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Average impact and important features of onboard eco-driving feedback: A meta-analysis

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ABSTRACT

Eco-driving refers to suites of behavior a driver can engage in to improve fuel economy. The most common strategy used to promote eco-driving is onboard feedback that conveys information about fuel efficiency to the driver. This paper presents a statistical meta-analysis of eco-driving feedback studies in order to determine a weighted estimate of the average impact of feedback on fuel economy and explore potential moderators of its effectiveness, particularly regarding features of the feedback interface design. The main effect of onboard feedback on fuel economy across the final sample of 17 studies and 23 effect sizes was 6.6% improvement. Feedback that included information about both instantaneous and accumulated performance predicted larger effects. Though not statistically significant, trends in relationships between other feedback design features and fuel economy outcomes aligned with study hypotheses. Length of feedback intervention negatively related to effects, and pairing feedback with instructions or rewards predicted larger effects.

1. Introduction

Driver behavior has an immense impact on vehicle fuel economy and emissions. For example, Sivak and Schoettle (2012) demonstrated that inefficient driving behavior can diminish fuel economy by as much as 45%. Despite this potential, driver behavior has historically been treated as random error in models of motor vehicle fuel economy and neglected in energy and environmental policy making regarding fuel efficiency. For example, Corporate Average Fuel Economy (CAFE) standards for passenger cars and light-duty trucks are enforced via a process that literally removes the driver from the vehicle: Test vehicles are put through a precise, computer-regulated sequence of speeds and distances on a chassis dynamometer.

Spikes in oil prices in the late 1970s prompted some research into fuel-efficient driving behavior (Greene, 1986), but the topic fell back off the radar in the 1980s, perhaps because technical changes in vehicle drivetrain technology prompted by new CAFE standards and downward shifts in vehicle mass and size produced large improvements in on-road fuel economy. Recently, high fuel prices, concern about fossil fuel depletion and climate change, as well as the critical role of driver behavior in achieving the fuel economy benefits of new hybrid and electric vehicles, have renewed interest in what is now termed eco-driving (e.g., Barkenbus, 2010; Knowles, Scott, & Baglee, 2012).

Kurani, Sanguinetti, and Park (2015) defined eco-driving as anything a driver can do, given a particular vehicle, to increase fuel economy or otherwise decrease carbon intensity. Sanguinetti, Kurani, and Davies (2017) described 10 categories of eco-

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driving behavior, summarized in Fig. 1. These suites of driver behavior have been highlighted as a significant opportunity to support goals for carbon dioxide emissions reductions in the transportation sector (Barkenbus, 2010).

Strategies to promote eco-driving include educational programs such as training and coaching (Ho, Wong, & Chang, 2015; Spencer, 2008; Strömberg & Karlsson, 2013; Wåhlberg, 2007; Zarkadoula, Zoidis, & Tritopoulou, 2007), and regulations such as speed limits and restrictions on vehicle idling (Atkinson et al., 2010; Eghbalnia, Sharkey, Garland-Porter, Crumpton, & Jone, 2013; Kim et al., 2014; Ryan et al., 2013). Another common strategy, which is the focus of this paper, is providing drivers with feedback on their behavior. Feedback is typically visual and provided on-board the vehicle via digital screens (dash or instrument cluster displays, after-market devices, or web apps on personal smartphones or tablets).

No policies exist requiring manufacturers to provide eco-driving feedback, yet feedback systems of increasing variety are appearing in vehicles, especially hybrid, plug-in hybrid electric, and battery electric vehicles (Sanguinetti, Park, Sikand, & Kurani, 2017). Manufacturers have deployed many different designs, from numeric real-time and average fuel economy indicators, to imagery of growing trees and flowers reflecting recent or cumulative efficiency. This wide variation could indicate a belief in competitive advantage or a lack of evidence-based design and consistent assumptions about behavioral responses to feedback. The rapidly increasing prevalence and complexity of in-vehicle displays and concern for driver distraction (Rouzikhah, King, & Rakotonirainy, 2013) suggest standardization of eco-driving feedback may be warranted in the near future. Standardization will require a better understanding of the types of eco-driving feedback that are most effective.

Many studies have assessed the impact of eco-driving feedback interventions on fuel economy and related outcomes. Similar to manufacturers' designs, interfaces used in academic eco-driving research are widely variable, as are their impacts on fuel economy. An extensive review of this literature (Kurani et al., 2015) found outcomes ranging from no fuel savings to over 50%. Some researchers have put forth feedback design guidelines specific to eco-driving feedback (Young, Birrell, & Stanton, 2011). However, there is limited empirical research to support a comprehensive account of the influence of eco-driving feedback design.

By analyzing eco-driving intervention characteristics and fuel economy outcomes across many studies via a statistical meta-analysis, this study assessed the average effect of eco-driving feedback and the influence of different feedback design features on fuel economy outcomes. This research draws on theory from the broader topic of eco-feedback (eco-driving feedback is one application of eco-feedback). The results suggest some best practices for the design of effective onboard eco-driving feedback and identifies future research needs.

2. Literature review

This section reviews eco-driving feedback literature that points to the influence of feedback design features. To structure this review, findings are presented in the context of the Eco-Feedback Design-Behavior Framework (Sanguinetti, Dombrovski, & Sikand, 2018). Eco-feedback is any type of information about resource consumption delivered back to the consumer with the aim of promoting more sustainable behavior; applications are diverse and include eco-driving feedback and household energy and water consumption feedback, etc. The framework articulates eco-feedback design dimensions that have implications for user behavior change (Fig. 2). Each dimension has implications for at least one of three feedback qualities: salience, precision, and meaning, which in turn relate to three behavior change mechanisms: attention, learning,

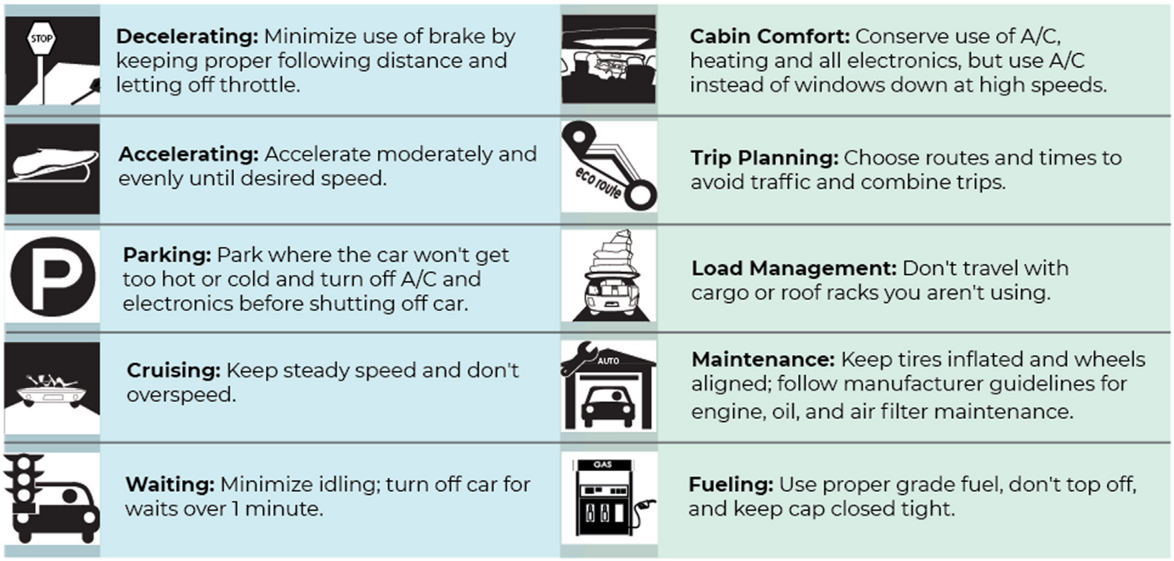

Fig. 1. Types of eco-driving. Adapted from Sanguinetti et al. (2017). The left column defines sub-categories of "Driving" behavior.

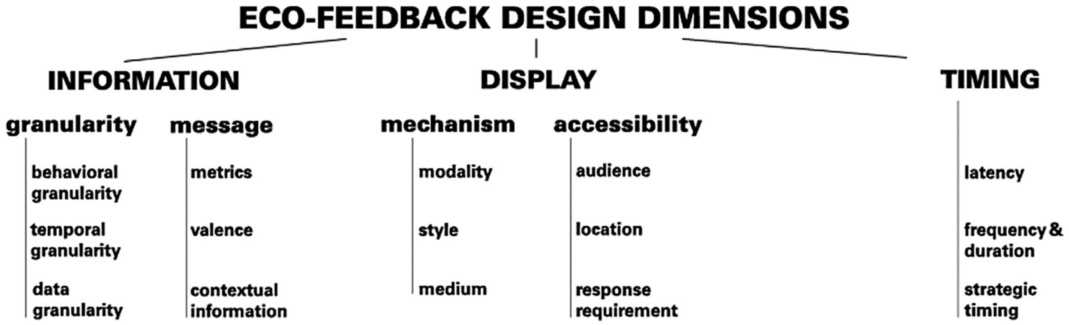

Fig. 2. Eco-feedback design dimensions with implications for behavior change; figure from Sanguinetti et al. (2018).

and motivation, respectively. See Sanguinetti et al. for a more thorough discussion of the behavioral theory and broader base of empirical research behind this framework.

2.1. Eco-driving feedback information

According to the Eco-Feedback Design-Behavior Framework, the granularity and message content of information presented in eco-feedback (Fig. 3) have implications for its effectiveness. Granularity refers to the level of detail in the information. There are three types of granularity: behavioral, temporal, and data. In general, high granularity feedback is useful for learning new or complex behaviors because it provides a precise connection between behavior and consequence, whereas low granularity feedback can be useful for goal-setting and tracking aggregate performance (Sanguinetti et al., 2018).

If feedback reflects a single specific response of one person it is high granularity. If it reflects many different behaviors and/or the behaviors of multiple people it is low granularity. Eco-driving feedback often includes an indicator of overall fuel economy, which is relatively low behavioral granularity because it reflects many different driving behaviors (anything that impacts fuel economy) rather than one specific behavior. Examples of higher behavioral granularity eco-driving feedback include information specifically about accelerating, braking, speed, idling, use of cabin electrical systems, or gear-shifting.

van der Voort, Dougherty, and van Maarseveen (2001) assessed how the granularity of gear-shifting feedback influences its effectiveness (e.g., "shift earlier" versus "shift earlier from 2nd to 3rd gear"). There was no significant difference in fuel economy, although the group with extended advice showed significantly greater reductions in extreme accelerations compared to the control group ($N = 88$). Along the same lines, Graving, Rakauskas, Manser, and Jenness (2010) found that feedback specific to acceleration was more effective than fuel economy feedback, for males only. However, Manser, Rakauskas, Graving, and Jenness (2010) found the reverse--that mileage feedback was more effective than acceleration feedback.

Few studies have assessed the influence of eco-driving feedback temporal granularity. van der Voort et al. (2001) did not empirically test different levels of temporal granularity, but eloquently described a theory of optimization: "Achieving the right level of temporal granularity for optimization is important; too coarse and many opportunities to improve performance will be missed. Conversely, a fine-grained approach will operate in local optima which may or may not represent the global optimum over a longer period of time" (21). Rather than striking a balance, some studies suggest that instantaneous and accumulated feedback are both useful, but for different purposes. Qualitative data from participants in eco-driving feedback studies suggests that instantaneous feedback (e.g., momentary fuel efficiency) is primarily useful for experimentation and learning new behaviors, whereas accumulated feedback (e.g., average fuel-efficiency) is useful for goal-setting and assessing overall performance (Stillwater & Kurani, 2013; Tulusan, Staake, & Fleisch, 2012). Newsome (2012) found that juxtaposing instantaneous and accumulated feedback was more effective than either in isolation.

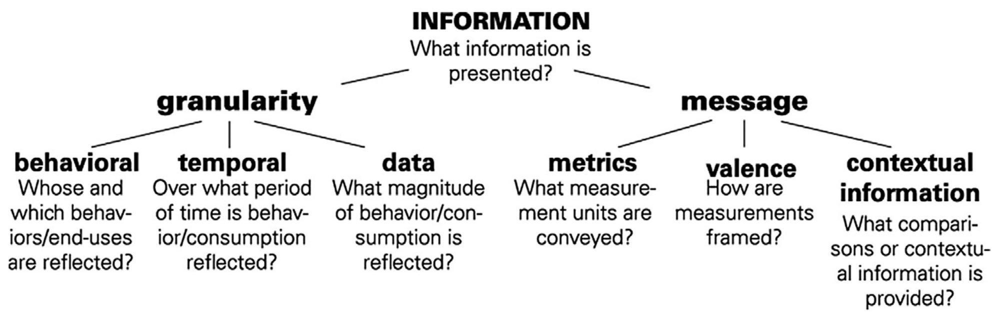

Fig. 3. Dimensions of feedback information; figure from Sanguinetti et al. (2018).

No empirical studies were found that have investigated the impact of feedback data granularity on fuel economy or other objective outcomes. This dimension describes the resolution of data presented, i.e., the amount of levels, or differentiation provided, in the data. Data granularity is often related to feedback modality (described below with display dimensions). For example, numeric data typically have high data granularity, whereas a light that changes colors between green, yellow, and red has low data granularity. Again, greater granularity would be expected to support learning since it could reflect very small increases and decreases in the magnitude of target behavior(s). However, ambient displays often call for reduced data granularity so that information can be absorbed while the user is attending to some other task, such as driving. Thus, when combined with high salience, low granularity feedback can call attention to a few important levels of information, which might trigger further investigation, at which point higher granularity feedback could be provided to support learning.

The feedback message (metrics, valence, and contextual information) can make it more or less meaningful to users. Dogan, Bolderdijk, and Steg (2014) conducted a survey in which they presented the monetary or carbon savings associated with various eco-driving scenarios and asked participants whether it would be worthwhile to modify their behavior. Carbon savings were more persuasive, and they concluded that monetary savings are not motivating if the potential savings presented is a negligible amount. No studies were found that compare different valences for a given metric (e.g., fuel cost versus fuel savings).

Contextual information includes feedback standards, such as historical self-comparisons, social comparisons to others, and goal comparisons that provide a target or optimal performance standard. Other contextual data may serve as a feedback standard even if it is not explicitly framed as a goal, e.g., estimated fuel economy for a vehicle or expected driving range. According to Feedback Intervention Theory (Kluger & DeNisi, 1996), the feedback standard is a critical element of feedback that motivates behavior change.

No studies have explicitly compared the impact of eco-driving feedback with versus without standards, or different types of standards (e.g., goal versus historical), but a couple studies have related findings. Rolim, Baptista, Duarte, Farias, and Pereira (2016) found that when weekly feedback indicated performance decline from previous week (i.e., historical self-comparison feedback standard) it led to greater improvements in multiple eco-driving behaviors (excess speeding, idling time, and aggressive acceleration or braking events) during the subsequent week, whereas the opposite occurred after a week when performance exceeded the standard. Wada, Yoshimura, Doi, Youhata, and Tomiyama (2011) demonstrated that feedback is more effective when standards are adaptive, raising the bar for performance as a driver's skill level increases. Feedback standards, especially when organized into levels or leaderboards, are a critical aspect of gameful design, which is the use of game design elements (e.g., points, levels, leaderboards, badges, and challenges) in non-game contexts (Zichermann & Cunningham, 2011).

2.2. Eco-driving feedback display

Dimensions of the feedback display characterize its formal characteristics and physical situation (Fig. 4). A number of experiments have compared different feedback modalities (visual, haptic pedal, auditory), though with mixed and inconclusive findings (Table 1). It is unclear how the different modalities rank in terms of effectiveness, though it seems that visual feedback may be less effective than haptic or auditory feedback, and multiple modalities may be more effective than a single modality. The latter finding is supported by meta-analyses of multimodal task feedback beyond the context of driving (Burke et al., 2006; Prewett, Elliott, Walvoord, & Coovert, 2012). Prewett et al. also found that vibrotactile (e.g., haptic) feedback is more effective for alerts but not for more complex direction cues. On the other hand, visual feedback can be more distracting to drivers than haptic feedback (Jamson, Hibberd, & Merat, 2015).

Several studies have compared different styles of feedback within the same modality. Hammerschmidt and Hermann (2017) found that a guzzling sound when engine speed exceeded a threshold was more effective in reducing fuel consumption compared to a constant noise signal with frequency corresponding to instantaneous fuel consumption. Jamson, Hibberd, and Jamson (2015) and Jamson et al. (2015) both found that haptic force pedal was more effective than haptic stiffness pedal feedback in terms of reducing pedal error. In contrast, Mulder, Mulder, Van Paassen, and Abbink (2008; $N = 21$) concluded that haptic stiffness pedal was more effective than haptic force because drivers in the force feedback condition exerted sig-

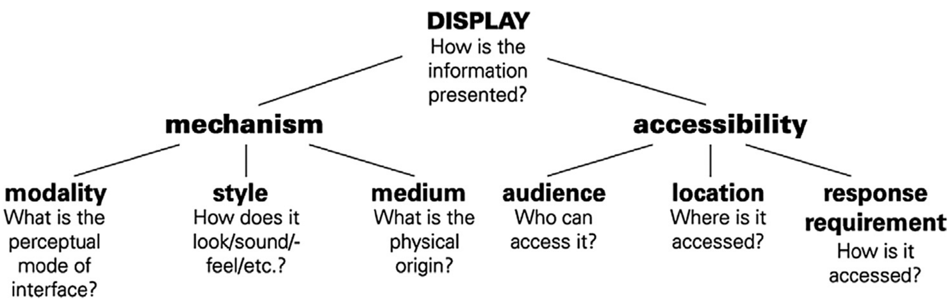

Fig. 4. Dimensions of feedback display.

Table 1
Experiments comparing feedback modalities.

Study	Modality Comparison	Outcomes Measured	Results
Azzi, Reymond, Mérienne, and Kemeny (2011; *N* = 28)	Haptic v. Visual	Modeled total polluting emissions	No difference
Hibberd et al. (2015; *N* = 24)	Haptic v. Visual + Auditory	Efficient decelerating, accelerating and cruising	Haptic more effective for efficient decelerating
Jamson et al. (2015; *N* = 21)	Haptic v. Visual + Auditory	Pedal error during cruising and accelerating	Visual + Auditory more effective for efficient cruising
Hammerschmidt and Hermann (2017; *N* = 30)	Auditory v. Visual v. Auditory + Haptic v. Auditory + Visual	Fuel consumption, engine speeds	Auditory alone or in combination more effective reducing fuel use and engine speeds
McIlroy et al. (2017; *N* = 30)	Auditory v. Visual v. Haptic v. Aud + Vis v. Aud + Hap v. Vis + Hap v. Aud + Vis + Hap	Fuel consumption; efficient decelerating, accelerating and cruising	Aud + Hap and Aud + Vis + Hap more effective than Visual for reducing harsh accelerations
Staubach et al. (2014; *N* = 24)	Haptic v. Visual v. Visual + Haptic	Efficient accelerating and shifting	Visual + Haptic more effective for efficient acceleration and gear-shift behavior

nificantly more force on the pedal, indicating greater workload and resistance to comply, and stiffness feedback led to greater reductions in standard deviation of gas pedal depression. Exploring different mediums for haptic feedback, Riener, Ferscha, Frech, Hackl, and Kaltenberger (2010; *N* = 10) found that a vibrating seat belt was more effective than a vibrating seat for improving fuel economy.

No studies were found that examined the impact of eco-driving feedback accessibility. With onboard feedback, location is limited to the vehicle, but it could be situated in the instrument cluster on the driver's side, a center dashboard display, mounted smartphone, or even a heads-up display on the windshield. In terms of audience, feedback is always available to the driver, but may also be available to others (e.g., via social-sharing or in the context of commercial driver feedback that is accessible to managers). Response requirement could have implications, such as when the driver has to change display settings in order to view eco-driving feedback versus when it shows up by default.

2.3. Eco-driving feedback timing

The finding from Hammerschmidt and Hermann (2017; *N* = 30) regarding the advantage of an intermittent guzzling sound over a continuous tone also pertains to feedback timing (see Fig. 5)—particularly feedback frequency. Kircher, Fors, and Ahlstrom (2014) recommended intermittent rather than continuous visual eco-driving feedback because it results in lower "dwelling times", distracting the driver from the road and environment. In contrast, Fors, Kircher, and Ahlström (2015) found that drivers performed better with continuous compared to intermittent visual feedback on coasting (though neither was a statistically significant improvement from baseline; *N* = 23). Some studies have considered strategic timing of advice about when to start decelerating for a slowing or stopping event (McIlroy, Stanton, & Godwin, 2017; Staubach, Schebitz, Köster, & Kuck, 2014; Staubach, Schebitz, Fricke et al., 2014).

2.4. Other considerations

Some studies suggest feedback is more or less effective for different types of drivers. For example, Rolim et al. (2016; N = 40) and Kurani, Stillwater, Jones, and Caperello (2013; N = 118) both found that feedback was more effective with female drivers. Lee, Lee, and Lim (2010; N = 14) found that although older drivers consumed less fuel both with and without feedback, younger drivers demonstrated greater improvements in response to feedback. Zhao, Wu, Rong, and Zhang (2015; N = 22) suggested there might also be differences between civilian and professional drivers (see also Newsome, 2012). Other

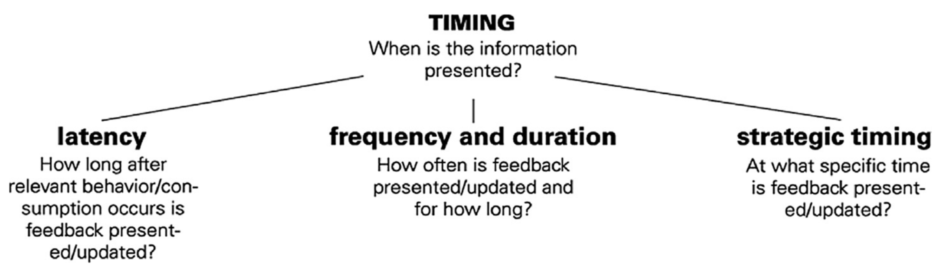

Fig. 5. Dimensions of feedback timing.

studies have found differential effects of feedback depending on road type and traffic; overall, it seems that feedback may have a larger impact on urban roads compared to rural highways, with the exception of heavy traffic when safety needs to be prioritized over fuel efficiency (Table 2).

Feedback design, driver characteristics, and road characteristics also interact to influence feedback effectiveness. For example, Kurani et al. (2013) suggested that feedback is more effective when design features align with the driver's goals (e.g., to save money, save time, or save fuel). Additionally, different feedback designs may be more or less effective for different eco-driving behaviors. For example, Wu, Zhao, and Ou (2011, N = 8) found that visual feedback on acceleration and deceleration was more effective during acceleration conditions than deceleration conditions. Seewald et al. (2013; N = 22) found that visual feedback better supported optimal pedal position, whereas haptic feedback better supported steady acceleration.

The outcomes of feedback interventions are also undoubtedly influenced by the length of time over which the intervention takes place, the setting, and whether feedback is combined with other strategies. Várhelyi, Hjälmdahl, Hydén, and Draskóczy (2004) looked at both short- and long-term effects of onboard feedback on 206 drivers' speed and found that speed decreases from baseline were greater in the short-term (up to one month) than over the long-term (5–11 months). Many eco-driving feedback studies have been conducted using vehicle simulators, a contrived context that might not be representative of drivers' response to feedback in real-world settings. Finally, combining onboard feedback with other strategies, such as instructions, online feedback (Hibberd, Jamson, & Jamson, 2015; Várhelyi et al., 2004), and rewards (Mullen, Maxwell, & Bedard, 2015) is more effective than onboard feedback alone. Studies of home energy feedback have also found that effects are strongest in the short-term and feedback is more effective in combination with other interventions (Karlin, Zinger, & Ford, 2015).

3. Methodology

While onboard feedback interventions to promote eco-driving have generally been found effective, the effects vary widely. Most studies have had relatively small sample sizes and many did not include inferential statistics to determine whether observed outcomes were statistically significant. The present study presents a meta-analysis as a rigorous method for articulating a main effect of onboard feedback on eco-driving and its statistical significance. As opposed to qualitative reviews and simple averaging of effects, statistical meta-analysis weights effects based on study sample size and methodological rigor and provides a measure of statistical significance.

Studies comparing different types of feedback have been sparse and yielded inconsistent findings. Thus, the second aim of this meta-analysis was to conduct moderator analyses to better understand characteristics of feedback that influence its effectiveness. Moreover, hypotheses guiding these moderator analyses were developed based on the Eco-Feedback Design-Behavior Framework, in hopes of unifying idiosyncratic studies through a theoretically grounded analysis.

3.1. Hypotheses

Hypotheses regarding eco-driving feedback information dimensions are as follows:

H1. Feedback that includes information of both low and high behavioral granularity (i.e., aggregate and behavior-specific) is more effective than feedback with only one or the other.

H2. Feedback that includes information of both low and high temporal granularity (i.e., accumulated and instantaneous) is more effective than feedback with only one or the other.

Table 2
Experiments comparing impact of feedback on different road types.

Study	Road Type Comparison	Outcomes Measured	Results
Larsson and Ericsson (2009; N = 20)	Urban v. Rural v. Mixed	Fuel consumption, emissions	Significant increase in fuel economy (4%) only on urban route; emissions reductions on urban and rural routes
Boriboonsomsin, Vu, and Barth (2010; N = 20)	City v. Highway	Fuel economy	Improved 6% on city streets, 1% on highways
Várhelyi et al. (2004; N = 206)	Arterial 70 km/h v. Arterial 50 km/h 2 lane v. Arterial 50 km/h 1 lane v. Main v. Main mixed traffic v. Central	CO2 emissions	Largest emissions reductions on dual carriageway arterial streets with 50 km/h speed limit
Staubach et al. (2014; N = 30)	Rural v. Urban	Fuel use	16% reduction in urban, 18% reduction in rural; highest potential on curves and in light traffic with 30% speed reduction recommendation
Jamson et al. (2015; N = 22)	Low v. High density traffic	Throttle pedal errors (deviation from optimal position)	Larger errors in high density traffic

H3. Feedback that includes information of both low and high data granularity (i.e., discrete and continuous) is more effective than feedback with only one or the other.

H4. Feedback is more effective if it includes a feedback standard.

H5. Feedback is more effective if it include elements of gameful design (e.g., scores, levels, badges).

Hypotheses regarding eco-driving feedback display dimensions are as follows:

H6. Haptic feedback is more effective than visual feedback.

H7. Auditory feedback is more effective than visual feedback.

H8. Multiple modality feedback is more effective than single modality feedback.

Hypotheses regarding eco-driving feedback timing dimensions are as follows:

H9. Intermittently presented or strategically timed feedback is more effective than continuous or on-demand feedback.

Hypotheses regarding driver, road, and intervention characteristics are as follows:

H10. Feedback is more effective with younger drivers.

H11. Feedback is more effective on urban roads compared to rural.

H12. Vehicle simulator experiments show greater impacts than field studies.

H13. Shorter studies show greater impacts than longer studies.

H14. Feedback with instructions or rewards is more effective than feedback alone.

These hypotheses were tested in the present research to the extent possible (i.e., as the data from existing studies allowed). Interactions between moderator variables (e.g., impact of visual feedback in simulator versus field studies) were not explored in the present study because a much larger sample size would be required for a fully crossed comparison of combinations of levels of different variables.

Statistical meta-analysis enables two outcomes. First, it enables a pooled estimate of an effect and subjects the effect to significance testing. In this case, it allows us to derive an estimate of the effect of onboard feedback on eco-driving that is closer to the true average effect than that observed in any individual study. Second, meta-analysis enables the identification of variables that moderate an effect; in our case, this means we can identify how characteristics of feedback studies, such as feedback modality and study setting, influence effects on eco-driving.

3.2. Literature search

The first step in a meta-analysis is a literature search. The literature search for this study was completed in Spring of 2017. The following databases were searched: Google Scholar, TranStats: The Intermodal Transportation Database, TRID (Transport Research International Documentation), and the ACM Digital Library. Google Scholar was included as a general database to help us identify eco-driving feedback studies regardless of disciplinary background of the authors. Additional databases were selected to represent the fields in which eco-driving feedback is typically studied: transportation and human-computer interaction (ACM).

In each database, searches were conducted for the term ''feedback'' in combination with each of the following: ''eco-driving''; ''fuel economy''; ''fuel'' AND ''savings''; ''fuel efficiency''; ''fuel use''; ''fuel consumption''; ''speeding''; and ''aggressive driving''. These terms to substitute with eco-driving were included in order to capture studies that pre-date the term eco-driving or are conducted by researchers whose focus was more specific (e.g., speeding) or related to fuel and not broader impacts implied by the term eco-driving. Searches were not restricted by publication year, type, or any other factor.

Papers identified via literature search were filtered based on the following inclusion and exclusion criteria. First, the main intervention component (independent variable) had to be onboard technological feedback. Studies in which feedback was provided exclusively outside the vehicle or by non-technological means (delivered on paper or in person) were excluded. Design solutions for feedback provided in these other formats are likely much different from the case of onboard feedback (e.g., different driver attentional capacity).

The feedback intervention had to deliver information to the driver about fuel economy, fuel consumption, emissions, or specific eco-driving ''driving'' behaviors, as defined in Sanguinetti et al. (2017; left column in Fig. 1). This excluded studies of navigation systems that offer advice on eco-routing (e.g., Ahn & Rakha, 2013), which is often considered distinct from eco-driving (Alam & McNabola, 2014). If the offered information included what might technically be considered ''feedforward'', rather than feedback, such as gear-shifting advice, the study was not excluded as long as it promoted eco-driving behaviors under the aforementioned definition.

Studies were excluded if feedback was conflated with other major intervention components, such as eco-routing (Caulfield, Brazil, Fitzgerald, & Morton, 2014), training, in-vehicle coaching, or employer reward/punishment systems for professional drivers, as this would not allow for determining the impact of feedback regarding eco-driving "driving" behaviors (Sanguinetti et al, 2017). However, interventions that included simple instructions to drive efficiently were included since this did not constitute a major, separate intervention component. Interventions that included small monetary rewards based on efficiency of driving behaviors demonstrated in a simulator context were also included because saving money is a realistic outcome of eco-driving. The presence of these additional intervention components (instructions or rewards) was included in moderator analyses.

Only studies that involved research participants were included; modeling exercises or field tests performed by the researchers themselves were excluded. Studies that used vehicle simulators, as well as actual vehicles, and studies involving private or commercial passenger vehicles, trucks, or buses, were all included in order to increase the sample size. These factors were considered in the moderator analyses where sample sizes allowed.

Included studies had to measure and report an objective indicator of eco-driving, including fuel economy, emissions, or specific eco-driving "driving" behaviors. These related outcome measures were required for meta-analysis. Studies that measured safety, interface usability, or driver preferences, and did not also include an objective measure of eco-driving, were excluded.

Finally, studies had to have an experimental design, including either a control group (between-groups design), a baseline condition (within-subjects design), or both (mixed design). This was necessary so that an effect size could be calculated, which is required for meta-analysis. Studies were excluded if the experimental design did not include a control group or baseline condition without any intervention (e.g., a control group that received instructions to drive efficiently), as this would not allow for determining the impact of feedback on eco-driving. Studies were also excluded if they only provided preliminary findings and/or lacked basic details about study methodology (e.g., sample size), since this precludes sufficient assessment of the validity of the results.

Twenty-five studies from our initial search met these criteria. Next, we conducted forward and backward searches from these 25 papers, as well as from 5 review papers (Alam & McNabola, 2014; Dahlinger & Wortmann, 2016; Hinton et al., 1976; Kurani et al., 2015; Vaezipour, Rakotonirainy, & Haworth, 2015). These searches resulted in an additional 18 studies.

3.3. Data preparation and analysis

The next step was to prepare the data for the meta-analysis. This process included coding each study according to key variables (potential moderators), and calculating a common effect size for each study. Two research assistants independently coded the studies on feedback design characteristics, driver and road characteristics, intervention characteristics, and publication type. They conferred about their results and consulted with the lead researcher until agreement was reached. Interrater reliability was not calculated.

The lead researcher reviewed all coding, corrected errors, and created higher level coding schemes to increase sub-sample sizes for moderator analyses where possible (i.e., sample sizes were small and aggregating levels would still be meaningful with respect to study hypotheses). The authors decided to set a criterion that each level of a variable should be represented by at least five effect sizes from at least four different studies in order to test it as a moderator. There were arbitrary criteria selected to enable moderator analyses to address the study hypotheses. It is lower than typical recommended standards (10 studies per level minimum), though there is some support for conducting moderator analysis with as few as 2–8 studies per level of the variable tested, particularly when based on a-prior hypotheses and used for exploratory value (Pincus et al., 2011). This will be discussed further in the limitations section.

The lead researcher and a research assistant calculated effect sizes and variances for the studies, which were the two parameters required for the meta-analysis. Fuel economy was the most common outcome measure in the studies and it is easily interpreted; therefore, relative change (i.e. percent improvement) in fuel economy was calculated as an effect size for studies that measured fuel economy. A standardized effect size, Cohen's d, was also calculated for all studies, including fuel economy studies and studies with other eco-driving outcome measures (i.e., specific driving behaviors, emissions, fuel use, or other general eco-driving performance indicators). The intention was to conduct two meta-analyses: one with fuel economy studies using relative change as the effect size to calculate a summary effect of the impact of feedback on fuel economy, and another with all studies using Cohen's d as the effect size to have a larger sample size for more powerful moderator analyses. However, Cohen's d values for studies measuring outcomes were generally much larger than Cohen's d values for fuel economy studies. This may be partly due to these studies choosing specific outcome measures more sensitive to changes in targeted eco-driving behavior compared to overall fuel economy. Thus, the decision was made to include only the fuel economy studies in the meta-analysis, and to use relative change in fuel economy as the effect size for both the summary effect and moderator analyses.

Relative change in fuel economy was calculated using the following formula, where *T* is the feedback condition or group and *B* is the baseline condition or control group:

$$R* = \frac{\bar{X}_T - \bar{X}_B}{\bar{X}_B}$$

The variance of relative change was calculated as follows:

$$Var(R*) = e^{2lnR}\left[\frac{s_T^2}{n_1\bar{X}_T^2} + \frac{s_B^2}{\bar{X}_B^2}\right]$$

When the calculations or raw data to derive means or standard deviations were not provided in a study, the researchers contacted the study authors (beginning with the first author and then contacting supporting authors if the first author could not be reached after at least two email messages). If the author(s) were not responsive or could not supply the necessary aggregate or individual data, the study was excluded. After excluding studies that did not measure fuel economy and studies for which required outcome measurement data was not available, the sample size was diminished to 17 studies.

Multiple effect sizes were calculated for each study that included comparative information (i.e., comparing the effects of different types of feedback displays, with different types of drivers, or on different road types; $n = 5$). It was important to retain this information since it was pertinent to our hypotheses about moderating variables. This increased the sample size to 25 cases across the 17 studies. Two outliers in effect size (41% and 53%), both in Manser et al. (2010), were removed from the analysis. These were simulator studies that focused on "stop and go" scenarios with apparently high potential for eco-driving. Thus, the final sample size consisted of 23 effect sizes from 17 studies. Two of the studies were reported in the same publication (Newsome, 2012), but the samples were different.

The first step of the meta-analysis was to create a model estimating the main effect of onboard eco-driving feedback on fuel economy. A two-level (univariate) random-effects model and a three-level random-effects model were conducted, using a structural equation modeling approach with the "metasem" package in R statistical environment (Cheung, 2014, 2015). Random-effects models were used because they assume the true effect may vary based on different parameters of the intervention (as opposed to a single true underlying effect). Cheung describes how three-level meta-analysis is appropriate to account for dependence in the data. In this case, multiple effect sizes contributed from the same study may have more in common with each other than the other effect sizes in the sample. The metasem package also allowed for the use of relative change as the effect size, whereas other R packages and commands the authors explored did not.

The two- and three-level models were compared using a likelihood-ratio test to determine if the three-level model was statistically better. The likelihood-ratio test was 0.052 ($df = 1$), $p = .812$, indicating the three-level model was not statistically better than the two-level model. Thus, we used the two-level model, which also had the benefit of strengthening statistical power for the moderator analyses. Moderator analyses were conducted by including each variable in a two-level mixed-effects model. The significance of each potential moderator was estimated by the p-value of the coefficient of its slope in the model.

4. Results

The main effect of onboard feedback on fuel economy across all 23 effect sizes was 6.6% improvement (with 95% confidence that the true population effect would fall between 4.9% and 8.2%). This is a statistically significant effect ($p < .0001$). These results were nearly identical to the three-level model. The unweighted mean effect was 8.2%. Fig. 6 is a forest plot for the studies included in the meta-analysis.

The forest plot displays relative change in fuel economy for each study (e.g., 0.04 = 4% improvement in fuel economy) and its 95% confidence interval, as well as the summary effect across studies and its confidence interval. The confidence interval is interpreted as a 95% chance that the true effect lies between the lower and upper limits. The diamond shape at the bottom of the figure represents the summary effect size and its confidence interval.

4.1. Moderator analyses

The two-level random-effects model yielded an I^2 of 0.1391, indicating a relatively low degree of heterogeneity in the effect sizes. That is, the variables tested as moderators had the potential to explain approximately 14% of the variance in effect sizes. The final sample of studies and effect sizes supported moderator analyses to test most of our hypotheses, with the criteria of at least five individual effect sizes from at least four separate studies per variable level. Exceptions were H3,

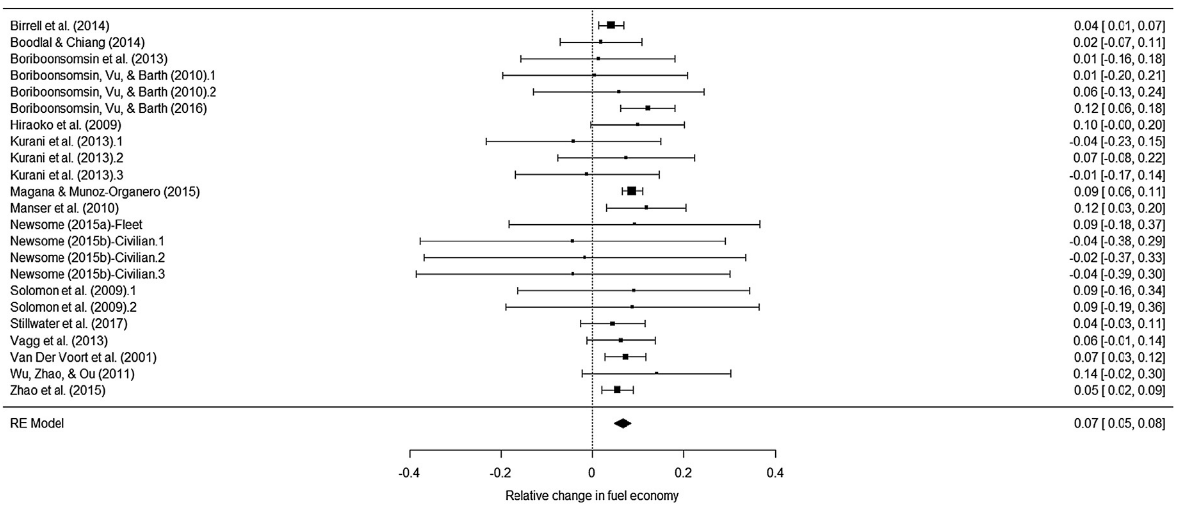

Fig. 6. Forest plot of individual study and summary effect sizes and confidence intervals. (See below mentioned references for further information)

H6, H7, H9, and H11. Regarding H3, many studies had insufficient information about feedback data granularity. The sample only allowed one comparison of feedback modalities: Visual compared to Visual + Auditory, enabling a test of H8, but not H6 or H7. Most feedback was displayed continuously rather than intermittently- or strategically-timed, so there was not enough variability to test H9. Regarding H11, there were insufficient effect sizes for exclusively urban or exclusively rural roads to enable comparison.

Moderator analyses coding and results are presented in Table 3, which also includes sample sizes and either mean effect size (R^*) for each level of categorical variables or correlation with R^* for continuous variables (study length and driver age). All categorical variables were coded as binary variables, with the level hypothesized to predict higher R^* coded as 1 and absence of that level coded as 0. Effect sizes from studies with no value coded for a particular potential moderator variable (due to lack of information provided in the study and by the authors upon inquiry) were excluded from that respective analysis.

Only one of the variables related to feedback design (temporal granularity) was statistically significant in the mixed-effects moderator analyses. Specifically, the inclusion of information regarding both instantaneous and accumulated behavior in a feedback intervention, rather than just one or the other, predicted larger effect size. All other relationships between moderators and effect size trended in the predicted direction. For example, the mean effect of feedback that included a feedback standard was 7% improvement in fuel economy, compared to only 1% average improvement for performance feedback that did not include a standard for comparison (see Table 3 for other trends).

Length of feedback intervention, and combination of feedback with instructions or rewards were also marginally significant predictors of relative change in fuel economy (significant at the alpha = 0.10 level). The former relationship was negative (depicted in Fig. 7) and the latter positive, such that interventions with additional strategies, rather than feedback alone, predicted larger effect size.

5. Discussion

Based on the results of this meta-analysis, onboard eco-driving feedback can be expected to result in an average of 6.6% improvement in fuel economy. This is a more conservative estimate than the simple average of effects calculated in previous reviews (e.g., 9% in Kurani et al., 2015), but far from a dramatic difference. However, it does provide a more rigorous estimate. Average fuel economy without feedback in the studies assessed (i.e., in baseline phases or control groups) was about 25 MPG. A 6.6% improvement from this baseline would be equivalent to a 1.7 MPG improvement.

5.1. Practical implications

Though feedback has a statistically significant positive impact on fuel economy overall, the results of the moderator analysis suggest that effectiveness wanes over time. This is consistent with other findings of a novelty effect with eco-feedback, whereby effects are strongest in the short-term (Karlin et al., 2015; Várhelyi et al., 2004). This has implications for eco-driving feedback programs and technologies. For example, such programs may not achieve persistent effects and should assess program costs accordingly.

Table 3
Moderator variable levels, descriptives and results of mixed-effects models.

Hypotheses, variables, and levels			*n* studies	*n* effects	Mean R^* (or *r*)	*B*	*p*
H1	Behavioral granularity	1 = Aggregate + Specific$^{(+)}$	9	10	6%	0.012	0.535
		0 = Aggregate or Specific	10	13	4%		
H3	Temporal granularity	1 = Instant. + Accumulated$^{(+)}$	14	18	6%	0.037	0.006***
		0 = Instant. or Accumulated	4	5	1%		
H4	Feedback standard	1 = Yes$^{(+)}$	12	13	7%	0.013	0.598
		0 = No	4	8	1%		
H5	Gamification	1 = Yes$^{(+)}$	7	9	6%	0.030	0.136
		0 = No	11	14	4%		
H8	Modality	1 = Visual + Auditory$^{(+)}$	5	5	7%	0.008	0.674
		0 = Visual	12	18	4%		
H10	Age	Mean age in years$^{(-)}$	9	15	(−0.1)	−0.001	0.649
H12	Setting	1 = Simulator$^{(+)}$	6	6	10%	0.023	0.188
		0 = Field	11	17	3%		
H13	Length	# of days with feedback$^{(-)}$	17	23	(−0.7)	−0.001	0.051*
H14	Combined intervention	1 = Feedback plus$^{(+)}$	8	10	8%	0.030	0.065*
		0 = Feedback only	9	13	2%		

(+/−)Hypothesized to be positively or negatively related to impact of feedback on eco-driving.

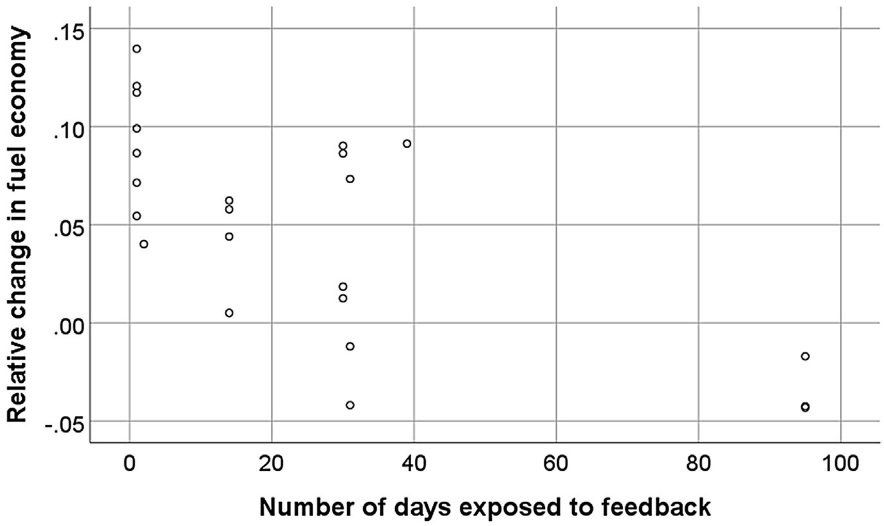

Fig. 7. Relative change in fuel economy as a function of length of feedback intervention (number of days).

Given the potential novelty effect of eco-feedback, it is crucial to understand how interface design can maximize and prolong positive eco-driving outcomes. For example, the meta-analysis results suggest that feedback reflecting both instantaneous and accumulated behavior is more effective than feedback with only one or the other types of information. Though not reaching statistical significance in the models, trends in the data lend some support to the other hypotheses about effective design, which are rooted in behavioral theory and eco-feedback research. Specifically, these trends suggest eco-driving feedback designers and vehicle manufacturers should also seriously consider including feedback standards, behavior-specific and behavior-aggregate information, gameful design elements (e.g., points, levels, leaderboards, badges), and multiple modalities in their products.

The results also support previous findings that feedback is more effective when combined with other strategies, such as education and rewards contingent on performance (Hibberd et al., 2015; Karlin et al., 2015; Mullen et al., 2015; Várhelyi et al., 2004). Private and public organizations with vehicle fleets and driver training programs are uniquely positioned to combine feedback with educational and incentive programs. Newsome (2012) calculated the potential for large savings and quick return-on-investment for organizations with large fuel budgets to install onboard eco-driving feedback devices in their vehicle fleets. The basics of eco-driving could be integrated into driver's education in high schools, vehicles used for driver's training could be equipped with eco-driving feedback, and the Department of Motor Vehicles driver's license exam could test new drivers on their eco-driving knowledge and skills.

5.2. Future research

Experiments in this area going forward should carefully consider the feedback design best practices outlined in this review, provide detailed descriptions of their feedback designs (with images), and compare multiple designs when possible. Ideally, an experimental research program would systematically test the effectiveness of feedback in relation to information, display, and timing design dimensions in order to provide a more holistic and comprehensive understanding. Eco-driving feedback timing is a particularly underexplored and important area that could help address the feedback novelty effect. Drivers may be more likely to "tune out" or ignore information that is available continuously, particularly if it is visual and requires the driver to actively access it.

This meta-analysis should be replicated in the future with a larger number of studies to test for more moderating variables and to consider interactions between multiple design dimensions (i.e., to understand optimal information-display-timing combinations). To enable a future meta-analysis, studies should provide effect sizes for the impact of feedback (on fuel economy whenever possible) or raw data from which to calculate effects sizes (sample sizes, means, and standard deviations). A multivariate meta-analysis could enable inclusion of studies that measure outcomes other than fuel economy (e.g., eco-driving behaviors or emissions estimates). Future models should control for length of feedback intervention as a covariate when exploring relationships between design features and feedback effect.

The results of this meta-analysis suggest general best practices for the design of effective eco-driving feedback, but greater specificity is required to identify promising solutions for standardization. Further consideration of manufacturers' practices and constraints could help hone in on opportunities and for standardization. For example, Sanguinetti et al. (2017) identified 15 distinct types of eco-driving feedback provided by vehicle manufacturers. Feedback designs in this meta-analysis did not often fit cleanly in this typology since the studies used aftermarket devices and researchers often design their own interfaces to test. Future studies could compare the effectiveness of variations on each feedback type identified by Sanguinetti et al., or compare across types with overlapping information. This would help determine most effective designs that are acceptable and feasible for manufacturers.

However, manufacturers might also need to be encouraged to adopt new interfaces if they are more effective and still acceptable to consumers. For example, despite academic research findings that non-visual and multimodal feedback can be more effective (Hammerschmidt & Hermann, 2017; McIlroy, Stanton, Godwin, & Wood, 2017; Staubach, Schebitz, Köster et al., 2014), virtually all feedback available from vehicle manufacturers is visual only (the ECO Pedal by Infiniti/Nissan is an exception). One reason for this may be manufacturers' reluctance to voluntarily include stimuli consumers might find annoying or otherwise off-putting. Research that measures both consumer preferences and effectiveness, comparing the exact feedback solutions manufacturers are already using to variations that may challenge perceived constraints, could identify an optimal solution. For example, a non-abrasive auditory prompt to turn the engine off while idling, that is salient but can be easily disregarded, will be much more acceptable than something more like the beeping seatbelt reminder that can only be terminated through compliance.

Finally, future research should integrate insights from eco-feedback theory and research into the broader context of evolving requirements for in-vehicle information systems. New contexts of vehicle automation and shared and multimodal mobility present new information requirements for drivers and passengers. The literature on eco-feedback has relevant insights for this broader space. For example, levels of partial vehicle automation present a critical case where the driver needs salient, precise, and meaningful information to understand and negotiate control of the vehicle.

5.3. Limitations

The largest limitations of this study were a function of lack of sufficient data.

Given the small sample size and low degree of heterogeneity in effect sizes (lower than the broader literature suggests), moderator analyses were constrained. Some hypotheses were not tested due to underrepresentation of one or more variable levels in the data. Moreover, the analyses that were run may have lacked statistical power to identify an effect. Only one feedback design variable (temporal granularity) emerged as statistically significant, despite all relationships trending in the predicted direction. Thus, results of the moderator analyses should be considered exploratory, not confirmatory.

The models used did not account for dependence in the data (i.e., the inclusion of multiple effect sizes from some studies). Although a three-level model was not statistically significantly better than the two-level model used, a three-level model is better suited to the data structure. A superior three-level model would likely require a much larger sample size, particularly in order to incorporate moderator analyses.

This study did not consider potential differences in feedback effectiveness for light- versus heavy-duty vehicles. Fuel economy in heavy-duty vehicles might be more sensitive to improvements in eco-driving due to their lower power-to-weight ratio. Only two studies in this review involved heavy-duty vehicles (Boodlal & Chiang, 2014; Boriboonsomsin, Vu, & Barth, 2016).

5.4. Conclusion

This paper presented a meta-analysis that estimated the average impact of onboard eco-driving feedback to be a 6.6% improvement in fuel economy. Moderator analyses assessed the degree to which feedback design features, and other study characteristics, influence its effectiveness. These analyses were limited by a small sample size and results are considered exploratory. A negative relationship between length of exposure to feedback and effect size was interpreted as a feedback novelty effect. Multiple feedback modalities (i.e., not just visual, but also auditory and/or tactile/haptic interfaces) and strategic timing or intermittent feedback presentation are suggested as possible strategies to improve the persistence of effects. Other results and trends from the moderator analyses, taken together with past research and eco-feedback theory, suggest onboard eco-driving feedback should include both high and low granularity information, standards against which to compare one's performance, and gameful design elements.

CRediT authorship contribution statement

Angela Sanguinetti: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Ella Queen:** Validation, Investigation, Data curation, Writing - original draft. **Christopher Yee:** Validation, Investigation, Data curation, Formal analysis. **Kantapon Akanesuvan:** Software, Methodology, Formal analysis.

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