# Onboard Feedback to Promote Eco-Driving: Average Impact and Important Features

September 2018

A White Paper from the National Center for Sustainable Transportation

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# TABLE OF CONTENTS

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## EXECUTIVE SUMMARY

Driver behavior has an immense impact on vehicle fuel economy and emissions, yet it has historically been treated as random error in models of fuel economy and neglected in energy and environmental policy-making regarding fuel efficiency. Recently, 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, has created interest in eco-driving. 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 feedback that conveys information about fuel efficiency to the driver. 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, likely due to advances in telematics and decreasing costs of new technologies. The rapidly increasing prevalence and complexity of in-vehicle information systems, along with concern for driver distraction, suggest standardization of eco-driving feedback may be warranted in the near future. Thus, there is a need to understand what types of eco-driving feedback are effective.

Although the literature generally suggests that feedback can be effective in supporting eco-driving, results are widely variable. This inconsistency is likely due to variation among studies, e.g., in terms of feedback design, sample, setting, and length of intervention. For example, many studies use vehicle simulators, while others outfit participants' personal or work vehicles with feedback devices. Some involve professional drivers of fleet vehicles and others civilian drivers of private vehicles. Feedback design ranges widely, for example, from haptic accelerator pedals that create resistance when the driver attempts to over-speed, to complex visual displays that gamify fuel economy, rewarding the driver with points or growing trees.

This white paper presents a statistical meta-analysis of eco-driving feedback studies in order to determine a pooled estimate of the impact on fuel economy and explore how characteristics of feedback interventions influence their impact. This review is for policy-makers and fleet operators who have a stake in reducing vehicle fuel consumption and emissions. It provides the most accurate estimate to-date of the average impact of in-vehicle feedback on fuel economy and summarizes the current state of knowledge regarding characteristics of eco-driving feedback interventions that determine effectiveness.

A literature search was conducted for studies with experimental designs that measured the impact of onboard feedback on objective eco-driving outcomes. Studies were coded on variables related to feedback design, intervention, and study characteristics. The meta-analysis was conducted using the metasem package for R statistical software, using a random effects, three-level model. Outcome measurements were translated into a common effect size: relative

(i.e., percent) improvement in fuel economy. After excluding studies that were not amenable to the analysis, the final sample size included 23 effects in 17 studies.

The main effect of onboard feedback on fuel economy across all 17 studies and 23 effect sizes was 6.6% improvement (with 95% confidence that the true population effect would fall between 4.9% and 8.3%). The average fuel economy without feedback in these studies (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.

The rate at which Corporate Average Fuel Economy (CAFE) standards are progressing may slow considerably under the Trump administration. Eco-driving feedback is a strategy that enhances consumers' own control over their fuel economy, which may align better with conservative ideology.

This study also tested fourteen hypotheses, grounded in behavioral theory and past empirical research, about the characteristics and contexts that make eco-driving feedback more effective. Only one hypothesized relationship emerged as statistically significant at the alpha = .10 level; this was the negative relationship between length of intervention (i.e., number of days drivers were exposed to feedback) and effect size. On average, the effect of feedback decreased as length of intervention increased, suggesting eco-driving feedback programs and technologies should not count on persistent savings and should assess program costs accordingly.

Given that eco-driving feedback outcomes are generally better in the short-term, it is crucial to understand how feedback design can maximize and prolong effects. Likely due to small sample sizes, feedback design variables did not emerge as statistically significant moderators of effectiveness. However, trends in these variables aligned with study hypotheses, suggesting feedback should: (a) be provided in multiple modalities (e.g., visual and haptic or auditory rather than visual only); (b) include both fine- and course-grained information; (c) provide feedback standards against which to compare performance; (d) integrate gameful design elements (e.g., points, levels, badges); and (e) be combined with other interventions, such as education and rewards contingent on performance. More experiments that compare the impact of different feedback designs are needed in order to identify the most promising designs, which can then be promoted to manufacturers and inform potential future standardization of fuel economy and related displays.

# Introduction

Driver behavior has an immense impact on vehicle fuel economy and emissions. Sivak and Schoettle (*1*) 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 (*2*), 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, 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, has renewed interest in what is now termed eco-driving.

This paper defines eco-driving as anything a driver can do, given a particular vehicle, to increase fuel economy or otherwise decrease carbon intensity. As part of a prior NCST project (*3*), this author developed a comprehensive and precise typology of the behaviors that constitute eco-driving (Figure 1; adapted from *4*). These suites of driver behavior have been highlighted as a significant opportunity to support goals for carbon dioxide emissions reductions in the transportation sector (*1, 5*).

Educating drivers about eco-driving practices is one important promotional strategy. In-vehicle coaching or training drivers on eco-driving methods can also be effective (*6-10*). Regulation can be used to enforce eco-driving practices, such as speed limits and restrictions on vehicle idling (*11-14*). The most common strategy used to promote eco-driving is providing drivers with feedback concerning the efficiency of their driving 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 (HEVs), plug-in hybrid (PHEVs) and electric vehicles (EVs). One reason for this differential attention is that fuel economy in efficient vehicles is actually more sensitive to driver behavior. Manufacturers have deployed many different designs, reflecting various driver behaviors and vehicle states. This wide variation could indicate a belief in competitive advantage or a lack of evidence-based design and consistent assumptions about human behavior. The rapidly increasing prevalence and complexity of in-vehicle displays and concern for driver distraction (*15*) suggest standardization of eco-driving feedback may be warranted in the near future. To inform such standardization, better understanding of the types of eco-driving feedback that are most effective is needed.

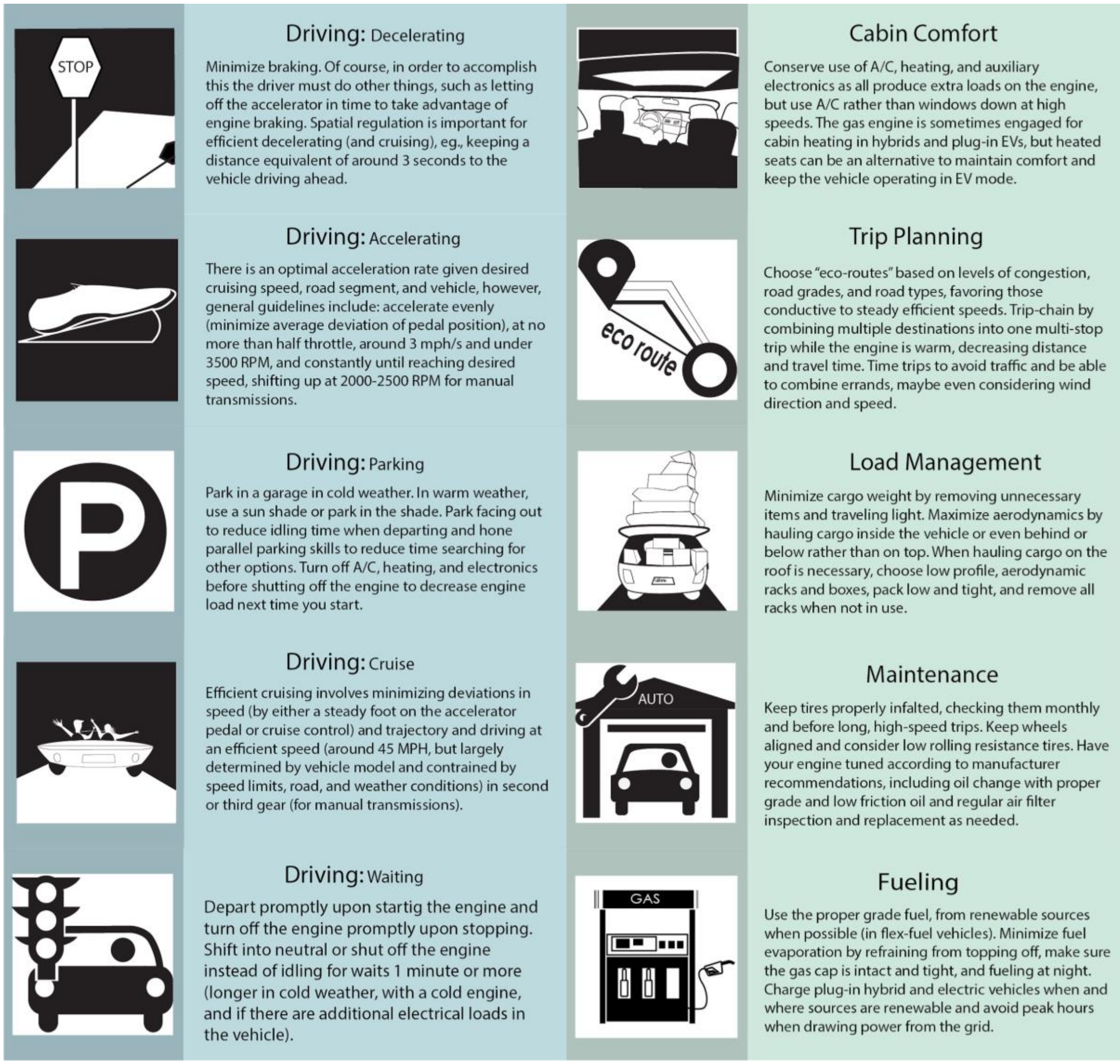


**Figure 1. Types of eco-driving. See Sanguinetti, Kurani, & Davies (*4*) for a full discussion of types of eco-driving.**

Available literature generally suggests that feedback can be effective in supporting eco-driving. The most comprehensive review of eco-driving feedback studies to-date was part of the author's prior NCST project (*3*), which calculated an (unweighted) average fuel savings of 5.6%. However, results of eco-driving feedback interventions are widely variable--from no fuel savings to over 50% (*16*). This inconsistency is likely due to variation among studies in terms of feedback design, sample, setting, and length of intervention. The goal of this project was to systematically analyze eco-driving feedback studies, via a statistical meta-analysis, in order to more precisely estimate the average effect of onboard feedback in promoting eco-driving and identify key moderating variables that explain the wide range of effects.

## Background: What Makes Eco-driving Feedback Effective?

Past research has shed some light on characteristics of onboard feedback that determine, or moderate, its effectiveness in promoting eco-driving. These characteristics fall into the following categories: feedback design, driver characteristics, and road characteristics. The next sections review this literature, which informs the hypotheses tested in this meta-analysis.

### Feedback Design

Another product of our previous NCST project was an analysis of eco-driving feedback design dimensions that could have implications for its effectiveness in modifying driver behavior (*17*). We later broadened this analysis to develop a general framework for effective eco-feedback design (*18*; Figure 2).

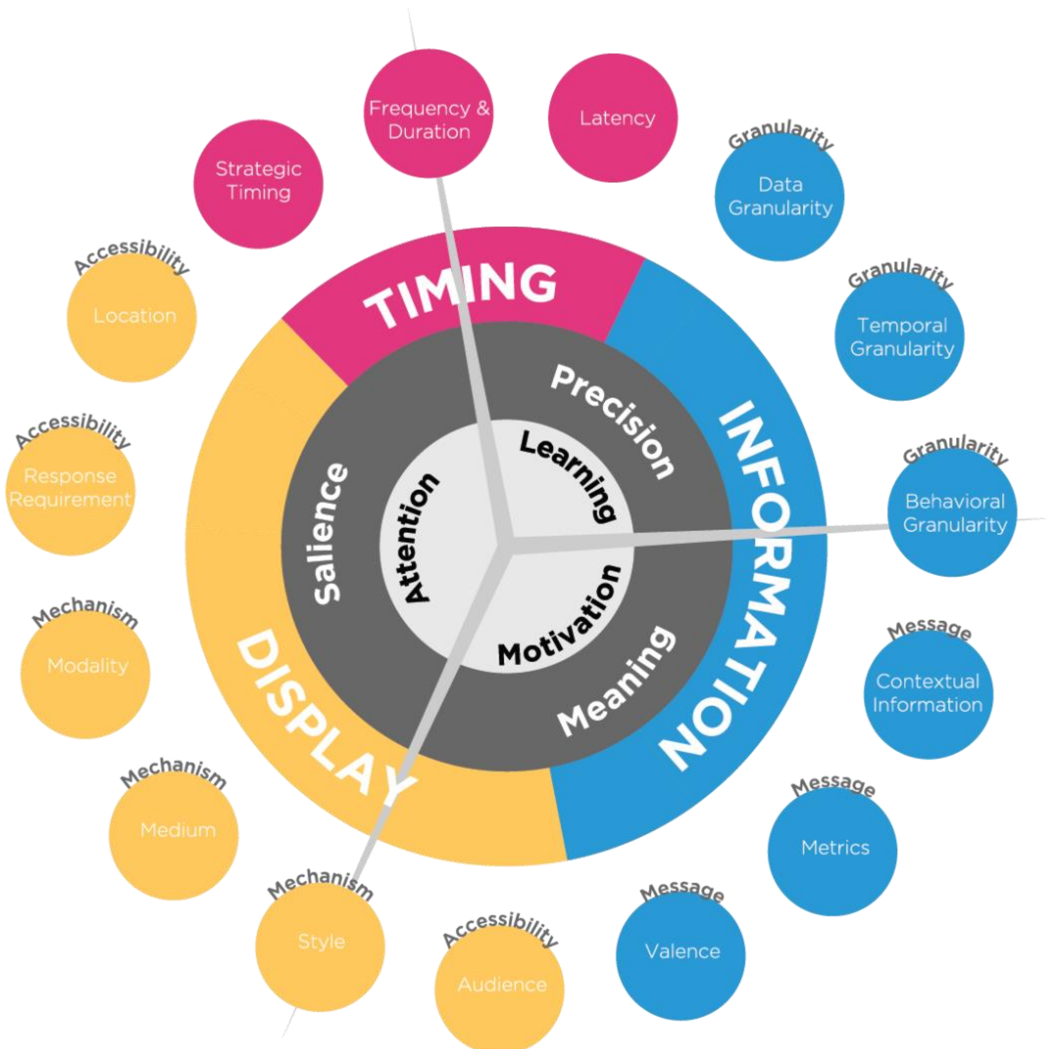


**Figure 2. Eco-feedback design-behavior framework**

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. Our framework categorized three types of eco-feedback design dimensions that have implications for user behavior change; they are: information, timing, and display. Each dimension has implications for at least one of three feedback qualities: salience, precision, and meaning, which in turn relate to behavior change mechanisms attention, learning, and motivation, respectively.

This framework is based on behavioral theory and empirical research across various applications of eco-feedback, including eco-driving feedback. Some researchers have put forth feedback design guidelines specific to eco-driving feedback (*19*). However, there is limited empirical research comparing different eco-driving feedback designs in terms of objective outcomes such as fuel economy, vehicle emissions, or specific eco-driving behaviors. The following sections review this research within our framework of behavior-relevant design dimensions: information, display, and timing. The reader should refer to Sanguinetti et al. (*18*) for a more thorough discussion of the behavioral theory and broader base of empirical research behind this framework.

### *Information*

According to our framework, the granularity and message content of information presented in eco-feedback has implications for its effectiveness (Figure 3). Granularity refers to the level of detail in the information. There are three types of granularity: behavioral, temporal, and data. 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 (*18*).

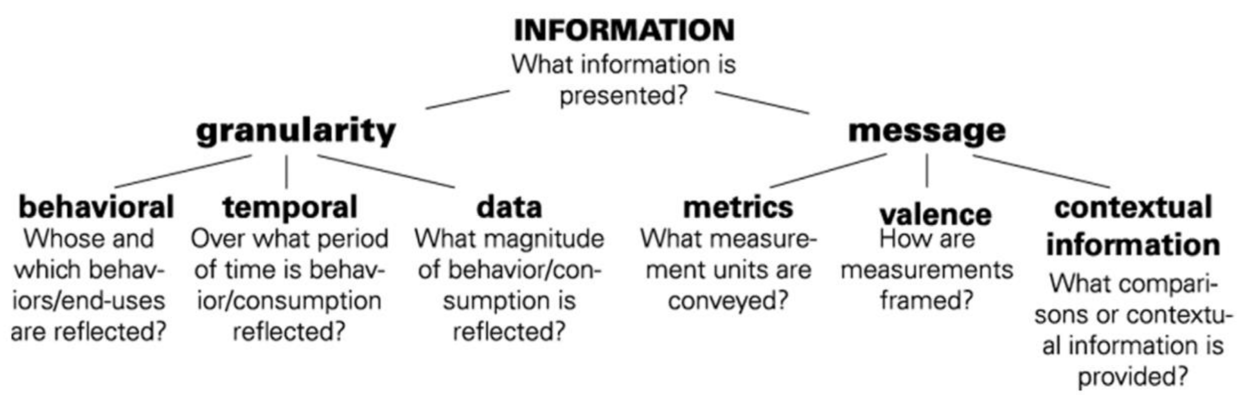


**Figure 3. Dimensions of feedback information**

Eco-driving feedback often includes an indicator of overall fuel economy, which is low ***behavioral granularity*** because it reflects anything the driver does that impacts fuel economy (i.e., all eco-driving behaviors). Examples of more granular eco-driving feedback include van der Voort (2001), who assessed how the granularity of gear-shifting feedback influences its effectiveness (e.g., “shift earlier” versus “shift earlier from 2nd to 3rd gear”). She found no significant differences 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 et al. (*20*) found that feedback specific to acceleration was more effective than fuel economy feedback, for males only. However, Manser et al. (*16*) found the reverse--that mileage feedback was more effective than acceleration feedback. Which behaviors to target is an important question for specific eco-driving feedback. Behaviors that have the largest impact on fuel economy should be prioritized, but it is also important to consider which behaviors users are likely to change.

No empirical studies were found that have investigated the impact of feedback ***temporal granularity*** (e.g., feedback about instantaneous versus accumulated performance) on fuel economy or other objective outcomes. However, several studies present theories or qualitative data on user preference and experience. van der Voort et al. (*21*) eloquently described the importance of striking a balance with temporal granularity: “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. Participants in feedback studies have reported 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 (*22-23*).

Similarly, 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, thus impacting their motivation to engage with it. There were no actual driving experiments found that compared different ***metrics*** of eco-driving feedback, such as expressing mileage feedback as fuel cost instead of MPG. However, Dogan, Bolderdijk, and Steg (*24*) conducted a survey in which they presented the monetary or carbon savings associated with various eco-driving scenarios and measured participants’ perceptions of whether it would be worthwhile to modify their behavior; carbon savings were more persuasive. The monetary amount were negligible.

Only one study was found that has assessed the impact of eco-driving feedback ***valence***, which is the way measurement units are framed (e.g., positively or negatively as in money spent or saved, or carbon emitted or spared). Rolim, Baptista, Duarte, Farias, & Pereira (*25*) provided delayed feedback (i.e., weekly email reports) on six eco-driving indicators to 40 drivers over three months and found that negative feedback (performance decline from previous week) 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 with positive feedback (i.e., performance declined after a report that indicated improvement from previous week).

***Contextual information*** includes feedback standards, or comparisons (e.g., 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 (*26*), the feedback standard is a critical element of feedback that motivates behavior change. Feedback standards are common in eco-driving feedback, but no studies were found that have compared the impact of feedback with versus without standards, or different types of standards, on eco-driving outcomes. Wada et al. (*27*), however, did demonstrate 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 (*28*).

### *Display*

Dimensions of the feedback display characterize its formal characteristics and physical situation (Figure 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 (*29-30*). Prewitt et al. (*30*) 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 (*31*).

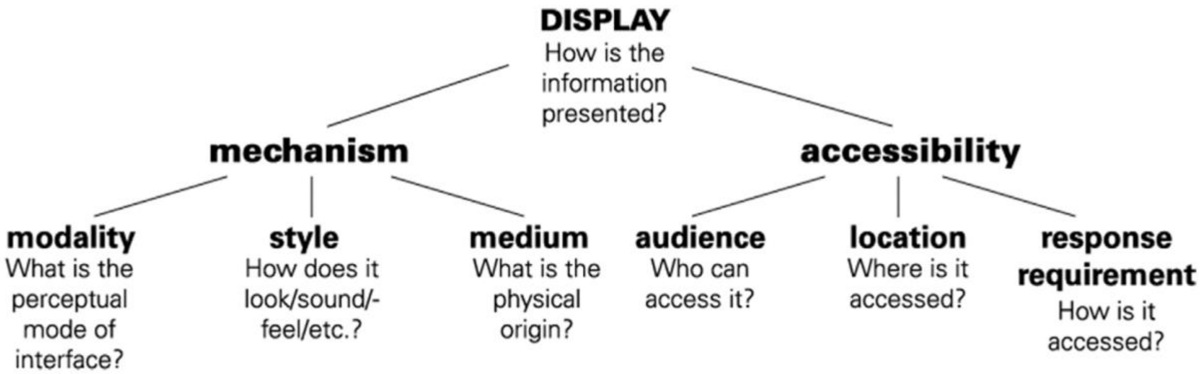


**Figure 4. Dimensions of feedback display**

Several studies have compared different ***styles*** of feedback within the same modality. Hammershmidt and Hermann (*32*) 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 Merat (*31*) and Jamson, Hibberd, and Jamson (*33*) 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 (*34*; *N* = 21) concluded that haptic stiffness pedal was more effective than haptic force because drivers in the force feedback condition exerted significantly 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 (*35*; *N* = 10) found that a vibrating seat belt was more effective than a vibrating seat for improving fuel economy.

**Table 1. Experiments comparing feedback modalities**

| Study | Modality Comparison | Outcomes Measured | Results |
|---|---|---|---|
| **Azzi (*36*; *N* = 28)** | Haptic v. Visual | Modeled total polluting emissions | No difference |
| **Hibberd, Jamson, & Jamson (*37*; *N* = 24)** | Haptic v. Visual+Auditory | Efficient decelerating, accelerating and cruising | Haptic more effective for efficient decelerating |
| **Jamson, Hibberd, & Merat (*31*; *N* = 21)** | Haptic v. Visual+Auditory | Pedal error during cruising and accelerating | Visual+Auditory more effective for efficient cruising |
| **Hammerschmidt & Hermann (*32*; *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, Stanton, Godwin, & Wood (*38*; *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. (*39*; *N* = 24)** | Haptic v. Visual v. Visual+Haptic | Efficient accelerating and shifting | Visual+Haptic more effective for efficient acceleration and gear-shift behaviour |

No studies were found that have examined the impact of feedback accessibility on eco-driving outcomes. Since we are focused on onboard feedback, ***location*** is limited to the vehicle, though 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.

### *Timing*

The finding from Hammershmidt and Hermann (*32*; *N* = 30) regarding the advantage of an intermittent guzzling sound over a continuous tone also pertains to feedback timing--particularly feedback ***frequency***. Kircher, Fors, & Ahlstrom (*40*) 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 (*41*) 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). Though technically not about feedback, some studies have considered strategic timing of advice (feedforward) about when to start decelerating for a slowing or stopping event (*39, 42*).

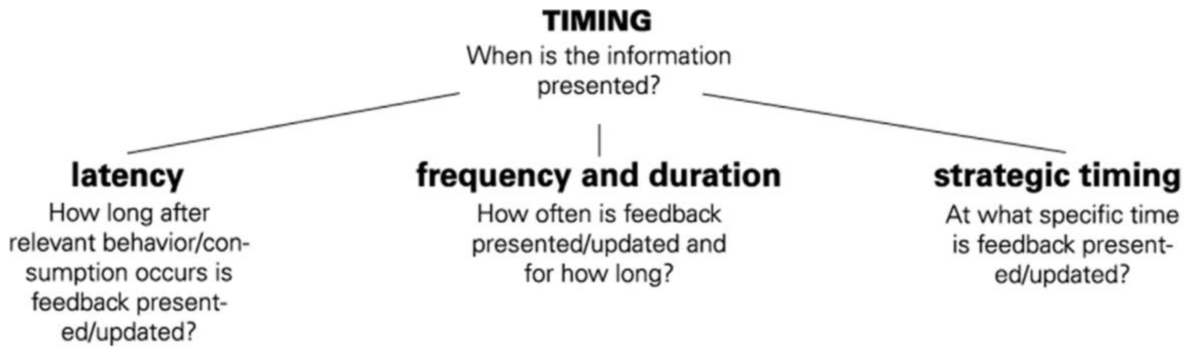


**Figure 5. Dimensions of feedback timing**

## Driver and Road Characteristics

Some studies suggest feedback is more or less effective for different types of drivers. For example, Rolim (*25*; *N* = 40) and Kurani et al. (*43*; *N* = 118) both found that feedback was more effective with female drivers. Lee (*44*; *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 (*45*; *N* = 22) suggested there might also be differences between civilian and professional drivers (e.g., of fleet vehicles). Other 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 of fuel efficiency (Table 2).

## Interaction Effects

Feedback design, driver characteristics, and road characteristics also interact to influence feedback effectiveness. For example, Kurani et al. (*43*) 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 (*46*; *N* = 8) found that visual feedback on acceleration and deceleration was more effective during acceleration conditions than deceleration conditions. Seewald et al. (*47*; *N* = 22) found that visual feedback better supported optimal pedal position, whereas haptic feedback better supported steady acceleration.

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

| Study | Road Type Comparison | Outcomes Measured | Results |
|---|---|---|---|
| **Larsson & Ericsson (*48*; *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 et al. (*49*; *N* = 20)** | City v. Highway | Fuel economy | Improved 6% on city streets, 1% on highways |
| **Varhelyi (*50*; *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. (*39*; *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, Hibberd, & Jamson (*33*; *N* = 22)** | Low v. High density traffic | Throttle pedal errors (deviation from optimal position) | Larger errors in high density traffic |

## Intervention Characteristics

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. Varhelyi (*50*) 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 simulator, 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 (*36, 50*), and rewards (*52*) is more effective than onboard feedback alone. Studies of home energy feedback have also found that effects can dwindle over time and feedback is more effective in combination with other interventions (*53*).

## Present Research: Meta-analysis of Eco-driving Feedback Studies

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 (*3*), 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 or different contexts are relatively sparse and inconsistent in terms of various study parameters (e.g., different settings, populations, feedback designs, and outcome measures). Thus, the second aim of this meta-analysis was to conduct moderator analyses to better understand the characteristics of feedback that influence its effectiveness and populations and settings that might be especially receptive and conducive.

### Hypotheses

Based on the literature reviewed above, the following hypotheses were formulated regarding feedback information dimensions:

> **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 aggregate feedback or only behavior-specific feedback.
>
> **H2.** Feedback that targets more specific eco-driving behaviors is more effective than feedback that targets fewer specific eco-driving behaviors.
>
> **H3.** Feedback that includes information of both low and high temporal granularity (i.e., accumulated and instantaneous) is more effective than feedback with only accumulated feedback or only instantaneous feedback.
>
> **H4.** Feedback that includes information of both low and high data granularity (i.e., discrete and continuous) is more effective than feedback with only discrete feedback or only continuous feedback.
>
> **H5.** Feedback that includes a feedback standard is more effective than feedback without.
>
> **H6.** Feedback with elements of gameful design (scores, badges, levels) is more effective than non-gamified feedback.

Hypotheses regarding feedback display dimensions are as follows:

> **H7.** Haptic feedback is more effective than visual feedback.
>
> **H8.** Auditory feedback is more effective than visual feedback.
>
> **H9.** Multiple modality feedback is more effective than single modality 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). The literature also raises many other questions without suggesting clear hypotheses (e.g., differences between professional and civilian drivers). These were also explored to the extent possible. 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.

## Methodology

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 truth than the effect 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.

### *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. 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". Searches were not restricted by publication year, type, or any other factor.

Papers found in these searches were filtered based on the following inclusion criteria:

- The main intervention component (independent variable) was onboard technological feedback.
- Interventions that included instructions to drive efficiently were included because quite a few studies did this so we did not want to exclude them and lose the other information.
- Interventions that included monetary rewards based on efficiency of driving behaviors were included because saving money is a realistic outcome of eco-driving, so small

monetary earnings is representative of the naturalistic eco-driving feedback experience. The presence of these additional intervention components (instructions or rewards) was included in moderator analyses.

- Feedback delivered information about fuel economy, fuel consumption, emissions, or specific eco-driving "driving" behaviors, as defined in Sanguinetti, Kurani, and Davies (*4*; Figure 1).
- Outcome measures included an objective indicatory of eco-driving, including fuel economy, emissions, or specific eco-driving "driving" behaviors.
- The study involved human research participants, not modeling exercises or field tests performed by the researchers themselves.
- The study had an experimental design, including either a control group (between-groups design), a  baseline condition (within-subjects design), or both (mixed design).
- We included studies that used vehicle simulators, as well as actual vehicles.
- Study samples included private and commercial passenger vehicles, trucks, and buses.

Exclusion criteria were as follows:

- Feedback was provided exclusively outside the vehicle or by non-technological means (delivered on paper or in person).
- Feedback was conflated with other major intervention components, such as training, in-vehicle coaching, or employer reward/punishment systems for professional drivers.
- Outcome measures (dependent variables) were usability, preference, or safety and did not include an objective measure of eco-driving.
- The study only provided preliminary findings and/or lacked basic details about study methodology (e.g., sample size).
- 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).

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 (*3*, *54-57*). These searches resulted in an additional 18 studies.

### *Data preparation and analysis*

After an initial pool of relevant studies were collected, the next step was to prepare the data for the meta-analysis. This process includes 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 adapted codes based on what was feasible for moderator analyses given the final sample used in the meta-analysis. Specifically, multiple levels of a variable were sometimes combined when sample sizes were too small in a given level to detect differences between levels. The author decided to set a criterion that each level of a variable should be represented by at least four different studies; otherwise, levels were combined or, in cases where that would leave no variation, moderator analyses were not performed.

The lead researcher and a research assistant calculated effect sizes for the studies. 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 meta-analysis was conducted using the metasem package for R statistical software. A random effects model was used, which assumes the effect may vary based on different parameters of the intervention (as opposed to a single true underlying effect). This package requires an effect size and its variance for each study. 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 author. If the author was not responsive or could not supply the 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; $n = 5$) in order to retain this information in the moderator analyses. This increased the sample size to 25 cases. A three-level meta-analysis was used to account for dependence of multiple effect sizes from a single study (this is what the metasem package enables).

Two outliers in effect size (41% and 53%), both in Manser et al. (*16*), 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 (58), but the intervention and the sample were different.

## Results

The main effect of onboard feedback on fuel economy across all 17 studies and 23 effect sizes was 6.6% improvement (with 95% confidence that the true population effect would fall between 4.9% and 8.3%). This is a statistically significant effect ($p < .001$). The unweighted mean effect was 8.2%; thus, the meta-analysis yielded a more conservative estimate.

Figure 6 is a forest plot for the studies included in the meta-analysis, which displays the relative change (e.g. 0.04 = 4% improvement in fuel economy) and its 95% confidence interval, as well as a 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.

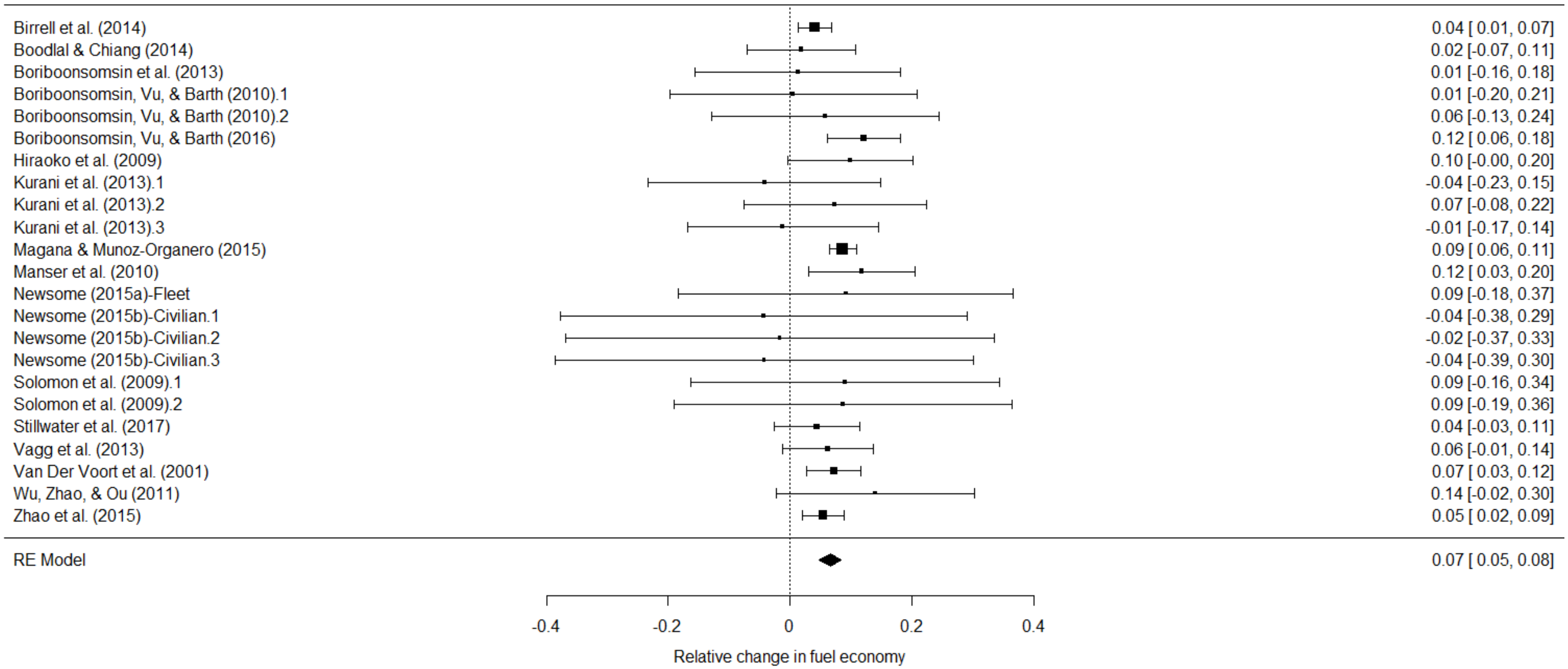


**Figure 6. Forest plot of individual study and summary effect sizes and confidence intervals**

## *Moderator analyses*

The final sample of studies allowed moderator analyses to test most of our hypotheses, with each level of a given variable represented by at least four different studies (and at least four individual effect sizes). Exceptions were **H4**, **H8**, **H9**, and **H13**. Regarding **H4**, many studies had insufficient information about feedback data granularity of the feedback interface. The sample only allowed one comparison of feedback modalities: Visual compared to Visual+Auditory, enabling a test of **H10**, but not **H8** or **H9**. Finally, regarding **H13**, there were insufficient studies with effect sizes for exclusively urban or rural roads to enable comparison**.**

Moderator analysis coding and results are presented in Table 3. All relationships between moderators and effect size were in the predicted direction with the exception of number of specific behaviors targeted by feedback.

**Table 3. Coding and moderator analysis**

| Variable | Levels | *n* studies | *n* effects | Mean R* or correlation | Beta | *p* |
|---|---|---|---|---|---|---|
| **Behavioral granularity** | Aggregate & specific$^{(+)}$ | 9 | 10 | 6% | 0.013 | 0.527 |
| | Aggregate or specific | 10 | 13 | 4% | | |
| **Behaviors targeted** | # driving behaviors targeted$^{(+)}$ | 17 | 23 | -0.1 | -0.004 | 0.598 |
| **Temporal granularity** | Instantaneous & accumulated$^{(+)}$ | 14 | 18 | 6% | 0.037 | 1 |
| | Instantaneous or accumulated | 4 | 5 | 1% | | |
| **Feedback standard** | Yes$^{(+)}$ | 12 | 13 | 7% | 0.013 | 0.615 |
| | No | 4 | 8 | 1% | | |
| **Gamification** | Yes$^{(+)}$ | 7 | 9 | 6% | 0.03 | 1 |
| | No | 11 | 14 | 4% | | |
| **Modality** | Visual+Auditory$^{(+)}$ | 5 | 5 | 7% | 0.007 | 0.686 |
| | Visual | 12 | 18 | 4% | | |
| **Driver** | Civilian (private vehicles) | 13 | 18 | 4% | -0.014 | 0.583 |
| | Professional (fleet vehicles)$^{(+)}$ | 4 | 4 | 7% | | |
| **Age** | Mean age in years$^{(-)}$ | 17 | 23 | -0.1 | -0.001 | 0.686 |
| **Setting** | Field | 11 | 17 | 3% | -0.027 | 0.191 |
| | Simulator$^{(+)}$ | 6 | 6 | 10% | | |
| **Length** | # of days with feedback$^{(-)}$ | 17 | 23 | -0.7 | -0.001 | 0.051 |
| **Combined intervention** | Feedback plus$^{(+)}$ | 8 | 10 | 8% | 0.03 | 1 |
| | Feedback only | 9 | 13 | 2% | | |
| **Publication type** | Journal | 7 | 7 | 7% | -0.009 | 0.643 |
| | Other$^{(+)}$ | 10 | 16 | 4% | | |

$^{(+)}$Hypothesized to be positively related to impact of feedback on eco-driving
$^{(-)}$Hypothesized to be negatively related to impact of feedback on eco-driving

Feedback was more effective when it included multiple modalities, information with both low and high behavioral and temporal granularity, a feedback standard, and gamification, and when it was combined with instructions to drive efficiently or monetary rewards contingent on performance. Feedback was more effective with professional drivers and younger drivers (slightly). Simulator studies and short studies showed greater impacts than field studies and longer studies. However, only one of these hypothesized relationships emerged as statistically significant at the alpha = .10 level; this was the negative relationship between length of intervention (i.e., number of days drivers were exposed to feedback) and effect size. Figure 4 shows that over half the variation in effect size can be explained by study length.

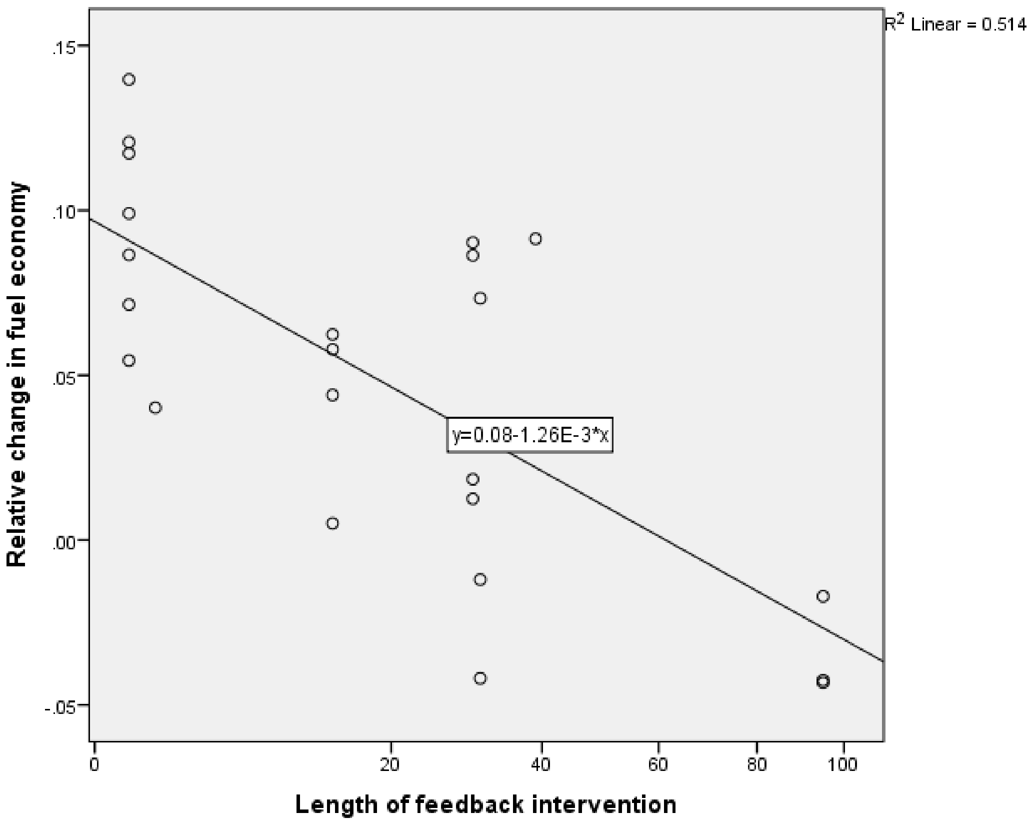


**Figure 7. Relative change in fuel economy as a function of length of feedback intervention**

## Discussion: Practical Implications and Future Research Agenda

Onboard eco-driving feedback interventions can be expected to result in an average of 6.6% improvement in fuel economy. The average fuel economy without feedback (i.e., in baseline phases or control groups) in the studies assessed was about 25 MPG. A 6.6% improvement from this baseline would be equivalent to a 1.7 MPG improvement.

The rate at which Corporate Average Fuel Economy (CAFE) standards are progressing may slow considerably under the Trump administration. Eco-driving feedback is a strategy that enhances consumers' own control over their fuel economy, which may align better with conservative ideology.

Though feedback had a statistically significant positive impact on fuel economy overall, the impacts are significantly reduced over time. This has serious implications for eco-driving feedback programs and technologies. For example, such programs should not count on persistent savings and should assess program costs accordingly.

Study setting (field or vehicle simulator) was not a significant moderator, likely due to the small sample size overall and relatively small sample of effect sizes from simulator studies ($n = 6$). However, effect sizes from simulator studies were much larger on average (10%) compared to field studies (3%). Given that the real-world impacts of eco-driving feedback only occur "in the field", this discrepancy is important to note. Simulator studies are typically a single session (counted in the meta-analysis as 1 day), therefore it is difficult to know how well simulator studies compare to field studies (i.e., since setting is confounded with study length, which we know has an impact).

Given these findings, it is crucial to understand how feedback design can maximize and prolong positive eco-driving outcomes. Likely due to the small sample size of studies available and ultimately usable in this meta-analysis, as well as the small sample sizes of participants within the studies, feedback design variables did not emerge as statistically significant in the moderator analyses. However, simple comparisons of level means within each moderator showed trends aligning with study hypotheses that were rooted in behavioral theory and eco-feedback research in the context of eco-driving as well as other domains.

For example, the meta-analysis and previous research suggest visual eco-driving feedback may be less effective than haptic, auditory or combined feedback modalities. This is particularly interesting considering very few manufacturers have included anything other than visual eco-driving feedback in their vehicles. The Eco (haptic) Pedal by Infiniti/Nissan is one exception. Findings also suggest eco-driving feedback should include both low and high behavioral and temporal granularity information, feedback standards against which to compare one's performance, and gameful design elements (e.g., points, levels, leaderboards, badges). When possible, feedback should be combined with other strategies, such as education and rewards contingent on performance.

The recurring finding that eco-driving feedback is more effective with younger drivers, including limited support from the meta-analysis, suggests that eco-driving programs should target new drivers. For example, the principles of eco-driving should be integrated into driver's education in high schools, vehicles used for driver's training, and the Department of Motor Vehicles driver's license exam. Though more research is needed, the meta-analysis also suggests feedback may be more effective among professional drivers, which points to the potential impact of promoting eco-driving to public and private organizations that have vehicle fleets. This should extend to ride-hailing companies like Uber and Lyft, whose drivers might be particularly motivated to engage in eco-driving. Fleet operators are driver trainers are uniquely positioned to combine feedback with educational and incentive programs.

More experiments that compare the impact of different feedback designs are needed in order to identify the most promising designs, which can then be promoted to manufacturers and inform potential future standardization of fuel economy and related displays. Future studies should also include relative change in fuel economy as an outcome measure, since it is a socially valid and relatable metric, and because it is most readily compared across existing studies. Behavioral outcomes, such as pedal error, are more sensitive measures of eco-driving than fuel economy (which also depends on the vehicle, road type, and weather conditions), but they are inconsistently operationalized across studies. Going forward, researchers should adopt standard measurements for eco-driving behaviors that can be compared across studies. Finally, this meta-analysis should be replicated with a larger sample size as more studies become available, enabling greater statistical power for moderator analyses to continue to improve our understanding of the characteristics and contexts of effective eco-driving feedback.

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