Using HVAC, windows, auxiliary electronics	Driver and passengers; en route; in vehicle
Trip planning	Get from point A to point B (and *k* destinations)	Selecting travel time and routes (road type, grade, right turns, congestion, trip-chaining)	Driver; pre-trip and en route; in vehicle
Load management	Be prepared	Managing cargo weight and aerodynamics (racks, etc.)	Driver or surrogate; pre-trip; home
Fueling	Fuel vehicle	Selecting fuel; fuel cap management; time of day/ temperature when fueling; PEV charging (frequency, level, and source)	Driver or surrogate; pre-trip(s); gas or charging station
Maintenance	Maintain vehicle	Changing oil; selecting oil; inflating tires; selecting tires; engine maintenance	Driver, surrogate, or professional; intervals based on use; auto shop

6.1. Limitations and future research

Our typology suggests that existing accounts of the savings potential of eco-driving are incomplete since they reflect only a subset of eco-driving behaviors (e.g., Barkenbus, 2010; Sivak and Schoettle, 2012); however, this paper in no way accounts for the overall or relative effectiveness of eco-driving behaviors. The hope is that this typology will be a foundation for future investigations of the technical potential of eco-driving, allowing a more complete and systematic assessment of the overall potential and relative contribution of each type of eco-driving to fuel efficiency and emissions reduction outcomes. Policy makers and researchers also need to consider the behavioral plasticity (Stern, 2011) associated with each type of eco-driving (i.e., the degree to which it is likely to be adopted by drivers) when selecting eco-driving behaviors to target.

Since our focus was on individual behavior with implications for personal efficiency and emissions, we did not consider network level impacts of collective eco-driving. For example, communication between drivers can improve collective efficiency via appropriate signaling, allowing drivers more time to respond to each other's behavior. If some drivers avoid high traffic roads and rush hour, there are benefits for others who decide to drive in those conditions. On the other hand, network level impacts of eco-driving may be negative under some circumstances. For example, accelerating "slowly" through intersections could impede the flow of traffic, resulting in a net increase in travel time, fuel consumption, and emissions (see Alam and McNabola, 2014, for review). We also did not consider community-level actions, such as adopting fuel efficient speed limits (Energy-efficient Driving, 2015, July 2).

6.2. Conclusions

In conclusion, fuel economy "will vary for many reasons, including driving conditions and how you drive and maintain your vehicle"... and how you manage cabin comfort, plan your trips, manage vehicle loads, and fuel your vehicle. This typology of eco-driving behaviors will enable more systematic study of eco-driving to identify the savings potential and behavioral plasticity of each type of eco-driving. It will also enable development of most effective strategies to promote each type of eco-driving. Ultimately, we believe this research can be foundational to the development of policies to successfully promote high leverage eco-driving behaviors.

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