Nudging Eco-Driving Behaviour Using Motive Substitution

by

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Abstract

The behaviour change technique of motive substitution may be a more effective method of motivating drivers to adopt an energy efficient driving style than existing strategies. Previous research has tested dashboard displays that inform, score, and advise drivers, but do little to overcome attitudinal barriers, intention-action gaps, and apathy. An animated sloshing coffee-cup display applies motive substitution by providing an alternate gameful experience that is intuitive, engaging, and congruous with the goal of low-acceleration driving. This intervention incorporates principles from cognitive and social psychology, human factors engineering, and behavioural economics to influence driver behaviour while managing distraction risks. The intuitive elements of the display were tested in an online survey with drivers reporting a significant preference for the coffee-cup display over an acceleration dial gauge. A driving simulator study was developed to test the behavioural impacts of a functional prototype using measures of acceleration, fuel consumption, and eye glance durations.

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Introduction

The research discussed in the following chapters brings together concepts from psychology, human factors engineering, and behavioural economics to develop a behaviour change intervention for energy efficient driving. This work builds on the recent research by Srivastava (2016) and Shu et. al. (2017) into Design for Behaviour Change methods while focusing on a specific case study. My objective was to fully design and test a practical and illustrative example of a behaviour changing design targeting a high-impact environmental problem. In exploring the existing literature on behaviour change and eco-driving, I identified some poorly defined and unexplored directions of research. Consequently, I propose a definition of motive substitution as a design for behaviour change technique where an alternate task is created to offer users a new motive for performing a previously unmotivating behaviour. I explore a motive substitution for eco-driving in the form of a dashboard display depicting an animated coffee cup that sloshes in response to longitudinal vehicle movements. I developed two studies to test the theoretical framework, effectiveness, and distraction risk of the coffee-cup display. The final experiment could not be completed due to the COVID-19 pandemic, but details are provided to facilitate continuation of this study by others. This research was highly iterative and is presented in a sequence that aims to be conceptually incremental rather than chronological.

Chapter 1. An outline of the motivation for this research and introductions to the fundamental concepts this work is built upon. Brief summaries of the relevant literature on pro-environmental behaviour, design for behaviour change, eco-driving, and driving safety, revealing an opportunity to pursue a unique approach.

Chapter 2. A proposed definition of motive substitution as a design for behaviour change technique and its implementation in an eco-driving intervention. Analysis of the resulting coffee-cup display from multidisciplinary perspectives.

Chapter 3. The development and analysis of Study 1, an online survey study investigating drivers' perceived effectiveness of the coffee-cup display compared to alternate displays that control for interface intuitiveness.

Chapter 4. The development and proof-of-method of Study 2, a driving simulator study to measure the behavioural impacts of the coffee-cup display prototype compared to alternate displays that control for interface intuitiveness and engagement.

Chapter 1

Brief Summary of the Literature on Designing for Pro-Environmental Behaviour and Eco-Driving

1.1 Motivation

Ecosystem degradation, resource depletion, and climate change are among the most complex and existential world problems facing the coming generations. This is by no means a new realization, as evidenced by such publications as “Silent Spring” (Carson, 1962) and “The Closing Circle” (Commoner, 1971), two books that highlighted environmental concerns with an urgency comparable to what we see today. Yet while the extent of collective research into matters of ecological sustainability is now monumental, large-scale change has been mired by neglected pleas and boutique solutions. Three main strategies are typically employed in the attempts to curb harmful practices:

- technological innovation to develop less-harmful alternatives and improve efficiency,
- legislation to steer organizations and people through incentives and enforcement, and
- information campaigns to encourage people to self-regulate their behaviour and support the technology and legislation changes.

Each of these efforts is vital but insufficient as they rely on many people to voluntarily behave counter to short-term self interest. Good intentions, where found, are easily undermined. One frequently mentioned example is the rebound effect (Herring, 2006). As technological advances improve consumption efficiency whether in the form of energy, material resources, or labour, the associated costs are also reduced. This increased affordability often results in increased usage that substantially counteracts the efficiency gains.

There is an immediate need for effective low-barrier initiatives, easy and cheap to implement and politically uncontroversial, even if they are only partial solutions. Thus, in my research I sought to generate a practical and illustrative example of applying behavioural theory in an engineering design solution for influencing the consumer class to adopt a meaningful waste-reducing habit. I chose to focus on addressing environmentally harmful behaviours of the global consumer class because this subset of the population generally has the following four distinguishing characteristics: the means to behave wastefully, the numbers for that waste to have major environmental impacts, isolation from first-hand experience of those impacts, and the luxury to form new lifestyle habits. A principal goal is plausible ubiquity, meaning a worthwhile proportion of the relevant population can reasonably be expected to adopt the proposed solution and be reliably influenced in the desired manner.

1.2 Designing for Pro-Environmental Behaviour

At the level of individual behaviours, Steg and Vlek describe pro-environmental interventions as either informational or structural strategies (2009). Informational strategies aim to change perceptions, motivations, and knowledge, whereas structural strategies aim to change external factors such as policy and technology. Structural strategies typically have high barriers to implementation. For policy changes, these often include political and corporate resistance. Technology developments often demand high infrastructure costs and receive low market buy-in, such that business decisions can impede eco-conscious design (Ramani et. al., 2010). Even in best-case-scenarios, structural changes tend to have very long timelines.

Informational strategies are far easier to implement but generally lead to increased knowledge without corresponding behavioral changes and have repeatedly failed to elicit action at the required scale (Abrahamse et. al., 2005; Shu et. al., 2017). Strategies that purely inform or educate the public face several critical limitations, such as a tendency to underestimate social norms and habitual behaviour (Jackson, 2005). Even for people who are receptive to pro-environmental messaging and eager to be energy efficient, there are a variety of barriers that interrupt the translation into meaningful actions (Kollmuss & Agyeman 2002). This is often called an intention-action gap, where a belief or attitude does not lead to corresponding behaviors. For example, social-desirability bias can lead to statements of good intention that are later sidelined to avoid compromises that frequently accompany pro-environmental behaviors. Various strategies aim to overcome this gap, but risk worsening adoption in people with neutral-to-averse attitudes toward environmental efforts (Goucher-Lambert & Cagan, 2015; She & MacDonald, 2018). Those people, with perhaps the most potential for improvement, may dismiss or respond negatively to interventions communicated as pro-environmental due to existing attitudes and beliefs.

Outside this informational-structural dichotomy, other strategies exist. These include strategies that aim to influence behavior by adjusting incentive structures, employing cognitive biases, or eliciting emotional responses (Bao et. al., 2018). Such strategies are relatively underutilized for encouraging pro-environmental behavior and offer another opportunity for progress.

Overall, pro-environmental behaviour interventions that affect the antecedents of behaviour are less effective than those that affect consequences (Flemming et. al., 2008). Antecedent strategies aim to modify the determinants of behaviour such as attitudes and knowledge, whereas consequence strategies aim to incentivize behaviour through feedback. Flemming et. al. found consequence strategies to elicit pro-environmental behaviours more effectively, but note that feedback design is rarely approached systematically, calling for greater application of human factors expertise to sustainability problems.

Designers might apply the same psychological principles that have been exploited by commercial interests to drive mass consumption, to instead drive sustainable behaviours on a similar scale (Shu et. al., 2017). Essentially all product and system design elements affect user behaviour and these considerations are often neglected by the designers and engineers who developed them. These designers consequently have, as Shu et al. describe it, a “disproportionate opportunity, and thus responsibility, to properly design and realize products and systems to most effectively minimize resource consumption”. The past few decades have seen considerable development of design methods that draw from behaviour theories to help designers modify user behaviour (Srivastava, 2016).

1.2.1 Dual-Process and Nudge Theories

Several dual-process theories model cognitive processing as a dichotomy between deliberative thinking and reflexive thinking (Chaiken, 1980; Evans, 1984; Kahneman, 2003; Stanovich & West, 2000). Broadly speaking, cognitive operations are predominantly governed by one of these two processing systems. Reflexive processing is largely subconscious and relies on decision-making heuristics. In contrast, deliberative processing is conscious and used with awareness when, for example, carefully considering an opinion, choice, or problem. Dual-process theories generally recognize that people are not perfectly rational actors and help explain why people consistently make suboptimal decisions in certain situations.

Informational strategies for behaviour change provide stimuli for the deliberative process in the hopes that new information will tip the balance toward a different decision. However, pro-environmental behaviors are often tangential or auxiliary behaviours that occur when deliberative processing is occupied with other goals. Thus, they are often controlled by the reflexive system and informational interventions are not given the opportunity to affect these behaviors. In such cases, interventions that influence reflexive decisions can be more effective.

Thaler and Sunstein, popularised the term “nudge” as a modification to the user’s environment that alters the user’s behavior in a predictable way without forbidding any options (2008). This is usually accomplished by targeting reflexive processing through the manipulation of factors such as framing and salience in the choice architecture. Nudging is a core concept in applied behavioural economics and has become commonplace in the business and marketing worlds as a technique for influencing user behaviour.

1.2.2 Design for Behaviour Change

Design for Behaviour Change (DfBC) is an interdisciplinary design approach applying theories from psychology to develop solutions that influence user behaviour, generally without direct incentives, persuasion, or deception. DfBC can be considered largely equivalent to the concept of nudging, with both sometimes listed under the umbrella of the other. Their distinctions are mostly a consequence of emerging from different disciplines, economics and engineering. DfBC methods have received growing recognition as a means for encouraging pro-environmental behaviour (Lehner, 2016; Niedderer et. al., 2016; Srivastava, 2016), in such cases often referred to as Design for Sustainable Behaviour (DfSB) (Wilson et. al., 2015). The terminology for DfBC and DfSB follows the “Design for X” philosophy introduced by Gatenby and Foo (1990) which isolates individual goals on which to focus during the design process (e.g. manufacture, assembly, safety, reliability). Neither DfBC nor DfSB typically appear among the standard Design for X items considered during product development, but engineers could benefit from including them.

Of course, there are important ethical considerations around the development of products and systems that aim to influence behaviour so as not to compromise quality of life, individual freedoms, and democratic rights (Pettersen & Boks, 2008). Srivastava notes that ethical criteria in design are largely unenforceable and proposes the use of checklists to aid designers in creating ethical behaviour changing solutions.

Previous work from this research lab has investigated DfBC methods extensively, conducting a thorough review of the existing literature and developing an ontology for designers (Srivastava, 2016; Shu et. al., 2017). The current work is guided by that foundation but recognizes a need for specific examples and case studies to demonstrate evidence of measurable benefits to the environment and facilitate adoption in industry (Niedderer et. al., 2016; Tang, 2010). Building from work on interventions to reduce unnecessary vehicle idling (Paniccia & Shu, 2018), I chose to expand the scope and consider behavioural solutions to vehicle energy consumption and emissions more broadly.

1.3 Eco-Driving

Household and individual energy use accounts for 32–41% of total CO_2 emissions, and personal vehicles are the largest single contributor (Barkenbus, 2010). In the United States, light-duty vehicles are responsible for 16.5% of CO_2 emissions nationwide (EPA, 2018). Recent vehicle technology developments, most notably hybrid and electric vehicles, have reduced or eliminated tailpipe emissions; however, even fully electric vehicles often generate substantial emissions at a system level. In addition, these new technologies are generally slow to reach and spread in the market due to very large infrastructure costs, slow vehicle turnover rate, and substantial resistance from the energy industry.

Eco-driving refers to practices undertaken by drivers to reduce vehicle energy use, such as reducing acceleration intensity and avoiding high speeds. Cumulatively, these practices represent significant value for resource conservation and climate-change reduction. Eco-driving is equally important for electric and hybrid vehicles which tend to have a greater convenience penalty for inefficient energy use due to limited range and long charging times (Kato, 2016; Galvin, 2017).

1.3.1 Eco-Driving Techniques

Eco-driving techniques can be classified into three categories of decisions (Sivak & Schoettle, 2012):

- Strategic decisions (e.g. vehicle selection and maintenance)

- Tactical decisions (e.g. route selection and load management)
- Operational decisions (e.g. speed, driving style, and idling)

Between strategic and tactical decisions, the most significant energy conservation comes from vehicle selection and route selection to avoid traffic and hills. However, these decisions are not consistently within a driver's control. Geographical location and reason-for-travel will dramatically constrain a driver's options for implementing strategic and tactical techniques. The majority of research into eco-driving focuses on operational techniques, seeking to understand the optimal set of on-road driving behaviours, how to encourage their use among drivers, and the potential impacts. I will similarly focus on operational techniques in this research.

Reviews of the eco-driving literature have found that operational techniques can result in anywhere from a 0–35% reduction in fuel use or CO_2 emissions in practice, with most studies reporting reductions of 5–10% (Dahlinger & Wortmann, 2016; Huang, 2018; Michelle, 2010). The field lacks a systematic approach to testing with the eco-driving techniques employed and study methods varying widely, some based on driver training and others on feedback (Rakotonirainy et. al., 2011). The most consistently recommended operational eco-driving techniques are as follows (Barkenbus, 2010; ECOWILL, 2013; Ericsson, 2001; Gonder et. al., 2012; Huang et. al., 2018; Michelle, 2010):

1. Accelerate and decelerate smoothly, coasting when possible
2. Avoid high speeds exceeding posted limits
3. Maintain steady speeds and make fewer stops
4. Maintain low engine revolutions per minute (rpm)
    a. On automatic transmissions by avoiding heavy use of the throttle
    b. On manual transmissions by selecting higher gears
5. Minimize idling
6. Minimize auxiliary power demands such as air conditioning

Techniques 1 and 3 relate to reduced acceleration (both positive and negative changes in velocity) which is regularly cited as the most impactful eco-driving practice overall (Huang et. al., 2018; Sivak & Schoettle, 2012). Techniques 2, 5, and 6 describe operations distinct from vehicle acceleration; however, all involve additional contextual complexity such as speed limits and safety for driving speed and weather conditions and auxiliary devices and idling. Technique 4 only pertains to internal combustion engine vehicles and is also directly related to acceleration for automatic transmissions, which are quickly becoming the norm. Techniques 1-3 and 6 are equally relevant for electric vehicles as for internal combustion engine vehicles. Notably, many of the more sophisticated driving efficiency displays are found in hybrid and electric vehicles due to limitations in range and recharging time.

One path researchers have taken is to model optimal driving behaviour, often using information a driver wouldn't have easy access to, or to a degree of computational precision that can't be expected of a human driver in the real-world (e.g. Levermore et. al., 2016; Malikopoulos & Aguilar, 2012). These models can then be used to either provide real-time advice to the driver or automate aspects of the driving task such as through cruise control, automatic transmission, and automated driving. Modern vehicles will undoubtedly move in this direction as automated driving technology develops, but as noted earlier, technological advances of this nature have a long timeline. In the meantime, there are opportunities to reduce energy use even with drivers following simplified eco-driving patterns.

There is still some disagreement regarding eco-driving behaviour recommendations. This is highlighted in two Japanese studies that compared so called "Japanese eco-driving" and "German eco-driving" which each give conflicting advice (Hiraoka, 2009; Matsumoto, 2014). "Japanese eco-driving" resembles the acceleration recommendations listed above, focusing on minimizing acceleration intensity and heavy use of the throttle. "German eco-driving" focuses on reaching the engine's optimal speed quickly and spending a greater proportion of driving time in the most efficient range. In other words, acceleration should not be excessive nor too gentle, but brisk until the vehicle's optimal speed or the posted limit is reached (Sureth et. al., 2019). This is based on the fact that internal combustion engines generate the most power per unit fuel at high torque and moderate engine speeds (see Section 4.3.3). While initially the two techniques appear to be mutually exclusive, they may simply represent different degrees of advice granularity. The comparison study results found evidence supporting each technique over the other, most likely because human drivers cannot accurately replicate optimal behaviour in diverse scenarios. Thus, neither technique is likely to be performed quite as described. Eco-driving as a behavioural exercise (as opposed to an automated algorithm) is not about optimization, but worthwhile improvement. A simple recommendation that a majority of drivers can easily implement is preferable to a complex and conditional one that demands more skill and attention.

1.3.2 Eco-Driving Interventions

There are two general approaches for encouraging drivers to adopt eco-driving practices and they closely mirror the informational and structural strategies (Steg & Vlek, 2009) or antecedent and consequence strategies discussed earlier (Flemming et. al., 2008). On the informational and behaviour antecedent side are driver training modules and education campaigns which seek to equip drivers with the knowledge and skills to perform eco-driving techniques. On the structural and behaviour consequence side are feedback devices which generally inform drivers about their performance, advise drivers with specific actions to take, or both. Feedback may be real-time, as with a fuel consumption gauge, or periodic, as with a post-drive summary of fuel consumption statistics. Training and feedback interventions are often used together, but while they should agree in terms of the techniques and behaviour they promote, the development process for each is mostly distinct. The dominant strategy thus far for motivating drivers to adopt eco-driving has been information based, but public education campaigns are unlikely to achieve the necessary changes (Barkenbus, 2010).

Applying DfBC methods to eco-driving primarily relates to feedback-based interventions. Feedback can be communicated to drivers through visual, auditory, or haptic cues. All of these have been studied as eco-driving interventions, but the vast majority of research has been dedicated to visual displays (Dahlinger and Wortmann, 2016; McIlroy & Stanton, 2018). The only fully developed haptic interface concept, the Nissan Eco Pedal, is a throttle pedal that increases backpressure in response to high fuel consumption (Birrell et. al., 2013). It demonstrated fuel saving results comparable to visual displays, but is generally unpopular among drivers, many of whom find it intrusive and confusing. Auditory cues are relatively untested for eco-driving, only occasionally used in conjunction with visual displays (e.g. Birrell et. al., 2014). This is partly because the nature of the eco-driving task is poorly suited to an auditory interface. A consistent or frequent sound stimulus related to driving efficiency could very quickly become irritating to drivers or be ignored due to alarm fatigue (Lee et. al., 2017). In a vehicle, auditory cues are typically associated with important warnings (e.g. seatbelt or collision warnings) or control feedback (e.g. multimedia buttons). Eco-driving is not critical to the driving task and would risk interrupting the safe execution of that task by introducing additional alarms.

In-vehicle displays have become even easier to implement in a wide range of new vehicles since many major manufacturers share common operating systems for dashboard and multimedia interfaces. QNX and Automotive Grade Linux (AGL) are two such platforms that are each embedded in the vehicles of over ten different manufacturers. This level of software standardization makes it considerably easier from a technical perspective to introduce a new display design across a range of vehicle makes and models. For existing vehicles, mobile devices may present an opportunity to introduce new eco-driving displays, especially if combined with navigation applications. However, there are critical distraction-related safety considerations to contend with as well as far greater difficulty in promoting usage since there is no way to make a particular mobile display a default while driving.

A variety of survey, driving simulator, and field studies have been performed over the past two decades evaluating eco-driving interventions. From an extensive search of the academic literature, 42 distinct real-time visual display designs were identified, as listed in Table 1. This listing does not include the many subtle variations of fuel consumption gauges found in most vehicles today. A categorization scheme was devised to distinguish displays based on the type of feedback they provide. Each listed display provides real-time feedback in one or more of the following forms:

- **Inform**: Quantitative information about the driver’s behaviour without evaluation (e.g. fuel consumption, acceleration).
- **Score**: Qualitative performance evaluation of the driver’s efficiency (e.g. green/yellow/red, stars out of 5).
- **Aid**: Targets and/or boundaries to aid in achieving efficient driving behaviour (e.g. speed range, acceleration range).
- **Advise**: Specific event-based recommendations for the driver (e.g. shift gears, change pedal pressure).
- **Engage**: Symbolic representations that aim to motivate efficient driving (e.g. growing trees/leaves, emoting faces).

These five categories are not fully independent, but in the absence of a systematic categorization scheme used in the eco-driving literature, they are useful as a rough indication of the existing distinct forms of display feedback. The majority of display elements found in the literature were easily matched with the five categories as defined. Occasionally a single display element performed more than one feedback function simultaneously.

The performance column lists the empirical results from a simulator or field study for the given display, where available, as a percentage reduction in fuel consumption. However, the specific methods in each study vary dramatically and it is beyond the scope of this thesis to perform a detailed review of these studies. Rather, the intention was to examine the range of display designs tested in eco-driving research and identify unexplored directions in design strategy. Two recent eco-driving review papers have examined eco-driving intervention performance in greater detail (Huang et. al., 2018; Dahlinger & Wortmann, 2016).

Table 1. Eco-Driving displays from academic literature indicating feedback types

Source		**Inform**	**Score**	**Aid**	**Advise**	**Engage**	**Performance (% fuel use reduction)**
Vaezipour et. al., 2019	(a)				✓		1.6% (simulator)
	(b)		✓		✓	✓	6.9% (simulator)
Dahlinger et. al., 2018	(a)			✓			1.7% (field)
	(b)	✓	✓				0% (field)
	(c)	✓	✓			✓	2.9% (field)
McIlroy et. al., 2017			✓				-
Saint Pierre et. al., 2016			✓		✓	✓	1.5% (field)
Hrimech et. al., 2016		✓		✓			-
Magaña & Muñoz-Organero, 2016			✓		✓		3.8% (field)
Levermore et. al., 2016		✓			✓		-
Jamson et. al., 2015	(a)		✓				-
	(b)			✓			-
	(c)				✓		-
Brouwer et. al., 2015	(a)		✓	✓			-
	(b)		✓	✓			-
Dijksterhuis et. al., 2015		✓		✓	✓		-
Rios-Torres et. al., 2015		✓			✓		-
Zhao et. al., 2015		✓					5.5% (simulator)
Birrell et. al., 2014			✓	✓			3.7% (field)
Kircher et. al., 2014	(a)		✓		✓		-
	(b)			✓			-

Marcus, 2014	(a)	✓	✓			✓	-
	(b)	✓	✓				-
Staubach et. al., 2014				✓	✓		15.9% (simulator)
Rommerskirchen et. al., 2014					✓		10.3% (simulator)
Stillwater & Kurani, 2013		✓		✓			-
Vagg et. al., 2013			✓				7.6% (field)
Tulusan et. al., 2012		✓	✓				3.2% (field)
Kim et. al., 2011			✓				-
Manser et. al., 2010	(01)	✓					4.8% (simulator
	(02)		✓	✓		✓	-
	(03)		✓			✓	-
	(04)	✓					-
	(05)	✓					-
	(06)	✓					-
	(07)	✓					-
	(09)	✓					-
	(FE)		✓	✓		✓	10.2% (simulator)
Meschtscherjakov et. al., 2009	(a)		✓				-
	(b)		✓			✓	-
Hiraoka et. al., 2009		✓					9.0% (simulator)
Van der Voort et. al., 2001					✓		4.1% (simulator)

A notable observation from this review of displays was that few designs (8 of 42) include an element aimed at engaging drivers. Of those that did, 7 of the 8 did so by depicting, with varying degrees of realism, a plant growing leaves (Figures 1 and 2). The only exception to this was the display designed by Vaezipour et. al. which depicted stylized faces for scoring ‘good’, neutral’, and ‘bad’ (Figure 3). All engagement elements in the listed displays were thus a form of performance scoring where few leaves and many leaves correspond to low and high scores respectively. No displays directly incorporated engagement into inform, aid, or advise information. Only two displays, both variations on the same basic design, included both driver engagement and aiding (Figure 1).

This revealed an unexplored opportunity to develop and test eco-driving displays that not only combine engage and aid elements but do so in an integrated manner and without judgement. A number of studies encourage further work in motivating drivers to practice eco-driving using alternate means (Dahlinger & Wortmann, 2016; McConky 2018). Drivers have reported that environmental and even monetary factors are often less important to them than convenience and time saving (Harvey et. al., 2013).

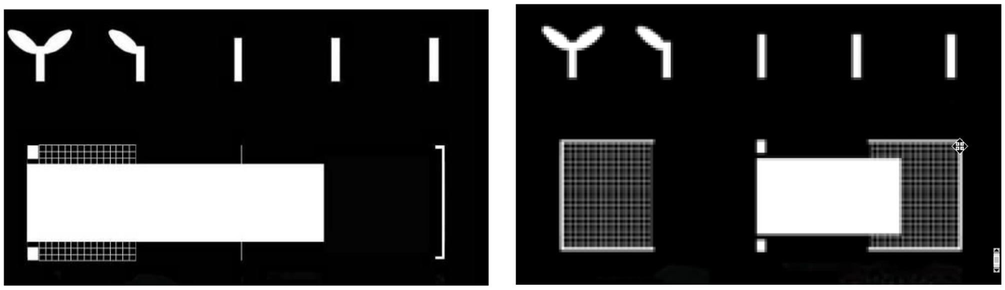


Figure 1. Final two displays from NHTSA's Fuel Economy Driver Interface study showing growing plants and instantaneous fuel consumption (left) or acceleration (right) (Manser et. al., 2010)

Figure 2. Three views of the final display from the ecoDriver project showing scoring levels and a growing tree (left) and driving advice (middle, right) (Saint Pierre et. al., 2016)

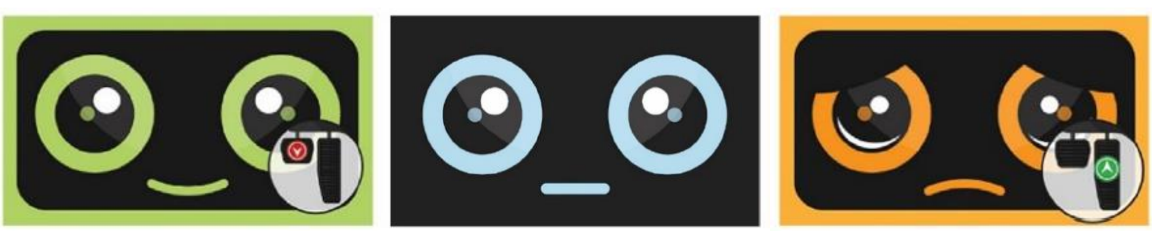


Figure 3. Eco-driving performance scoring face display with driver advice (Vaezipour et. al., 2019)

1.4 Eco-Driving and Safety

Nearly all eco-driving studies acknowledge that it is not enough for an intervention to be effective, it must also be safe. There are two main ways in which an eco-driving display can potentially compromise driving safety: by distracting drivers and by eliciting unsafe driving maneuvers. If the driver is overly attentive to a display, particularly by taking their eyes off the roadway, but also be devoting cognitive resources, they are at substantially higher risk of causing an accident (National Highway Traffic Safety Administration, 2014). If the driver is overly committed to maximizing driving energy efficiency, they may adopt unsafe driving practices such as rolling stops, reduced headway, and inappropriate speeds (Young et. al., 2011). On the other hand, eco-driving may also enhance driving safety by encouraging behaviours where safety and efficiency are compatible, such as avoiding high speeds and using smoother acceleration and braking (Young et. al., 2011).

1.4.1 Driver Distraction

Distracted driving, the attendance to secondary activities unrelated to the primary driving task, is a leading cause of vehicle crashes (NHTSA, 2014; Young et. al., 2003). Cognitive distraction can lead to significantly longer reaction times in drivers responding to both abrupt and gradual road hazards (D'Addario & Donmez, 2019). Glances away from the roadway begin to substantially increase the crash risk when longer than 2 seconds (NHTSA, 2010). While some driving distractions can and should be eliminated, such as prohibiting interaction with mobile devices, some secondary activities can be effectively managed such that their impact on driving safety is minimal.

The United States' National Highway Traffic Safety Administration (NHTSA) has conducted extensive studies on distracted driving and offers guidelines and test methods for evaluating distraction potential of in-vehicle devices (2010; 2013). The Visual-Manual NHTSA Driver Distraction Guidelines for In-Vehicle Electronic Devices pertains to the human-machine interfaces of embedded devices used for performing all non-driving-related tasks and some driving-related tasks (2010). An applicable driving-related task is one that aids the driver in performing the driving task but is neither related to the safe operation and control of the vehicle nor involves the use of a system required by law. Observation of fuel economy displays are listed as an example of applicable driving-related tasks which should be designed in accordance with the guideline. Three acceptance criteria are proposed for evaluating an applicable task in a driving simulator equipped with eye tracking (each for at least 21 of 24 test participants):

1. No more than 15 percent (rounded up) of the total number of eye glances away from the forward road scene have durations of greater than 2.0 seconds while performing the testable task one time.
2. The mean duration of all eye glances away from the forward road scene is less than or equal to 2.0 seconds while performing the testable task one time.
3. The sum of the durations of each individual participant's eye glances away from the forward road scene is less than or equal to 12.0 seconds while performing the testable task one time.

Portable and aftermarket devices are subject to the same criteria along with some additional restrictions that are not applicable to the present research (NHTSA, 2013). These three acceptance criteria are based on the completion of a "testable task" one time, such as manually tuning a radio to a specific station or adjusting temperature controls to a specific setting. NHTSA defines a testable task as "a pre-defined sequence of interactions performed using a specific method leading to a goal toward which a driver will normally persist until the goal is reached". In particular, the full definition also stipulates a defined start and end state. Fuel efficiency displays are among several devices listed as falling within the scope of the guideline, but which generally do not have a distinct testable task. The first two acceptance criteria are not time dependent and are measurable for any representative test period that involves the activity in question. The last acceptance criteria regarding the total glance time away from the forward roadway while performing the task cannot be reasonably applied to a non-interactive device like an eco-driving display.

These criteria constrain the visual distraction potential of displays, but they do not account for cognitive distraction. It remains the responsibility of the display designer to factor in cognitive resource demand and test for its potential impact on driving safety. When the cognitive demands of the primary driving task increase, such as in high-density traffic, drivers have been found to reduce their engagement in eco-driving practices and increase their visual attention on the roadway (Dogan et. al., 2011; Jamson et. al., 2015). The best eco-driving displays will demand the least cognitive attention from drivers while still offering worthwhile environmental benefits.

1.4.2 Safety of Eco-Driving Maneuvers

Safe driving and energy efficient driving can be largely compatible endeavours, but safety must always take precedence. Young et. al. note that eco-driving practices such as reduced speed and acceleration intensity are conducive to safe driving, while others like avoiding stops and speed changes can compromise safety in many cases (2011). Aggressive and jerky driving, a primary target of eco-driving interventions, is associated with heightened crash risk (Bagdadi & Varhelyi, 2011). Overall, a safe driver is also a relatively energy efficient driver, looking ahead to anticipate events and driving more smoothly as a result (Stahl et. al., 2013). An efficient driver may be a safe driver, as long as commitment to safety supersedes the pursuit of efficiency (Haque & Abas, 2018). For example, drivers engaging in eco-driving have been found to maintain greater headway, the distance to the vehicle directly in front, which is associated with lower crash risk (Birrell et. al., 2014). On the other hand, high-intensity accelerations are often required to perform defensive or evasive maneuvers. Anticipatory driving might hold the key to optimal safe and efficient driving behaviour and Stahl et. al. suggest that appropriately designed interfaces can support drivers' anticipatory performance (2013).

1.5 A Simplified Eco-Driving Model

Most currently used driving-efficiency displays show energy consumption either graphically or numerically. In internal combustion vehicles, this measure is usually in miles per gallon (MPG), gallons per 100 miles (gal/100 mi), or liters per 100 kilometers (L/100 km). While less precise than direct energy consumption, the use of acceleration as a measure of driving efficiency may be more intuitive and easier for drivers to operationalize. This is important, as a lack of awareness of energy interactions is a major cause of energy overuse (Withanage et. al., 2016).

Additionally, acceleration can be measured in the negative direction (deceleration) as wasted kinetic energy whereas energy consumption is only measured at the moment of use when applying power. Even for electric vehicles with regenerative braking, maintaining kinetic energy will always outperform energy regeneration due to losses in energy conversions. Route characteristics, such as grade profile (flat versus hilly) and traffic patterns are often beyond drivers' control but influence their acceleration behaviors. Several of the displays listed in Table 1 show acceleration information in addition to, or instead of fuel consumption. With so many eco-driving techniques directly related to reducing acceleration, it may serve as a useful proxy for fuel consumption in eco-driving displays.

I will refer to a driving style characterized by low longitudinal acceleration and deceleration intensities as “smooth” and a driving style with high intensities as “dynamic.” A driving style with higher intensity acceleration is often described as “aggressive” (Michelle, 2010). However, I instead use “dynamic” to avoid any emotional connotation which is not relevant to the present discussion.

1.6 Conclusion

Environmental challenges must be approached from all strategies and disciplines. Here I will consider light-duty vehicle energy use and emissions from the perspective of a nudge to influence driver behaviour. Driving is a high-skill activity, but one that most drivers are so habituated to that much of the task is performed using reflexive decision-making. This type of behaviour is not easily influenced by informational interventions but may be effectively manipulated using design for behaviour change techniques. Past eco-driving research has tested a variety of displays, but some unexplored opportunities were identified. Missing from the literature are displays that engage and motivate drivers in the practice of smooth driving while also aiding them in the performance of those behaviours. In the next chapter I discuss the conceptual design of an eco-driving display that aims to accomplish that goal without introducing a problematic driving distraction.

Chapter 2

An Eco-Driving Intervention Applying Motive Substitution

Previous eco-driving intervention designs have drawn from a diversity of behaviour and design theories. While many interfaces appear to have been developed with little or no justification for the design choices, several projects have taken more systematic approaches. However, an examination of the resulting displays made it apparent that some avenues for applying DfBC to eco-driving feedback design remain unexplored. The effectiveness of existing interfaces is also difficult to compare due to lack of consistent test methods, with many results conditional on a motivated user. For these reasons, I chose to focus my research on a novel and untested type of eco-driving display that exemplifies a distinct perspective on DfBC more generally. In this chapter I first propose a definition of motive substitution as a DfBC technique, demonstrate its application as an eco-driving intervention, and finally consider that intervention from a multidisciplinary perspective.

2.1 Defining Motive Substitution

The concept of motive substitution is not an original design method for behaviour change, but rather an original classification of interventions including many existing ones that currently lack a shared descriptor. By differentiating this important subset of DfBC interventions from other types, designers can more easily apply the method to behaviour change problems they face. I define motive substitution as follows:

> Motive substitution is the design technique of presenting a user with a motivating alternate task that elicits the same behaviour as a desirable, but less motivating task.

This is distinguished from related concepts in a few key ways:

- It specifically describes a DfBC technique involving a designer and a user, not a self-control or communication strategy.
- It refers to substitution of the motive that triggers a behaviour which is not necessarily a reward for performing a behaviour. Any reward is intrinsic to the alternate task.

- The motivating alternate task must be impossible to perform without also accomplishing the unmotivating one.
- The alternate task is entirely voluntary and does not punish users who do not engage it.

The following interventions are examples of motive substitution:

1. A set of tip jars in a cafe are each labelled with a different dish option for addition to next month's menu. The dish receiving the greatest proportion of tips is selected for the menu. The motive of tipping has been substituted with the motive of selecting the menu item.
2. The well-known Schiphol Airport urinal fly (Thaler & Sunstein, 2008). A picture of a fly is placed near the drain of each urinal, prompting users to aim for the fly and improve accuracy, thereby reducing spillage. The motive of keeping the washroom clean has been substituted with the motive of engaging in a gameful experience with the fly image.
3. A staircase is equipped with sensors on each step that trigger rhythmic sounds, creating an interactive musical interface (Pink, 2014). The motive of taking the stairs to avoid elevator or escalator backlog has been substituted with the motive of engaging in a playful music experience.

Note that in all these cases, reward is intrinsic to the substituted task and thus cannot be obtained without performing the task and accomplishing the original objective. The challenge is in offering a sufficiently compelling substitute motive to consistently achieve the desired behaviour from users.

The concept of motive substitution is similar to several other concepts that exist in the behaviour change literature. Behavioural economist Dan Ariely uses the term "reward substitution" to describe choice architecture that causes people to behave in the right way because of the wrong reason (Ariely, 2011; Garza et. al., 2016). Initially this appears to be identical to motive substitution, and Ariely's intended definition of reward substitution may in fact be equivalent, but I have chosen to define a separate term for two reasons. First, reward substitution is presented as a self-control strategy where long-term rewards (e.g. positive health outcomes) are augmented with immediate hedonic rewards (e.g. fun activities). Examples of reward substitution often require self-enforcement, such as rewarding oneself with a small piece of chocolate each time you go to the gym. One is perfectly capable of gaining the reward without performing the associated behaviour and relies on willpower to prevent this. Motive substitution strictly refers to interventions where any reward is built into the alternate task such that it cannot be obtained without performing the desired behaviour. Second, the term reward substitution very rarely appears in academic literature, referred to in writing mainly in various online blogs. While it is consistently attributed to Ariely and the usual examples are discussed in his well-known books, the term itself is absent from the books and thus no clear definition is ever offered. Instead of presuming to offer a definition for Ariely's term reward substitution, I opted to define the separate but related term motive substitution.

Motive substitution also resembles the concept of "bundling" listed in Dan Lockton's Design with Intent patterns (2010). Bundling is described as including something designers want users to do with something users themselves want to do. While the two concepts overlap in many cases, bundling often involves tempting the user with a substantial reward for doing something in the designer's interest.

Finally, Tromp et. al. list 11 strategies to design for socially responsible behaviour where one is to "trigger different motivations for the same behaviour" (2011). Only a very brief explanation is offered with the example of a roadside garbage bin mounted to resemble a sports goal basket for passing drivers. This example is very similar to the Schiphol airport urinal fly and is also motive substitution according to the definition above. I consider this to be an equivalent concept, but it lacks elaboration by the authors.

2.1.1 Criteria for a Motive Substitution Intervention

I propose that a motive substitution intervention must meet three essential criteria to be effective (Figure 4):

- The alternate task must be **intuitive** such that the user can perform the task with minimal guidance, instruction, or training.
- The alternate task must be **engaging** such that it qualifies as a motive that triggers voluntary action without extrinsic rewards.
- The original and alternate tasks must have **congruous** goals such that they elicit equivalent behaviours and thus achieve, at a minimum, the same end result.

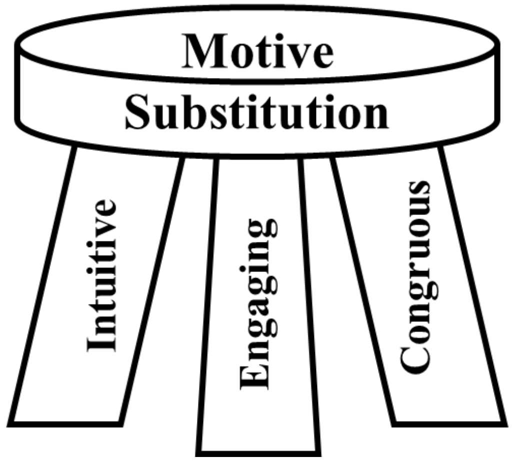


Figure 4. Three essential components of an effective motive substitution intervention

This is the initial conceptualization of motive substitution as a DfBC technique and further work is needed to refine the definition. I believe it offers a useful and original grouping of interventions that warrant greater application to problems where users tend to be apathetic toward the original motive. Pro-environmental behaviours consistently face this problem and motive substitution might help designers make them enjoyable rather than burdensome.

2.1.2 Applying Motive Substitution to Eco-Driving

The example of motive substitution investigated in the remainder of this thesis was devised before the conceptual framework of motive substitution just proposed. I sought to develop an eco-driving display that might effectively influence drivers to adopt a more energy efficient driving style using a novel approach. My first step was to clarify the desired behaviour that leads to lower energy consumption. As established in Section 1.5, the most impactful operational eco-driving recommendations can be summarized as adopting a smoother driving style with reduced accelerations and decelerations. I then realized there may be other motives that elicit equivalent behaviour and devised the alternate task of driving with an open beverage in the car. In that scenario, the driver will drive more smoothly to avoid spilling the drink. While a real open beverage is an impractical intervention for obvious reasons, the scenario can be simulated in a display to recreate the experience. This led to an animated dashboard display depicting the cross-section of a full cup of coffee that moves in response to longitudinal vehicle acceleration. That is, the coffee simulation would realistically slosh left and right in the cup in relation to forward and backward movements of the vehicle. If the movements become too intense, the coffee will spill over the lip of the cup. Single frames from the mock-up used in Study 1 and the final prototype for Study 2 are shown in Figure 5 for clarity, but explanation of the detailed design choices follow in later chapters during discussion of prototype development.

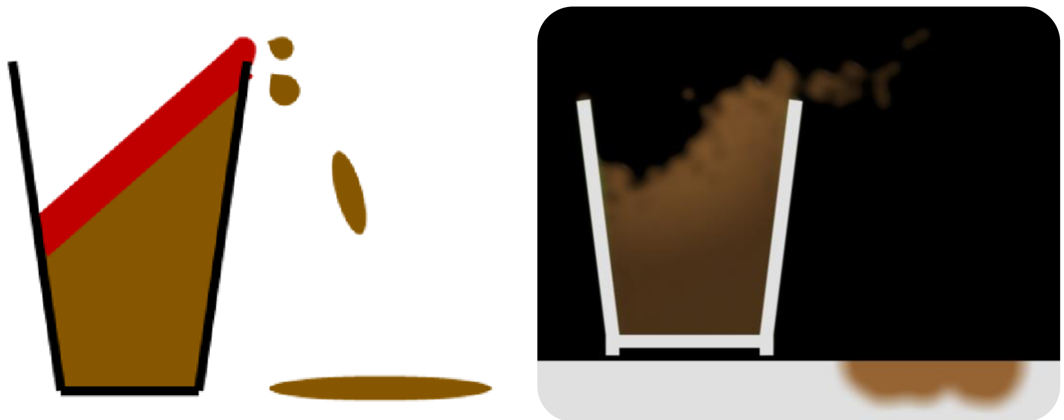


Figure 5. Single frames from Study 1 mock-up (left) and Study 2 functional prototype (right) of the coffee-cup eco-driving display spilling due to high intensity deceleration

The expectation is that drivers will have a visceral response to the possibility of spilling even a simulated cup of coffee, thereby engaging them in the desired behaviour through a game-like experience. An intuitive mental model facilitates a transition to the driving style people might adopt if they had a real, open cup of coffee in their vehicle. The resulting behaviour is likely to be very similar to a purposeful low acceleration driving style, thus achieving congruous goals. While high-acceleration maneuvers are still occasionally required for safe driving, the lack of real consequence from an animated display should allow safety considerations to take precedence.

No specific concept generation method was used to conceive the animated coffee cup display. Rather, it arose organically while deliberating on the problem. Other display concepts were subsequently considered, but none were perceived to improve on the coffee cup, so it was selected as the design to evaluate in empirical studies. Motive substitution is thus the term I have given to what proved to be a useful and novel strategy to develop the conceptual design of an eco-driving display that aids and engages drivers.

By presenting a visualization of acceleration intensity using fluid simulation, the coffee-cup display is a form of acceleration gauge with thresholds. As such, the display aids drivers in performing eco-driving practices related to acceleration. By the earlier classification of eco-driving displays in Chapter 1 (inform, score, aid, advise, engage), this display purely aids and engages drivers and does so in a single integrated display element. The coffee-cup interface could potentially benefit from additional features. For example, at the end of each drive the display could show some form of cumulative performance information to encourage continued adherence and improvement. Such additions are worth investigation in future work, but conceptual simplicity was favoured for the purposes of the research covered in this thesis, so the core aiding and engaging coffee cup visualization will be considered in isolation.

2.2 Analysis of the Coffee-Cup Display as an Effective Motive Substitution

The coffee-cup display might initially come across as frivolous compared to existing displays, yet by meeting the three requirements of motive substitution, it fulfills many important criteria for an effective behavioural eco-driving intervention. In the following sections I examine the coffee-cup concept from a variety of perspectives and disciplines and consider how and why it might achieve the desired outcome by being intuitive, engaging, and congruous.

2.2.1 Is It Intuitive?

Intuition can be considered the result of purely reflexive cognitive processing as opposed to deliberative processing, as defined in dual-process theories. An interface is intuitive if it can be understood and used effectively by accessing reflexive processing almost exclusively. For most, a digital clock is intuitive while for many younger people an analog clock may not be, at least until the skill is learned.

2.2.1.1 Skilled Intuition

Depending on the circumstances, intuition can lead to expert decisions or flawed judgements. Good outcomes rely on the appropriate application of skilled intuition (Kahneman & Klein, 2009). Naturalistic decision making is founded on the premise that skilled experts make good and fast decisions based on intuition. This contrasts with the heuristics and biases model of reflexive processing that has revealed the extensive fallibility of intuition. Skilled intuition arises from repeated responses to reliable cues in a consistent environment. Cues that provide valid information about the nature of a situation develop a skill within the given environment. Skilled intuition is thus recognition of a cue in context and the execution of the associated memorized response (Simon, 1992). If the correct circumstances are created with the coffee-cup display, drivers can use the interface according to skilled intuition, making use of faster and less cognitively demanding reflexive processing.

2.2.1.2 Ecological Interface Design

Ecological Interface Design (EID) is a design approach that arose from a similar foundation, the skill-, rule-, and knowledge-based (SRK) model of behaviour (Vicente & Rasmussen, 1992). Skill-based behaviour describes direct reflexive interactions with the environment, essentially the execution of skilled intuition. Rule-based behaviour involves the conscious association of a situational cue with a corresponding action, which might also be considered the practice phase that leads to skilled intuition. Knowledge-based behaviour involves the application of slower deliberative and analytical processing to respond to less familiar situations. Cognitive resource demands are lowest with skill-based behaviour and increase with rule-based and again further with knowledge-based behaviour. EID has two parallel objectives, first to encourage the use of the least cognitively demanding behaviour mode required for the task, and second to facilitate effective use of more cognitively demanding modes when needed (Vicente, 2002). A display designed according to EID allows users to make use of skill-based and rule-based behaviour during regular use and engage in knowledge-based behaviour in atypical situations. EID is a method generally used for the development of interfaces for complex dynamic systems like power plants and aircraft cockpits while an eco-driving display is relatively basic. However, the driving task as a whole is highly complex and dynamic, and the eco-driving display is just a component of the entire driving interface. Given that eco-driving is a non-essential aspect of the driving task, it makes sense to follow the principles of EID to minimize cognitive demands associated with that task so more can be allocated to critical driving tasks.

Looking at eco-driving as a skill, it is one that most drivers have not developed. Additionally, it is a skill most drivers are unmotivated to learn since it is of little consequence to each individual driver. The coffee-cup display aims to overcome this by accessing an existing skill most experienced drivers should have innately, that is driving with a liquid in the vehicle. Drinking a beverage is a common task while driving (Stutts et. al., 2005), and a cup of coffee in a cup holder is expected to be a widely relatable scenario. Even though any real beverage is likely to be covered and some drivers might never drive with liquids at all, it is the intuitive physical phenomenon that nearly every driver should understand innately. If a real open coffee cup were placed in any driver's vehicle, it is reasonable to expect they would immediately know how to drive to avoid spilling it.

The coffee-cup display also supports simple rule-based behaviour by providing the cue of a spilled liquid which is preventable with a reduction in acceleration or deceleration intensity. This relationship is easy to understand and learn. The extent of knowledge-based interaction with the display is when a driver is conscious of and motivated toward eco-driving and wishes to drive optimally. In such cases, the coffee cup's fluid simulation can effectively aid that driver in regulating their acceleration and minimizing their energy use but does not provide additional cues that might cause distraction.

2.2.1.3 Associative and Contextual Elements

The coffee-cup display is thus expected to be an intuitive interface due to a combination of what I have termed associative and contextual elements. The associative element refers to depicting an accurate real-life dynamic physical scenario, which the coffee-cup display clearly does. Other examples of associative driving displays might depict the realistic movement of in-vehicle objects or the vehicle on the road. The contextual element refers to depicting stimuli relevant to an activity and familiar to the user. For example, the depiction of traditional dashboard instruments, primary vehicle components, or passing scenery are contextually relevant to driving and widely familiar to drivers. These associative and contextual elements hypothesized to contribute to the coffee-cup display's intuitiveness are evaluated in Study 1 which is discussed in Chapter 3.

2.2.2 Is It Engaging?

In addition to being intuitive, the coffee-cup display must also motivate users to adopt more energy-efficient driving behaviours. Essentially all existing eco-driving interventions either assume environmental responsibility is already a strong enough motive for drivers to trigger pro-environmental behaviour or seek to engage using environment-centric symbolism. The coffee-cup display makes no association with the environment or energy efficiency to account for drivers' varying attitudes and beliefs regarding the environment and inclinations toward efficient driving. An eco-driving display should also not be so intrusive that it prompts drivers to deactivate it or distracts from the driving task.

2.2.2.1 Self-Determination Theory

Among the most widely applied theories of motivation is self-determination theory which suggests that intrinsic motivation is achieved through the fulfillment of three fundamental needs: autonomy, competence, and relatedness (Deci & Ryan, 2000). The enhancement of a person's perception of any of these factors is associated with increased motivation and satisfaction.

Autonomy refers to the feeling of engaging in activities freely or spontaneously with an internal perceived locus of causality (i.e. participation was your choice). Motive substitution, as with all nudge interventions, is intended to be perceived as voluntary, in part because greater imposition often leads to lower intrinsic motivation and increased resistance toward the behavior (Deci & Ryan, 2000). The direct use of environmental responsibility as the motivator in most pro-environmental behaviour interventions can be problematic for maintaining a feeling of autonomy. The prevalence of environmental messaging means that reminders of one's duty to be environmentally friendly can often be perceived as nagging or preaching. While the coffee-cup display doesn't specifically conceal its purpose, the absence of "green" or "eco" related symbolism is intended to avoid such negative reactions. Additionally, it imposes negligible consequences for drivers who choose not to engage it for whatever reason, permanently or temporarily.

The need for competence describes both the desire to perceive consequences of your actions through feedback and a capacity to achieve positive outcomes (Deci & Ryan, 2000). The same factors that make the coffee-cup display conducive to skill-based intuitive behaviour make it likely to elicit feelings of competence in drivers. Unlike simplified scoring displays that grade your overall driving performance, the coffee-cup gives drivers immediate and clearly mapped feedback on their driving behaviour. While during initial experiences with the display it might prove difficult to avoid spilling, most drivers are likely to quickly access the appropriate existing skills to achieve competence.

Relatedness, the desire to interact and connect with others, has generally been found to play a smaller role in fostering intrinsic motivation (Deci & Ryan, 2000). The coffee-cup display as presently conceived does not specifically address intrinsic motivation of drivers through relatedness, though this could be examined further in future research.

2.2.2.2 Gameful Design

The term gamification is commonly used to describe the use of game design elements in non-game contexts. However, in practice, gamification has usually been limited to the inclusion of stereotypical game elements such as points, levels, leaderboards, and achievements. Gameful design is a broader concept that involves designing for the experiential and behavioural quality found in games (Deterding, 2011). Self-determination theory is often used to explain the behavioural impacts of gameful design, especially through autonomy and competence (Sailer et. al, 2017; Zhang, 2008). Gamefulness differs from playfulness in its use of structured rules and pursuit of a defined goal. Both can be very effective tools for user engagement, and many products use gameful and playful design to engage users (Hamari et. al., 2014; Sailer et. al., 2017) including many examples of motive substitution. The Schiphol urinal fly and the coffee-cup display are both motive substitution interventions that rely on subtle gameful design to entice users to behave in the desired way.

The coffee-cup display is a very simple gameful interface. Without requiring any instruction, a driver will discover that certain behaviours cause the coffee to spill, namely high intensity accelerations and decelerations, while avoiding these behaviours prevents the negative outcome. Even without the addition of any traditional game design features such as scoring or levels, the interactive coffee cup creates a game-like experience not found in most other eco-driving displays. This may not be a very compelling experience compared to traditional games, but as part of the driving task, it need only be more engaging than alternative eco-driving displays or no such display at all.

2.2.2.3 Regulatory Focus Theory

Another social-psychological theory with relevant implications here is Regulatory Focus Theory (RFT) and its associated regulatory fit effect (Higgins, 2000; Lockwood et. al., 2002). RFT proposes that people pursue goals from either a promotion orientation (i.e. the pursuit of maximal gains) or a prevention orientation (i.e. the pursuit of minimal losses). Achieving a fit between framing a goal as a loss or a gain and a person’s regulatory focus has been found to increase both motivations toward the goal and success in achieving it. While regulatory focus is a relatively stable aspect of personality, a specific orientation can be primed by situational context. Given the prominent safety considerations involved in driving, it is possible that people on average adopt a prevention orientation and avoid hazards while driving. In this case, a driving-behavior intervention that is framed toward prevention could be more influential than one framed toward promotion. Additionally, the prevention framing of these displays might itself prime prevention orientation in drivers and make them more safety conscious. Thus, prevention orientation for safe driving and eco-driving may be complementary.

2.2.3 Is It Congruous?

The requirement for a motive substitution intervention to be congruous is to verify that the behaviour the alternate task elicits from users is acceptably similar to the original task. That means the coffee-cup display must suppress drivers' acceleration and deceleration intensities enough to measurably reduce energy consumption without compromising safety. It seems likely that the goals involved in the coffee-cup display are congruous with those of smoother driving behaviour. Given sufficient skill and motivation, a driver performing well at one task should inherently perform well in the other. However, this must be confirmed empirically and is the primary objective of Study 2. Despite the theoretical justifications for expecting the display to be effective, certain negative outcomes are possible. If the display is too salient and engaging, it may draw drivers' eyes away from the roadway to an extent that it becomes a distraction hazard. Another possibility is that drivers may adopt a goal of intentionally spilling the liquid, rather than preventing spills, if they perceive spilling as more fun.

2.3 Conclusion

I originally sought to develop a practical pro-environmental intervention that exemplifies the design for behaviour change approach. An interesting opportunity became apparent for an eco-driving display that cohesively aids users in driving more smoothly and engages them to consistently participate in that practice. In this pursuit, I first propose a definition of motive substitution as a relevant technique within the DfBC framework and then explore its application to eco-driving in the form of a coffee-cup display. The theoretical rationale for this display being effective is considered through the three suggested criteria of motive substitution: that it be intuitive, engaging, and congruous. I further suggest the intuitive nature of the display is due to associative and contextual elements that promote the use of skill-based behaviour. Chapter 3 covers the development and analysis of Study 1 where the perceived effectiveness of the coffee-cup display is evaluated in an online study in comparison to alternate displays that control for the associative and contextual elements. Chapter 4 covers the development of Study 2, a driving simulator experiment that aims to measure the actual behavioural impacts of the coffee-cup display in comparison to less intuitive and less engaging variants.

Chapter 3

Study 1: Evaluating the Perceived Effectiveness of the Coffee-Cup Display in an Online Survey

3.1 Introduction

3.1.1 Study Objective

In the previous chapter I outlined the conceptual design of the coffee-cup display as an eco-driving intervention that aims to be effective for a diversity of drivers. In addition to demographic factors, this diversity includes differences in driving experience and frequency, existing driving styles, and attitudes toward energy efficiency and the environment. I further discussed why the coffee-cup display is expected to be intuitive for drivers due to associative and contextual elements present in the display. This chapter, adapted from previously published work (Potvin-Bernal et. al., 2020), examines the impact of associative and contextual factors on drivers' perceived effectiveness of the coffee-cup display in an online survey.

Two additional displays were conceived that constitute the associative element without the contextual one and vice versa. An animated wrecking ball, hung between two walls, would respond to changes in vehicle acceleration by swinging and striking the walls, cracking them. The wrecking-ball display is associative as it represents the physics of a real wrecking ball, which would cause genuine damage. However, the contextual element is absent since a wrecking ball is foreign to the context of driving a car. The third display is a dial gauge, similar to traditional speedometers or tachometers, and shows the current acceleration and its directionality. The dial gauge is contextually relevant, resembling displays often found in vehicles, but lacks the associative element since it doesn't represent a real-world physical scenario with inherent consequences. The three intervention displays, dial gauge, wrecking ball, and coffee cup, were mocked up for evaluation as four sample frames of the intended animated concepts, shown in Figure 6. Each display is merely an example of a display that is contextual, associative, and both elements combined. Specific display concepts were required for the purposes of testing, but any specific display design that is developed for testing has inherent limitations in generalizability.

An online survey was conducted to measure each display's perceived effectiveness for eliciting a smoother driving style across a series of driver subgroups. These subgroups differentiated drivers by seven demographic and driving-related measures. As described in Section 1.5, a smooth driving style is characterized by low acceleration and deceleration intensities, in contrast to a dynamic driving style.

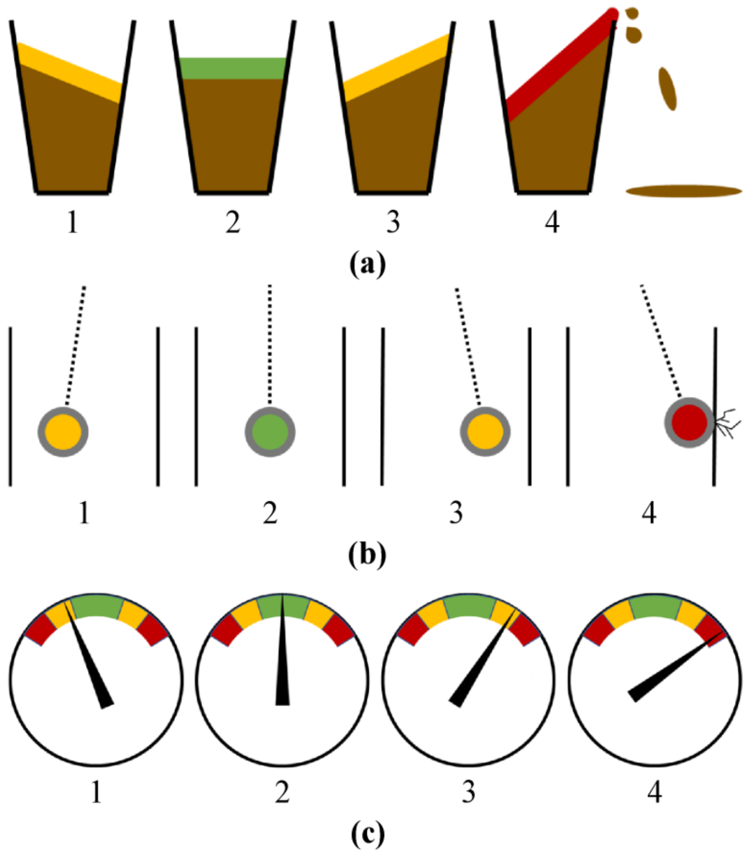


Figure 6. Frames of coffee-cup (a), wrecking-ball (b), and dial-gauge (c) displays, corresponding to 1, moderate acceleration; 2, constant speed; 3, moderate braking; and 4, hard braking

3.1.2 Research Questions

The present work is a preliminary evaluation of the displays' self-reported effectiveness and is intended to answer the following research questions:

RQ1: Is the coffee-cup display perceived to be more effective than the wrecking-ball and dial-gauge displays when controlling for all of the following variables?

- driver age and gender
- driving experience and frequency
- driving style (smooth/dynamic)
- driver inclination toward efficient driving (eager/averse)
- use of a vehicle with an existing efficiency display

RQ2: Among drivers whose primary vehicle has an existing efficiency display, is the perception of each intervention display's effectiveness different when comparing to the existing display?

3.1.3 Display Mock-up Design

Static frame mock-ups were created for each display, requiring some additional design choices to be made for drivers to understand the displays without any instruction or training. Further refinement of the cognitive ergonomics was made by following display design principles that consider attention, perception, memory, and mental models (Lee et. al., 2017). The implementation of these usability principles has enabled profound improvements in high-risk environments such as aviation and industrial facilities. Interestingly, many of the displays found in the eco-driving literature do poorly when considered from this perspective.

An eco-driving display that is incorporated into a dashboard interface must be salient enough to be an effective reminder, while not being distracting. Movement and color are helpful for increasing salience, the former being inherently part of the coffee-cup and wrecking-ball displays. While using movement to increase salience could also increase distraction, a moderate rate of movement can help maintain low visual fixation times during use. All three proposed display mock-ups use color to improve threshold detection by providing redundancy. Three colors, green, yellow, and red, were chosen for their well-understood relation to "good/go," "warning/slow down," and "bad/stop." No additional information is shown that competes for attention.

One aspect of the coffee-cup and wrecking-ball displays involves a compromise between multiple display-ergonomics guidelines. These displays depict longitudinal (forward and backward) accelerations using the side-to-side motion of an element in a two-dimensional (2D) display. This movement mapping is not the most compatible but was chosen to maintain very simple depictions. A fully compatible mapping of vehicle motion to display motion would require three-dimensional (3D) depictions of the coffee-cup and wrecking ball. The significantly increased display complexity may interfere with ease of processing the displayed information. St. John et al. compared comprehension of 2D and 3D displays and found relative position judgments to be more accurate in 2D displays (2001). While the mapping incompatibility may confuse some new users, the relationship is expected to very quickly become apparent once in use.

3.2 Methods

The online survey received 92 valid responses, sufficient to maintain a 5% type I error rate and 80% power to detect effects of size d = 0.3. This effect size lies between the small (0.2) and medium (0.5) effect thresholds suggested by Cohen (1988). The survey is similar in structure to the eco-driving survey conducted by McIlroy and Stanton (2018).

3.2.1 Survey Platform

The survey was offered on Amazon Mechanical Turk (MTurk), a crowd-sourcing platform of anonymous workers who complete tasks online for modest financial compensation. MTurk worker demographics have been found to be diverse, but not exactly representative of the general population in the United States, where over half of workers reside (Ross et. al., 2010). While a popular source of data for social-science research, MTurk worker education, employment, and income levels suggest a more educated, but underemployed population. Task visibility was restricted to the United States and Canada since the international diversity of the MTurk worker pool is too sporadic to appropriately account for regional effects. The survey was identified only as a “Survey on Driving Style” to avoid revealing the study’s true objective. Approved workers were paid $0.50 USD for finishing the survey, and the average completion time was 7.5 min. An attention-check question was included in the survey to remove the results of inattentive workers.

3.2.2 Survey Design

The survey comprised the following five sequential segments:

1. Screening and demographics

2. Driving style

3. Intervention displays

4. Existing display

5. Driver inclination toward efficient driving

The questions were phrased and ordered so as to postpone hinting at the study's objective, which may bias responses to remaining questions. No explicit mention of energy efficiency was made until segment 4 of the survey and no mention of the environment until segment 5 of the survey. Most of the questions used some variation of a Likert scale. All but one question (discussed below) used a six-point scale to force participants to choose at least a slightly directional response and avoid large numbers of neutral responses. Question order was randomized within the driving style (segment 2) and driver inclination (segment 5) questionnaires, as was the order that the three intervention displays were presented. In addition, all questions were mandatory such that participants could not continue without answering.

3.2.2.1 Screening and Demographics

Screening questions selected for participants who self-reported the following: (a) held a valid full or intermediate/provisional driver's license, (b) had at least 2 years of driving experience, and (c) had driven at least once per week during the last 6 months. These criteria selected for routine drivers who were more likely to possess consistent driving habits. These questions also provided data on driver demographics and were followed by questions on age and gender (Appendix A, Q2–Q6).

3.2.2.2 Driving Style

The next survey segment assessed participants' driving style on the "smooth" to "dynamic" scale described in Section 1.5. As the first of two parts, a questionnaire asked participants to indicate how accurately ten statements described them (Appendix A, Q7). Responses were collected using the following six-point Likert scale: (1) Not at all, (2) Slightly well, (3) Somewhat well, (4) Moderately well, (5) Very well, and (6) Extremely well. Questionnaire statements included: I accelerate out of intersections faster than other vehicles; My driving style would be more accurately called "sporty" than "relaxed"; and Loose items in my car often shift backward and forward as I drive. All statements were worded in the same direction, i.e., responding with 6 (Extremely well) always corresponded with a more dynamic driving style. Reverse wording was avoided to reduce misinterpretation of questions, which often results in the emergence of a separate unintended factor (van Sonderen et. al. 2013).

Next, participants were presented with a looping animated video that showed two cars, X and Y, driving between two stop signs, one car at a time (Figure 7). Participants were asked to indicate which car more accurately reflected their own driving style (Appendix A, Q8). Car X accelerated and braked harshly, with moderately noticeable car tilting, and completed the road segment in 8 seconds. Car Y accelerated and braked gently and evenly, completing the segment in 12 seconds. Responses were made with a six-point slider that ranged from Car X at one extreme to Car Y at the other. Participants were not allowed to proceed until the 20-second animation had completed one full loop. The next question aimed to confirm participant understanding that Car X's style would be referred to as "dynamic" and Car Y's style as "smooth." These terms were important points of reference for answering subsequent intervention questions.

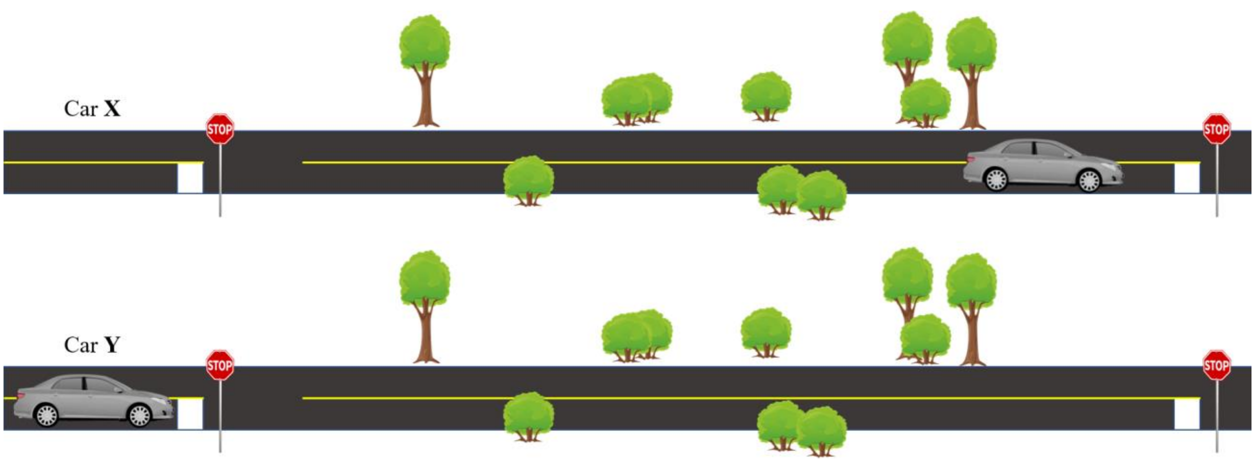


Figure 7. A single frame of the driving-style animation where Car X displayed the harsh movements of a "dynamic" style and Car Y the gentle movements of a "smooth" style

3.2.2.3 Intervention Displays

The three intervention display mock-ups, shown in Figure 6, were presented to participants simultaneously on one page, but in a random sequence. The question briefly explained that each mock-up showed four sample frames of an animated display that would respond to the vehicle's forward–backward motion (Appendix A, Q11). Participants were then asked to indicate, for each display, how effectively it would influence them to drive more smoothly or dynamically than they typically do. Responses were made using the following seven-point Likert scale: (1) Very (2) Moderately (3) Slightly effective for driving more smoothly, (4) No effect, and (5) Slightly (6) Moderately (7) Very effective for driving more dynamically. By giving participants freedom to choose the direction of influence, the question avoided hinting at the study's objective or eliciting a socially desirable response. Note that each display was evaluated independently, not ranked.

3.2.2.4 Existing Display

Participants were then asked whether the vehicle they typically drove had an existing efficiency display. Those who answered in the affirmative were presented with additional questions as follows (Appendix A, Q14–17) that were analyzed as part of RQ2. First, participants were asked to indicate how effective their existing display was in influencing them to drive more efficiently. Next, they were shown the same intervention displays as before. Participants were asked to indicate, relative to their existing display, how effective each display would be in influencing them to drive more efficiently. Note that, different from the first intervention-display question, this question (a) was asked in relation to the driver's existing display and (b) asked about efficient driving instead of smooth versus dynamic driving. This is because "efficiency" had not yet been mentioned when the first version of the question was asked, but it was necessarily revealed when referring to an existing display.

3.2.2.5 Driver Inclination Toward Efficient Driving

The final survey segment was a six-item questionnaire (Appendix A, Q18). This questionnaire was intended to assess participants' propensity for efficient driving, which I call "driver inclination" on a scale from averse to eager. Participants were again asked to indicate how accurately six statements described them on the same six-point Likert scale from (1) Not at all to (6) Extremely well. Questionnaire statements included: I would be willing to drive more smoothly than I do now; Environmental sustainability and preventing climate change are important to me; and I believe efficient driving is a worthwhile way to reduce environmental impacts. All statements were again worded in a consistent direction, where 6 (Extremely well) corresponded to an eager inclination.

3.3 Results

The responses of six participants who completed the survey in under 3 min (180 s) were removed. These durations were outliers, and the corresponding responses were deemed to have not been considered with sufficient care. This resulted in a final sample size of 92 (42 female, 50 male) participants.

3.3.1 Participant Demographics

Two participants had an intermediate/provisional license, and the rest had a full license. Regarding driving experience, 27 participants had 2–10 years while the remaining 65 had 10 or more years. Regarding an existing efficiency display, 38 participants indicated that the vehicle they typically drove had one, while the remaining 54 did not have one. The distributions of participants' age and driving frequency are shown in Figure 8. Notably, 23 participants indicated that they usually drive four or more hours per day. These people likely drive for work, e.g., for delivery or taxi/rideshare companies.

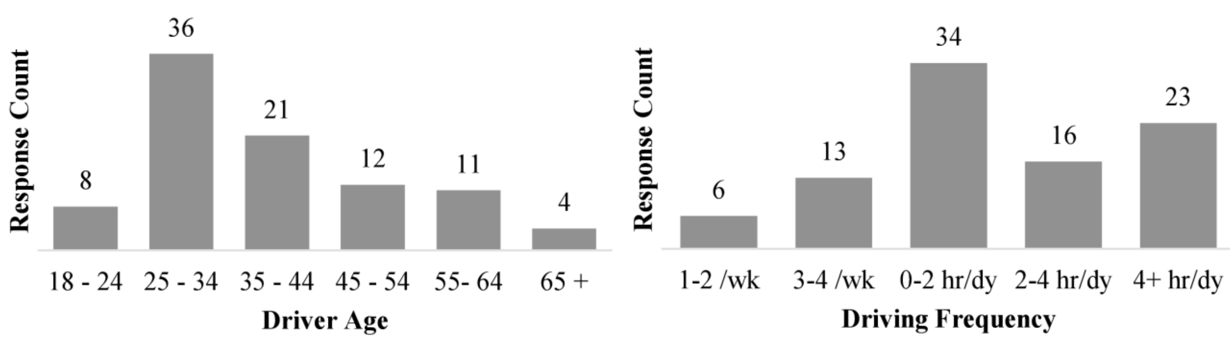


Figure 8. Distribution of participants' ages (left) and driving frequency (right)

3.3.2 Measurement of Driving Style

All scores from the driving-style questionnaire (Appendix A, Q7) were reversed such that high scores reflected a smooth driving style. A principal component analysis (PCA) was then performed on all the questionnaire items as well as the question based on the video shown in Figure 8 (Appendix A, Q8). A scree plot suggested the extraction of a single factor, which matched the questionnaire's objective to measure a single dimension of driving style from dynamic to smooth. Only items with PCA loadings above 0.4 were retained for scoring the factor, which eliminated two items (Appendix, Q7.8, Q8). That is, these two items did not accurately measure the same underlying construct as the other items. The final extracted factor with nine questionnaire items explained 60% of the variance, had a high model fit at 0.98, and very high reliability with Cronbach's $\alpha = 0.91$. A significant Bartlett's test meant correlations between items were sufficiently large for PCA, $\chi^2(36) = 505$, $p < 0.001$. The correlation-matrix determinant (*det* = 0.003) indicated no excess multicollinearity. Residuals were within acceptable limits.

The PCA generated a single standardized score for each participant, which represents the participant's relation to the dynamic-smooth factor. Positive scores pointed to a smoother driving style and negative scores a more dynamic style. A score near zero signified that the participant's responses to the questionnaire items were close to the mean.

3.3.3 Measurement of Driver Inclination Toward Efficient Driving

Another PCA was similarly performed on the driver-inclination questionnaire (Appendix A, Q18). Responses were analyzed as reported, where high scores reflected an eager inclination. A scree plot suggested two possible inflection points extracting either a single factor or three. A single factor was extracted for two reasons. First, only one eigenvalue exceeded 1, which follows the commonly used Kaiser criterion to drop factors with eigenvalues less than 1. Second, the objective of the questionnaire was to measure inclination toward efficient driving as a single dimension from averse to eager. All items had loadings above 0.4 and were thus retained for scoring the factor. The final model explained 58% of variance, had a high model fit at 0.94, and high reliability with Cronbach's $\alpha = 0.85$. Bartlett's test was significant, meaning that correlations between items were sufficiently large, $\chi^2(15) = 252$, $p < 0.001$. The correlation-matrix determinant (*det* = 0.057) indicated no excess multicollinearity. There was a high proportion of large residuals, suggesting that additional factors could have been extracted to improve model fit. The PCA generated standardized scores for each participant, which represented the participant's relation to the averse-eager factor. Positive scores pointed to a more eager inclination toward efficient driving, negative scores a more averse inclination, and scores near zero were close to the mean.

3.3.4 RQ1: Perceived Effectiveness of Displays

The first research question concerned whether the coffee-cup display is perceived as more effective than the wrecking-ball and dial-gauge displays when controlling for various demographics. A linear mixed-effects model was used to analyze participants' perceived effectiveness of the different display types to influence their driving style. Since each participant scored all three displays, the display type was a within-subjects variable with participants modeled as a random factor to account for individual variability. All other measures were included as between subject fixed-effect covariates to determine whether any effect of display type existed when controlling for these other fixed variables. These included categorical variables: age, gender, driving experience, driving frequency, and existing display, and continuous variables: driving style and driver inclination as standardized factor scores from the PCAs.

3.3.4.1 Variable Manipulation

Some of the categorical control-variable levels had very small group sizes. For example, age was recorded on a six-level scale, but the 18–24 and 65+ groups had only eight and four participants, respectively. Therefore, some levels had to be merged, otherwise sample-size limitations would have made estimation non-robust. The merging of levels was guided by sample distributions and practical perspectives with the final binary groupings presented in Table 2. From a practical perspective, crash rates have been found to drop dramatically with driver age in a roughly logarithmic decay until ages of at least 60–70 years (McCartt et. al., 2009). For the age distribution in this study, most of that decrease in crash risk occurs up to approximately 35 years of age. Thus, 35 years was chosen as the split point for a binary age variable. Regarding driving frequency, those who reported driving an average of two or more hours per day are likely to include professional and other high-volume and habituated drivers. This is a group which often consumes lower attentional resources while driving (Lyu et. al., 2017). Thus, two or more hours per day was chosen as the split point for a binary driving frequency variable.

The dependent variable, perceived effectiveness of the display, was reported on a seven-point Likert scale. Recall this scale ranged from (1) Very effective for driving more smoothly, to (7) Very effective for driving more dynamically, with (4) No effect, in the middle. The responses were centered such that "No effect" scored 0, "Very effective" toward smooth scored 3, and "very effective" toward dynamic scored −3. Thus, a positive perceived effectiveness corresponded to effectiveness toward smoother driving.

Table 2. Binary categorical demographic variables for RQ1 following group merging to avoid small sample sizes

Variable	Level 0	Level 1
Age	<35 years (n = 44)	≥35 years (n = 48)
Gender	Female (n = 42)	Male (n = 50)
Driving experience	<10 years (n = 27)	≥10 years (n = 65)
Driving frequency	<2 hrs/day (n = 53)	≥2 hrs/day (n = 39)
Existing display	No display (n = 54)	Has display (n = 38)

3.3.4.2 Model Construction

Of primary interest is whether the main effect of display type was significant while controlling for the effects of all other variables. An additional exploratory analysis looked at the two-way interactions of these covariates with display type. However, the sample was neither sufficiently large nor complete enough to examine all possible interactions at an adequate power level. Building the mixed-effects model progressively, a significant variance was accounted for in both random intercepts across participants and random slopes for display type, so both were included in the model. All covariates and their two-way interactions with display type were entered in the model in a single block. Next, a both-ways stepwise regression was performed to build the final model by minimizing the AIC (Akaike Information Criterion). The resulting model included only display type, driving frequency, and the interaction between the two as predictors, meaning that no other covariates had a significant effect on the model.

3.3.4.3 Model Results

Figure 9 shows the adjusted mean scores for each display type's perceived effectiveness, where error bars represent 95% confidence intervals. All mean scores are positive, indicating that participants predominantly felt that all the displays would influence them to drive more smoothly. The final stepwise reduced model is presented in Table 3 and adjusted means are reported below.

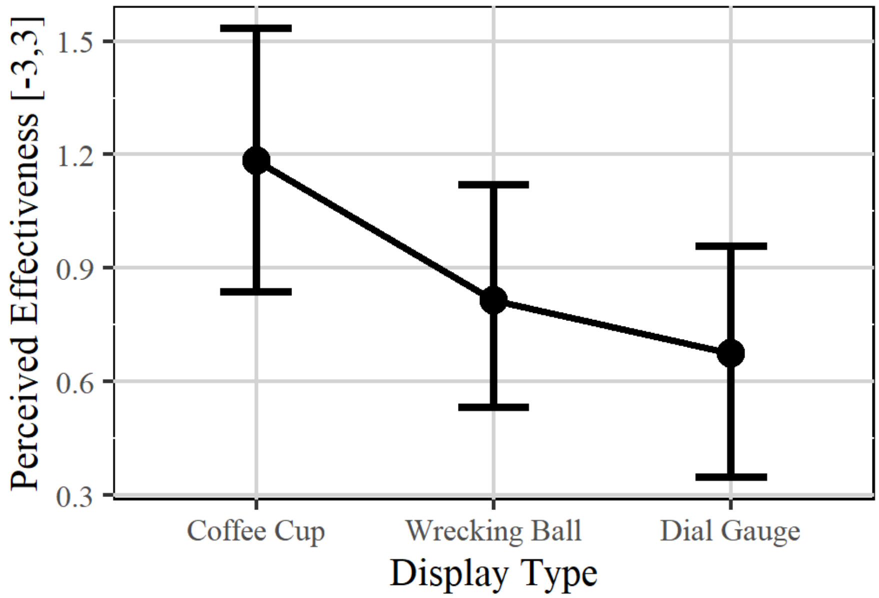


Figure 9. Mean perceived effectiveness (bounds: −3, 3) by display type, where error bars represent 95% confidence intervals. Perceived effectiveness of the coffee-cup display is significantly higher than the dial-gauge display but not significantly higher than the wrecking-ball display.

The main effect contrast between the coffee-cup display (M = 1.12, SE = 0.18) and the dial-gauge display (M = 0.67, SE = 0.16) was significant, $b = -0.45$, $t(180) = -2.21$, $p < 0.05$, d = 0.47. However, the main effect contrast between the coffee-cup display and the wrecking-ball display (M = 0.80, SE = 0.15) was not significant, $b = -0.32$, $t(180) = -1.80$, ns. Only one other covariate, driving frequency, was retained in the model and had a significant main effect on the perceived effectiveness of the displays, $b = 0.41$, $t(90) = 2.26$, $p < 0.05$, $d = 0.34$. Participants who drove less than 2 h per day perceived the displays as more effective overall in influencing a smoother driving style than those who drove 2 h or more per day. Figure 10 shows the interaction between display type and driving frequency; however, only the main effect of frequency was significant and not the interaction.

When the model was constructed using forced entry including all covariates and two-way interactions with display type, the significance of all covariates was unchanged. An examination of model assumptions revealed acceptable normality and homoscedasticity of residuals and no excess multicollinearity.

Table 3. Linear mixed-effects model of the perceived effectiveness of the intervention displays while controlling for driving frequency

	b	*SE*	*DF*	*t*	*p*
(Intercept)	1.12	0.18	180	6.25	<.001
Cup vs Ball	-0.32	0.18	180	-1.80	.073
Cup vs Dial	-0.45	0.21	180	-2.21	.028*
Driving frequency	0.41	0.18	90	2.26	.027*
Cup vs Ball : Frequency	-0.32	0.18	180	-1.80	.073
Cup vs Dial : Frequency	-0.38	0.21	180	-1.84	.068

* significant at p < .05

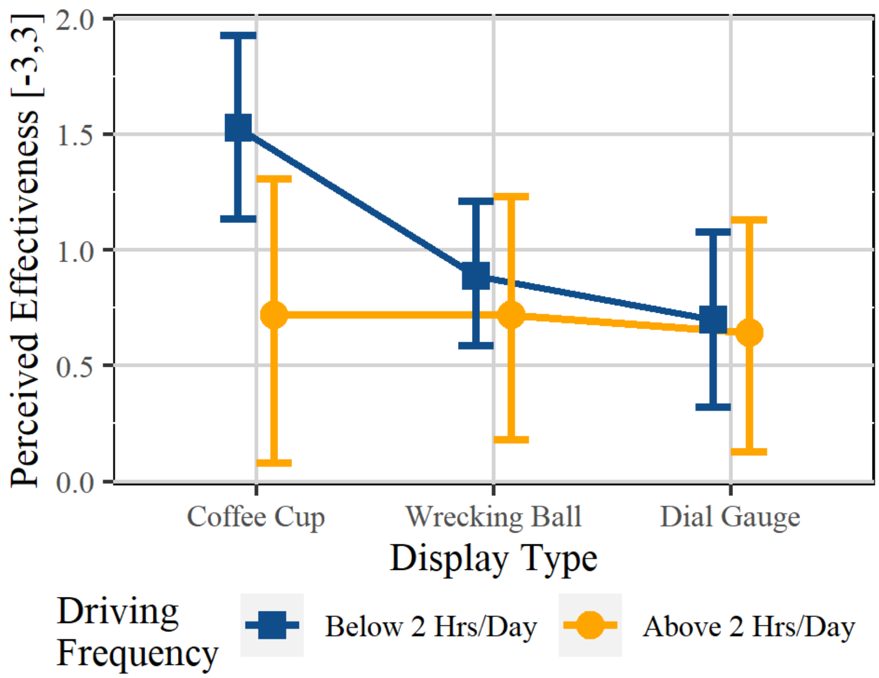


Figure 10. Mean perceived effectiveness (bounds: −3, 3) by display type and driving frequency, where error bars represent 95% confidence intervals. Significant main effect of driving frequency but no significant interaction with display type.

3.3.5 RQ2: Relative Effectiveness of Displays

The second research question was specific to participants reporting an existing efficiency display in their current primary vehicle: Do these drivers perceive each intervention display's effectiveness differently when asked to compare it with their existing display? To answer this question, two additional linear mixed-effects models were built to analyze these 38 participants. Both models included display type as a within-subjects variable with the participant modeled as a random factor to account for individual variability. The subgroup of participants who reported having an existing display was first asked how effective they felt their existing display was at influencing them to drive more efficiently. This perceived effectiveness of their existing display, and its interaction with display type, were included as between subject fixed-effect covariates in both models. The first model describes absolute effectiveness in terms of smoothness. This model examines whether the intervention displays (coffee-cup, wrecking-ball, and dial-gauge) were perceived to be effective for influencing smoother driving when controlling for existing display effectiveness. The second model describes relative effectiveness in terms of efficiency. This model examines whether participants perceived the intervention displays as relatively more or less effective than their existing display in influencing them to drive more efficiently when controlling for existing display effectiveness. In the absolute model, participants' ratings of the intervention displays were made as independent evaluations, while in the relative model, ratings were made as comparisons with their existing display. Further, the effectiveness ratings in the absolute model were in terms of influencing smooth driving style, while in the relative model they were in terms of influencing efficient driving.

3.3.5.1 Variable Manipulation

The existing display's effectiveness was reported on a six-point Likert scale from (1) Not effective at all, to (6) Extremely effective. Due to a low number of responses at some levels, the scale was grouped into two categories: "Lower effectiveness" including (4) Moderately effective and below (n = 22) and "Higher effectiveness" including (5) Very effective and above (n = 16).

The dependent variable for the absolute model was the same as in RQ1 and was scored equivalently. The dependent variable for the relative model was the effectiveness of each intervention display when compared with the existing display. This measure was reported on a six-point Likert scale from (1) Much less effective, to (6) Much more effective than the existing display at influencing more efficient driving. Since there was no neutral option, 0 was set between the two middle options such that the extremes were scored 2.5 for being much more effective and −2.5 for being much less effective. Thus, a positive relative effectiveness corresponded to a greater perceived effect of the intervention display over the existing display.

3.3.5.2 Absolute Effectiveness in Terms of Smoothness

Similar to the RQ1 analysis, the dependent variable here is the perceived effectiveness of intervention displays on influencing driving style. Building the mixed-effects model progressively, a significant variance was accounted for in random intercepts across participants, but not random slopes for display type, so only random intercepts were retained in the model. Both covariates and their interaction term were entered in a single block of the regression. The coffee-cup display (M = 0.96, SE = 0.27) scored higher than both the wrecking ball (M = 0.66, SE = 0.27, b = −0.29, t(72) = −0.95, ns) and the dial gauge (M = 0.71, SE = 0.27, b = −0.24, t(72) = −0.78, ns). Participants with an existing efficiency display appeared to have a slight preference for the coffee-cup display, as shown in Figure 11, but the difference was not significant. There was also no interaction between display types and the effectiveness of the driver's existing display, and no main effect of the existing display's effectiveness.

The model showed some evidence of non-normality and heteroscedasticity of residuals but did not appear to have major deviations from the relevant assumptions. Further, there was no significant multicollinearity.

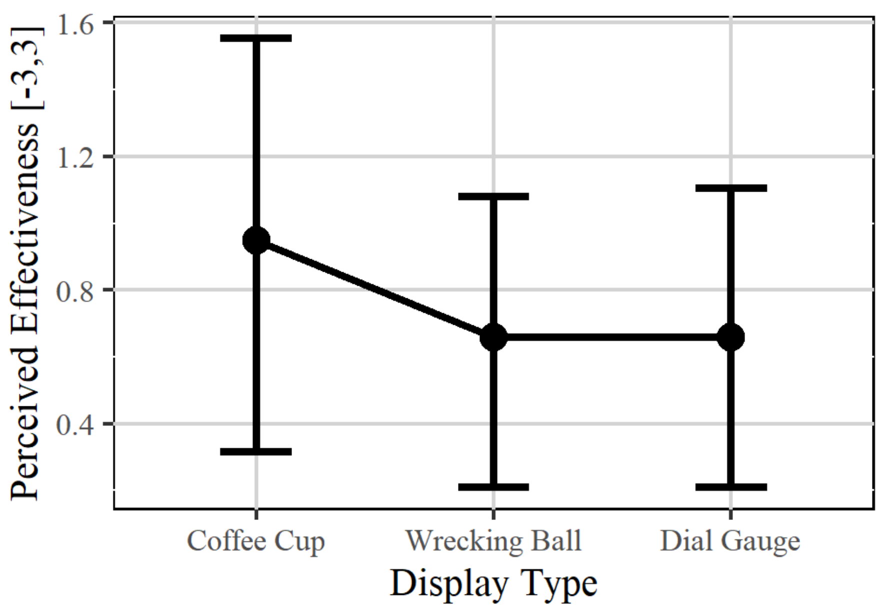


Figure 11. Mean absolute effectiveness (bounds: −3, 3) by display type for drivers with an existing display, where error bars represent 95% confidence intervals. The coffee-cup display scored higher on effectiveness than the other two displays but not significantly.

3.3.5.3 Relative Effectiveness in Terms of Efficiency

Drivers who reported that they had an existing display were asked to consider each intervention display again. This time, participants reported the effectiveness of the intervention displays relative to their existing display for influencing them to drive more efficiently. A linear mixed-effects model with the same subgroup of participants was run with the same covariates, but with relative effectiveness as the dependent variable. For this model, display type, existing-display effectiveness, and their interaction were again entered in the model in a single block. There was a significant variance in random intercepts across participants, but not in random slopes for display type, so only random intercepts were retained in the model.

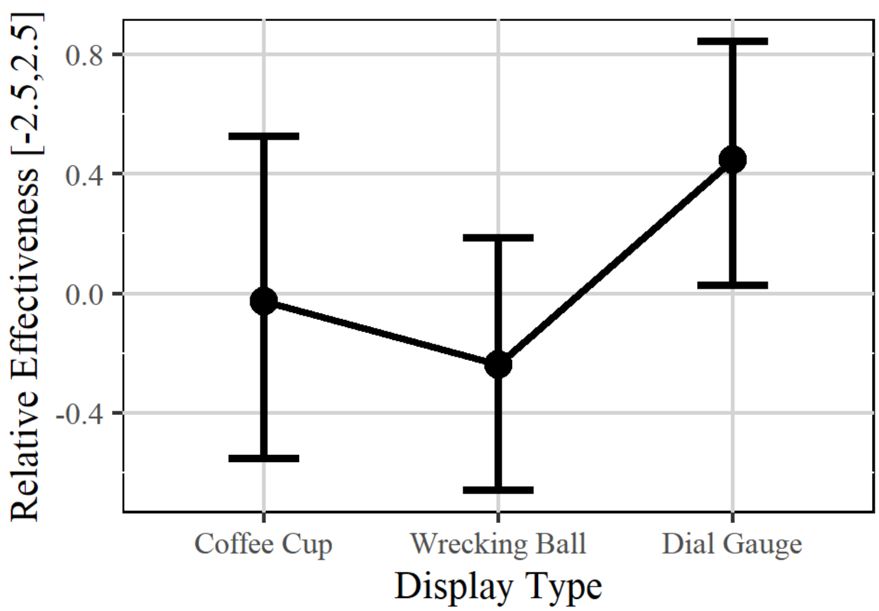


Figure 12. Mean relative effectiveness (bounds: −2.5, 2.5) by display type compared with drivers’ existing display, where error bars represent 95% confidence intervals. The dial-gauge display scored higher on effectiveness than the other two displays but not significantly.

Once again, no significant effects were found. However, the results revealed a different trend in scores between display types as shown in Figure 12. Scores for the coffee-cup display (M = 0.00, SE = 0.27) were higher than for the wrecking-ball display (M = −0.25, SE = 0.22, b = −0.25, $t(72)$ = −0.91, ns), but lower than for the dial-gauge display (M = 0.50, SE = 0.23, b = 0.49, $t(72)$ = 1.43, ns). More data are required to assess whether these trends are conclusive. There was no interaction between display type and existing-display effectiveness and no main effect of the existing display’s effectiveness. The model had an acceptable normality and homoscedasticity of residuals and no excess multicollinearity.

3.4 Discussion

This survey was a preliminary investigation into the effectiveness of the coffee-cup display as an intuitive eco-driving intervention. The results suggest the possible importance of associative and contextual elements in promoting a smoother driving style, with reduced acceleration variance and lower energy consumption.

3.4.1 RQ1: Perceived Effectiveness of Displays

The first research question was whether the coffee-cup display was perceived to be more effective overall than the wrecking-ball and dial-gauge displays at influencing participants to drive more smoothly. The coffee-cup display scored significantly higher on perceived effectiveness than the dial-gauge display, and higher, but not significantly, than the wrecking-ball display. The complete forced-entry model attempted to control for: driver age and gender; driving experience, frequency, and style; driver inclination; existing display; and two-way interactions between these covariates and display type. The elimination during AIC stepwise reduction of all predictors except display type, driving frequency, and their interaction, indicated that none of the other covariates accounted for significant variance in the model. The significant difference in perceived effectiveness between the coffee-cup and dial-gauge displays in both forced-entry and final models suggests that the coffee-cup display might be preferred across demographic factors. However, the merging of covariate levels limits the robustness of the findings. In addition, the analysis showed that none of the two-way interactions with display type were significant, suggesting that differences between displays may not have been moderated by the other variables. The investigation of interactions was performed as an exploratory analysis without an a priori hypothesis. A sample size sufficient to detect hypothesized main effects may be insufficient to detect interaction effects. Of interest, the difference in perceived effectiveness of the coffee-cup and dial-gauge displays was significant after controlling for driving style (dynamic to smooth) and driver inclination toward efficient driving (eager to averse). This suggests that the coffee-cup display may be effective for drivers of varying styles and environmental attitudes, which is a specific intention of this display design. However, this interpretation should be treated cautiously due to the study's small sample size, which may not have captured enough data to demonstrate this finding.

Participants who drive less than 2 h per day perceived a significantly higher overall effectiveness for all displays than those who drive more than 2 h per day. This could be because those who spend a large amount of time driving, possibly because they drive as their job, have more deeply ingrained driving habits that they do not feel a novel display would change. Of interest is whether this distinction would hold in a future study that takes direct measures of effectiveness instead of self-reported effectiveness.

Preference for the coffee-cup over the dial-gauge display, shown in Figure 9, had a medium effect size (d = 0.47), which is an encouraging finding. The coffee-cup display being perceived as more effective than the much more familiar looking dial-gauge display is notable. The significant result in favor of the coffee-cup display suggests that the associative element may be an important and compelling aspect of the intervention. Overall, the results are inconclusive regarding the hypothesis that the combination of associative and contextual elements is more effective than either element alone. Further study is required to determine whether these elements cause the coffee-cup display to be more intuitive and conducive to skill-based behaviour.

3.4.2 RQ2: Relative Effectiveness of Displays

The second research question asked whether drivers with an existing display perceived the interventions' effectiveness differently when comparing each with their existing display. The first model examined absolute display effectiveness in influencing driver style, while the second examined relative display effectiveness in influencing efficient driving. Both models controlled for existing-display effectiveness, since perceptions of new displays were likely to be influenced by the existing-display experiences.

No significant differences were found between display types, but interesting trends in the means are worth further consideration. When the displays were rated on absolute effectiveness, before the mention of fuel/energy efficiency, the coffee-cup display seemed to be preferred over the other two displays. A different trend arose when comparing each display's perceived effectiveness to influence more efficient driving with participants' existing displays. Here, the dial-gauge display scored higher and was the only display with a positive adjusted mean score. The coffee-cup display was second with an adjusted mean score of 0, and the wrecking-ball had the only negative adjusted mean effectiveness score.

The difference in results may be due to the framing of each question or the context in which they were asked, revealing potential bias toward the status quo. The absolute versus relative framing, and reference to influencing driving style versus more efficient driving, both changed between questions. In addition, comparing with an existing efficiency display may prime thoughts of energy efficiency which were absent in the first question, leading to different preferences. The relative-effectiveness question may have also introduced bias by referencing the existing display immediately after a question on its perceived effectiveness. Thus, the familiarity of the dial-gauge display may have become a greater factor in participants’ responses. Finally, the small subgroup sample size of 38 may have led to unrepresentative results.

3.4.3 Limitations

Generalizing the findings of this study raises several questions. Most fundamentally, participants self-reported the perceived effectiveness of interventions, and perceived effectiveness does not necessarily reflect actual effectiveness (Kormos & Gifford, 2014). Furthermore, interventions that employ reflexive-processing heuristics often influence users more than they would expect (Thaler & Sunstein, 2008).

Another source of uncertainty is gauging how consistent participants’ interpretations of the displays, questions, and response scales were with those intended. Since participants were shown very basic mock-ups of the proposed displays, it is unclear how closely their understanding matched the displays’ intended functionality. A driving simulator study that exposes drivers to functional displays and measures driving style quantitatively using acceleration data is developed in the next chapter. Finally, MTurk data quality and representativeness could be questioned. Despite these limitations, the results suggest there is a utility in further investigating the coffee-cup display and its theoretical framework.

3.5 Conclusion

This study was intended to gain preliminary insight into the coffee-cup display's potential to increase the adoption of a smoother driving style as an eco-driving practice. An animated coffee-cup dashboard display of instantaneous acceleration was perceived to be significantly more effective than a dial-gauge display among a variety of drivers (d = 0.47). Preference for the coffee-cup over the dial-gauge display was not predicted by any measured demographic variables (age, gender, driving experience/frequency, driver style/inclination, existing display) and was significant after controlling for those variables. Frequent driving (two or more hours/day) predicted a lower overall perceived effectiveness of the intervention displays to influence driving style. A larger sample size would allow further investigation of interaction effects and relative effectiveness. This study was an initial step and proof-of-concept to evaluate the perceived effectiveness of an intuitive eco-driving display. Study 2 will examine whether real reductions in acceleration and energy consumption arise if drivers use interfaces like the coffee-cup display in a driving simulator.

Chapter 4

Study 2: Developing a Simulator Study Testing the Effectiveness and Safety of the Coffee-Cup Display

4.1 Introduction

This chapter details the development of functional prototype displays and a driving simulator experiment for the direct evaluation of behaviour change according to acceleration, fuel consumption, and eye glances. Due to the COVID-19 pandemic, the execution of the study was postponed beyond the timeframe of this thesis. The intention is that the information provided in this chapter will enable other interested researchers to continue this work and potentially attract additional collaboration and funding.

4.1.1 Study Objective

In this study, I sought to test whether a functional prototype of the coffee-cup display influences users to drive significantly more smoothly and efficiently than a traditional fuel consumption display. This must be evaluated by direct measurement of acceleration and fuel consumption while the driver is presented with the display in a realistic driving environment. Additionally, I wished to examine whether the coffee-cup is effective due to its hypothesized intuitive and engaging nature. This would help with generalizing the results beyond the coffee-cup display to a potentially repeatable motive substitution strategy for similar behaviour change problems. To accomplish this, the coffee-cup display must be compared to control displays that selectively diminish how intuitive or engaging the display is while introducing as few confounding variables as possible.

A medium fidelity driving simulator study was planned where each participant would drive a predefined course multiple times, with a different intervention display shown for each drive. A repeated-measures design where every participant uses every display allows for fewer participants while retaining sufficient statistical power due to reduced participant-to-participant variability. One of the shortcomings of running the study in this way, as opposed to a longitudinal study, is that measurements of driving style will be taken during the period of initial exposure to the new displays. While the coffee-cup is specifically designed to be intuitive and not require any instruction, there will inevitably be a learning curve for participants to incorporate it into their driving habits. The initial exposure period may result in a different level of effectiveness, as well as cause a different level of distraction, than the long-term effects once a driver has become accustomed to the display. To partially control for these effects without substantially prolonging the study, participants will be first introduced to each display during a training drive. This offers participants an opportunity to learn the basic functionality of the display before data collection begins.

4.1.2 Research Questions

A new set of research questions were formulated, the first to investigate whether the coffee-cup display is effective when directly measuring driving behaviour, and specifically for the reasons theorized. Since driving simulator studies are impractical to scale to larger sample sizes, the universality of the intervention’s effectiveness cannot be studied by controlling for demographic or attitudinal variables. Instead, participants can be recruited to balance the most important demographic factors such as age and sex. Relevant behavioural and attitudinal measures can also be recorded to explore for potential large effects that could inform future studies.

RQ1. Do drivers complete a driving simulator route with lower measures of acceleration and fuel consumption when shown the coffee-cup display than when shown any of the control displays?

Another question worth investigating is whether drivers have positive opinions regarding the display. Drivers’ subjective opinions of the display are important since an effective, yet unpleasant interface is both less likely to get picked up in the market of consumer vehicles and more likely to get deactivated by drivers.

RQ2. Do participants perceive the coffee-cup display to be more useful and enjoyable than any of the control displays?

Finally, it is critical to test whether the display falls within acceptable limits of driver distraction. The relevant NHTSA in-vehicle device distraction guidelines for individual eye glances during driving simulator testing, discussed in Section 1.4.1, are as follows (NHTSA, 2010):

1. For at least 21 of the 24 test participants, no more than 15 percent (rounded up) of the total number of eye glances away from the forward road scene have durations of greater than 2.0 seconds while performing the testable task one time.
2. For at least 21 of the 24 test participants, the mean duration of all eye glances away from the forward road scene is less than or equal to 2.0 seconds while performing the testable task one time.

RQ3. Do drivers using the coffee-cup display meet both NHTSA eye glance testing guidelines?

In addition to visual distraction, cognitive distraction may impact drivers' road awareness even if their eyes are on the roadway. This can be measured using reaction times to abrupt encounters that prompt sudden braking such as a pedestrian entering the vehicle's path.

RQ4. Are pedal reaction times for sudden braking events longer for the coffee-cup display than for a standard fuel consumption display?

4.2 Intervention Design

4.2.1 Experimental Conditions

The primary intervention of interest is the coffee-cup display as designed according to the behaviour change and usability principles outlined in Chapter 2. However, one of the greatest challenges in behavioural intervention studies is to go beyond the evaluation a single intervention design and whether it worked or did not work. This research is as much about testing the implementation of the underlying theories as it is about testing the coffee-cup design that was conceived. To evaluate the contribution of the intuitive and engaging factors that are expected to contribute to its effectiveness, the coffee-cup display will be compared to three control displays. Unlike Study 1, this time I chose not to compare the coffee-cup display to substantially different display designs such as the wrecking ball and dial gauge because numerous variables change between conditions making it difficult to draw generalizable conclusions. Instead, visually and functionally similar displays were developed that aim to be strictly less engaging (a closed coffee cup) and less intuitive (an overflowing coffee cup). This isolates the key theoretical requirements of a motive substitution intervention with minimal change to the stimuli. The three resulting cup-based display conditions are listed in Table 4 and shown in Figure 13.

The closed cup shown in Figure 13(b), with a lid affixed, is expected to be less engaging because it eliminates any goal-orientation of the interface. If the coffee cannot be spilled, there is no reason to avoid high intensity accelerations and decelerations. Inevitably, this means the spill effect is eliminated, but the sloshing liquid otherwise presents drivers with the same information as the open cup display. The overflow cup shown in Figure 13(c) involves a different and unintuitive physical model. Instead of a fixed volume of liquid sloshing side-to-side in response to accelerations, the liquid functions as a vertical linear acceleration gauge. When acceleration is 0, the cup is empty, and as acceleration or deceleration increases to larger absolute values, the cup fills until it overflows. This maintains the engaging goal-orientation of the original open cup display but presents it with a non-standard and unrealistic physical analogy. Drivers are expected to have a more difficult time learning to use the overflow cup despite it offering equivalent information to the open cup display.

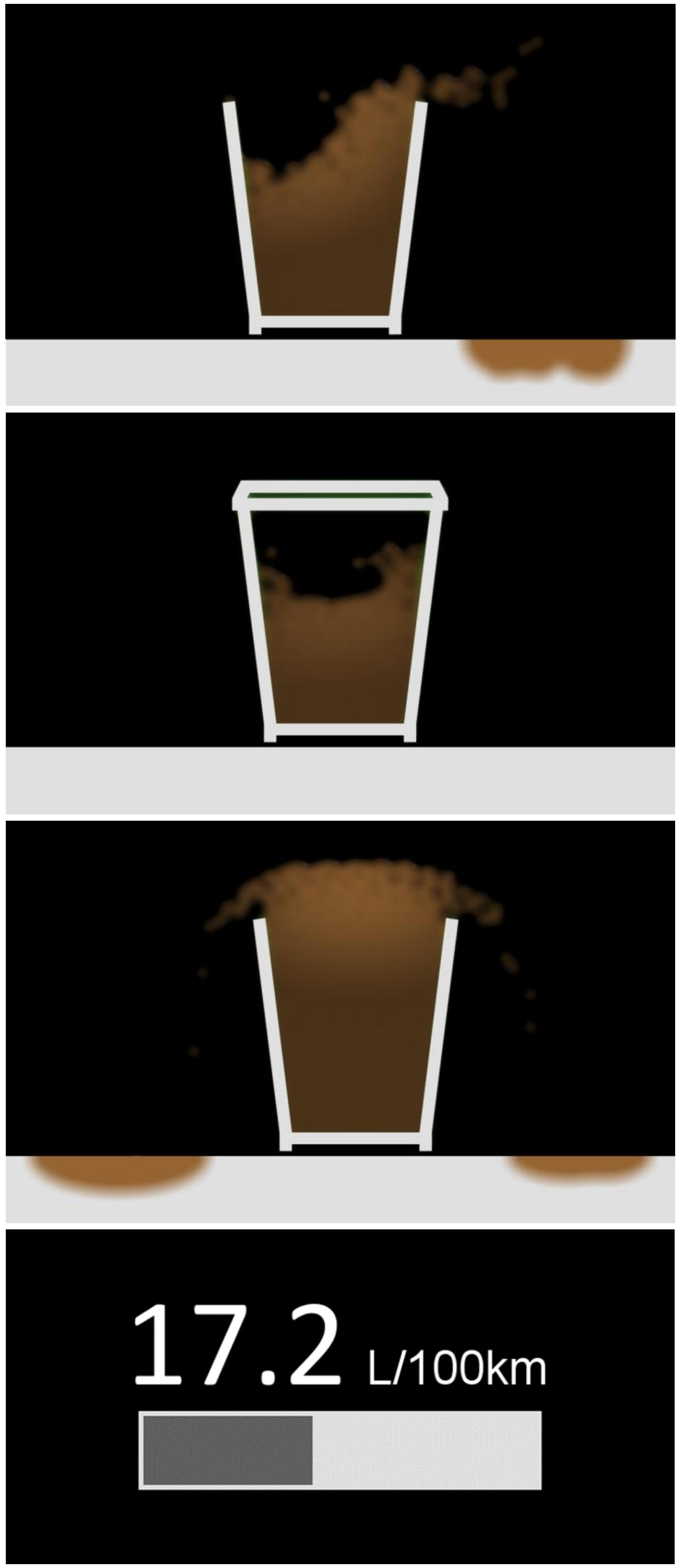
As a baseline control, the cup-based displays will be compared to a traditional fuel consumption gauge. While there are a variety of displays that could be used as a control, the most prevalent fuel efficiency interface in existing vehicles is an instantaneous fuel consumption gauge. This is often a digital numerical display, sometimes with a simple graphical aid, such as a horizontal bar or dial gauge (Jenness et. al., 2009). The prototyped fuel consumption gauge, shown in Figure 13(d), is substantially different than the cup-based displays, so element-wise comparison is not possible. However, this display will be used to set a baseline for the driving behaviour metrics against which the performance of the primary open coffee cup condition can be compared.

Table 4. Study 2 experimental display conditions

Condition Type	Condition Name	Condition Appearance
Intuitive and engaging	Open cup	Figure 13 (a)
Intuitive, less engaging	Closed cup	Figure 13 (b)
Engaging, less intuitive	Overflow cup	Figure 13 (c)
Baseline control	Fuel consumption gauge	Figure 13 (d)

4.2.2 Prototype Development

All intervention displays were created in Processing, a Java-based graphical library and integrated development environment that is popular for rapid visual interface creation. The realistic sloshing liquid effect was achieved using Processing’s LiquidFun and PixelFlow libraries and receive data inputs from the driving simulator.



(a)

(b)

(c)

(d)

Figure 13. Sample frames of (a) open coffee cup during spill, (b) closed coffee cup, (c) overflow coffee cup during spill, and (d) fuel consumption gauge

The development of the prototypes demanded that numerous minor design decisions be made, many of which can be considered from the perspective of the guiding theories discussed in Chapter 2, and others which are likely arbitrary and of little consequence. For instance, the background and cup colours, the geometry and size of the cup, the colour of the liquid, and the many fluid simulation parameters which affect the liquid's motion are all elements that could potentially enhance or interfere with the effectiveness of the display. Some of these detailed design elements are also exclusive to each display condition, complicating the comparison of results. Some important elements of interest are discussed below.

One notable change that was made to the cup-based displays compared to the Study 1 mock-up is the removal of the colour threshold indicator on the surface of the liquid which was left out for three reasons. First, when tested in the prototyped displays, the colour was distracting and made it difficult to identify the image as a cup of coffee. Second, the colour introduced a redundant element to the display that unnecessarily complicates the experiment when the aim in this study was to test the coffee-cup display in its simplest form. Lastly, colour-coded symbolism is problematic for the substantial proportion of the population who are colour blind.

The background and cup colours were chosen as black and pale gray respectively to match the widespread use of a dark-background colour scheme in vehicle dashboards. The geometry of the coffee cup was based on a Tim Hortons small take-out cup. The colour of the liquid was chosen to be easily identifiable as coffee while still being highly visible on the black background.

The open-cup and overflow-cup displays allow the possibility of spilling the liquid out of the cup. This is the state that drivers are intended to avoid due to its undesirability in the real-world. However, expressing that undesirability of spilling in the display design is non-trivial. If the cup is displayed as hovering in space and liquid that spills falls out of view at the bottom of the screen, this presents two problems. First, this may not be perceived as a sufficiently undesirable outcome to induce a change in behaviour. Second, and more importantly, the driver will only be aware that liquid was spilled if they are actively looking at the display during the few seconds it is occurring. This is an important opportunity to improve over standard fuel consumption gauges by reducing distraction. To overcome these problems, some way of displaying the spilled liquid below the cup is needed. This was achieved with a light-gray region below the cup which displays a spreading stain as liquid spills and lands on its surface. The behaviour of this surface is inspired by an absorbent car seat cushion, such that liquid would spread and soak into the material forming a large stain. The expectation is that a salient brown stain on a light background will effectively communicate the undesirability of spilling to drivers.

For drivers to observe, without distraction, that an acceleration event has caused the liquid to spill, the stain must persist on the display until the driver has a suitable time to glance. However, if the stain remains permanently, for example until the end of the drive, then each new stain could quickly become indistinguishable from those caused previously. A relatively dynamic driver could quickly stain the entire surface with spilled liquid, preventing any further spills from being visible. Additionally, the complete 'painting' of the surface with stains could be treated as an alternate gameful objective by the driver, resulting in more dynamic driving behaviour, opposite to the desired outcome. Consequently, the stains were programmed to linger for approximately 10 seconds, fading away in the last few seconds. When a driver causes a high acceleration event, they thus have 10 seconds to make a momentary glance at the display and verify whether it resulted in a spill. This sort of periodic glance habit being encouraged by the design of the open and overflow cup displays is similar to the glances made to a vehicle's speedometer and mirrors. For these additional glances to be safe and non-distracting, the information from each glance must be processed reflexively, a principle that has already guided the design of the open-cup display.

4.2.3 Display Calibration

The final step of prototype development for the cup-based displays was to link the data outputs from the simulator to the intervention displays and calibrate an algorithm for processing this data to enable a realistic dynamic response. For example, the coffee-cup display would be ineffective if it were to spill with every slight acceleration, only spill during severe braking events, or offer inconsistent functionality at high and low vehicle speeds. Passing raw acceleration data directly to the display's physics simulator as a scaled horizontal component of the gravity vector did not produce workable results. Vehicles can generate much higher accelerations at low velocities, so if the spilling acceleration threshold of the cup is calibrated for low velocities, the liquid will not spill at higher velocities. Through trial and error iteration, formulas were developed for transforming true acceleration from the simulator to adjusted acceleration inputs to the display.

The resulting relationships, distinct for acceleration (Accel +) and deceleration (Accel -), are given in the following equations:

$$\text{Accel} + _{\text{Display}} = \left(0.5\text{Accel}_{\text{True}} + 0.5\text{Accel}_{\text{Display, t-1}}\right)\left(1+\frac{\text{Velocity}}{30}\right)(1+\text{Throttle})$$

$$\text{Accel} - _{\text{Display}} = \left(0.5\text{Accel}_{\text{True}} + 0.5\text{Accel}_{\text{Display, t-1}}\right)\left(1+\frac{\text{Velocity}}{35}\right)$$

The positive acceleration formula has three components: a simple two-point moving average smoothing function, a velocity-scaled multiplier, and a throttle-scaled multiplier. Throttle is the amount the gas pedal is depressed, given by the simulator as a value between 0 and 1. The negative acceleration formula is nearly identical with a slightly different velocity multiplier and no throttle dependence. Using these acceleration transformations, the display provides a consistent experience while driving at a range of speeds, making the task of preventing spills more manageable and representative of the desired smooth driving behaviour.

4.3 Experiment Development

4.3.1 Apparatus

The study was designed to be run on the National Advanced Driving Simulator (NADS) Quarter Cab miniSim at the University of Toronto’s Human Factors and Applied Statistics (HFASt) Lab. The simulator cabin configuration is shown in Figure 14. This simulator offers a visually and mechanically realistic left-hand-drive cabin interface with seat, dashboard, steering wheel, pedals, and other standard driver controls. The roadway is displayed on three large monitors and vehicle and road sounds are played over built-in speakers. A sample of the simulated roadway environment, including the position of the intervention displays, is shown in Figure 15. The intervention interfaces are displayed on a Microsoft Surface tablet mounted to the right of the main vehicle dash, close to where a central media console would be on most vehicles.

Figure 14. NADS Quarter Cab miniSim driving simulator cabin configuration

Figure 15. NADS miniSim driving simulator driver's view showing positioning of intervention display on right side of dashboard area

The simulated environment is constructed using the Tile Mosaic Tool (TMT) and Interactive Scenario Authoring Tool (ISAT) software applications provided by miniSim. TMT is used to create the static environment using prebuilt modular tiles that include various sections of roadway with buildings and landscape. ISAT is then used to populate this environment with interactive elements including Autonomous Dynamic Objects (ADOs) and Deterministic Dynamic Objects (DDOs) such as vehicles and pedestrians. Only DDOs, which follow pre-defined paths, are used in this experiment to maintain consistency across participants and display conditions.

The HFASt Lab's miniSim installation also includes an Ergoneers eye tracking system to record participants' eye movements and fixations throughout a test drive. This will be used to measure the number and duration of glances away from the roadway and on the intervention displays to determine their distraction potential.

4.3.2 Output Variables

The miniSim records all available instantaneous data at a frequency of 60 Hz including the required output variables of longitudinal velocity and acceleration, engine speed and torque, and throttle. Acceleration demonstrates the degree to which each condition effects the driving smoothness, the specific eco-driving behaviour being targeted. Fuel consumption demonstrates the degree to which each condition effects actual energy use and emissions which are the real impacts of interest. In theory, the two measures should agree, but that cannot be assumed, so this is tested in the proof-of-method below.

Acceleration and fuel consumption are both instantaneous measures, but the intervention conditions are best compared by trip, so the variables must be represented through a cumulative measure such as averaging or totalling. Cumulative fuel consumption can be easily represented as total fuel consumed during the trip. However, acceleration has both positive to negative values and totals to 0 if the starting and ending velocities are equal, as they are for a single trip. Thus, other methods must be used to measure acceleration, such as separate mean positive and mean negative values, maximum and minimum values, or standard deviation of acceleration (Kircher et. al., 2013).

4.3.3 Estimating Fuel Consumption

Fuel consumption cannot be directly measured in most driving simulators since it depends on variables that are not included in the simulation model. However, it can be estimated using the available simulator outputs of torque, engine speed, and vehicle speed, together with the brake-specific-fuel-consumption (BSFC) data for the simulated vehicle engine. The first three variables are generated in real-time by the NADS miniSim and can thus be recorded throughout a test drive. BSFC is a matrix of the grams of fuel the engine consumes per kilowatt-hour of energy it generates. This relationship varies with engine speed and applied torque. Optimal fuel efficiency typically occurs at moderate engine speeds and high torque, though the precise characteristics vary between engines. While BSFC data is not generally publicly available, the fuel consumption rate matrix (from which BSFC is derived) for a Chevrolet Malibu 2.5L I4 engine is available from the Environmental Protection Agency (EPA, 2016) and miniSim also includes the Malibu as a simulated vehicle option. Matching the BSFC to the simulated vehicle is important to produce accurate results since engine speed and torque ranges vary between vehicles and the miniSim simulation model is engine specific. BSFC is provided as a fuel rate in units of grams-per-second (g/s) at each specified engine speed and torque value and an industry standard density of gasoline is used to convert to volume, 755 grams-per-litre. In Canada, the standard units for reporting fuel consumption are litres-per-hundred-kilometers (L/100km). Having all the necessary inputs, the instantaneous fuel consumption can thus be computed for each value of fuel rate in the matrix using the following equation.

$$\text{Instantaneous Fuel Consumption } \left(\frac{\text{L}}{100\text{ km}}\right) = \frac{\text{Fuel Rate}\left(\frac{\text{g}}{\text{s}}\right) \times 360{,}000\left(\frac{\text{s}}{100\text{ h}}\right)}{\text{Velocity}\left(\frac{\text{km}}{\text{h}}\right) \times 755\left(\frac{\text{g}}{\text{L}}\right)}$$

Bilinear interpolation is used to compute the fuel consumption at the precise engine speed and torque recorded throughout the test drive. At very low vehicle velocities, computed instantaneous fuel consumption approaches infinity, which is not accurate, so a lower bound of 5 km/h was imposed on the velocity value when performing the computation. The consequence is that fuel consumption values were artificially capped at low velocities resulting in overall values being slightly underestimated. This is not expected to compromise the ability to compare values between drives for the purposes of this research. Existing digital fuel consumption displays generally refresh at low frequencies, so a refresh rate of 1 Hz was imposed to better approximate real displays (i.e. the numerical value refreshes once per second).

4.3.4 Simulation Development

To generate a measurable signal for acceleration and fuel consumption in this experiment, the test drive must induce a large number of acceleration and deceleration events. That goal must be balanced with creating a natural driving experience to maximize the likelihood that participants would behave in a manner comparable to their real-world driving style. A route that simulates a suburban commute, including multiple intersections achieves these goals. A drive duration of approximately 7-8 minutes was selected to maintain a reasonable study session time for each participant completing four drives in addition to training and questionnaires. The final route, composed of the prebuilt TMT tiles, is shown in Figure 16.

The route begins in a suburban residential setting and ends in a commercial setting, passing through seven stop-sign and traffic-light intersections along the way and requiring a full stop at each. Extra tiles were added to fully populate the driver’s field of view and avoid edges in the simulated scene. The total length of the route is 5.6 km.

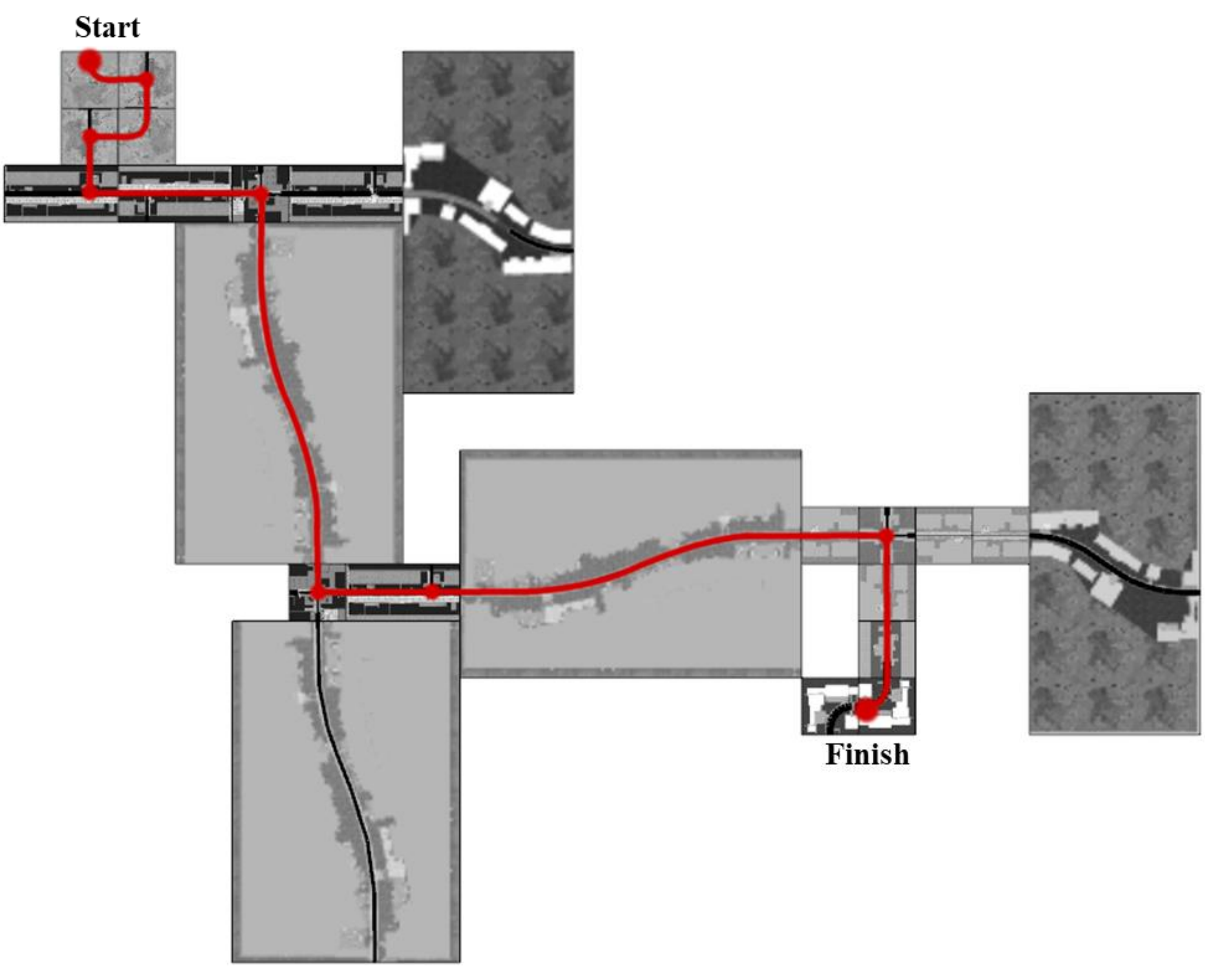


Figure 16. Simulator test route created in TMT intended to represent a 7-8 minute suburban commute including seven intersections

To maintain consistency between conditions, no traffic is included that the driver must interact with or respond to. Only deterministic simulator agents are included to create a more realistic environment. The exception is a single scripted event of a pedestrian abruptly walking into the path of the vehicle. This occurs in a different location for each of the four drives, as well as the training drive, but always at a location where drivers are expected to be at full speed. These scripted events are to measure pedal reaction time for the purposes of answering RQ4. The event is included in the training drive such that initial exposure does not occur during participants' first test condition. The acceleration data for the duration of the event will not be included in the acceleration measures of each drive.

4.3.5 Experimental Design

The simulator study was designed with four intervention conditions to be performed as a factorial repeated-measures experiment counterbalancing condition order. A sample size of 24 (i.e. 4 factorial) is required to achieve a fully crossed design. During the data-collection portion of the experiment, each participant would complete the given route four times, with a different display condition for each test drive. Counterbalancing condition order controls for learning and fatigue effects, but it also means the study objective may be divulged at different points for different participants. While participants will not be told in advance that the study is evaluating driving efficiency or smoothness, the presence of a fuel consumption gauge is highly suggestive of that purpose whereas the coffee cup displays are more ambiguous. This is a necessary side-effect of counterbalancing that is less problematic than using fixed condition order but must still be considered during analysis.

This repeated-measures experimental design enables a greater number of conditions to be tested without requiring a large number of participants. Large sample sizes are very resource intensive for a driving simulator study because the marginal time investment for additional each participant is high due to screening, calibration, simulator training, and questionnaires. Nevertheless, it is important to acknowledge that substantial limitations arise from such a small sample size. Only medium to large effects are likely to be detected, and power is substantially lower for between-subject variables such as age than within-subject variables, in this case display condition (Donmez et. al., 2006). The sample is also unlikely to be highly representative of the population.

4.3.6 Participants

Participants for this study would ideally be recruited from the local general public who pass a screening questionnaire and are willing to participate in-person at the lab housing the simulator in downtown Toronto. The screening questionnaire (Appendix B) asks two types of questions, those for screening out unqualified applicants, and those for acquiring demographic information to balance the participant pool. The screening questions select for applicants who hold a valid driver's license, have 3 or more years of driving experience, drive at least once per week, and are less likely to be prone to simulator sickness. Simulator sickness is a temporary condition similar to motion sickness induced by simulators or virtual reality devices which cause symptoms such as nausea, dizziness, and headache (Hock et. al., 2018).

Aside from the screening criteria, having a balanced demographic diversity of participants reduces bias and makes the results more generalizable. The demographic questions included in the screening questionnaire allow the selection of participants that will achieve a more balanced pool with respect to age, sex, driving experience, and driving frequency. The NHTSA guidelines for in-vehicle device testing recommend including 6 participants from each of four age groups (18-24, 25-39, 40-54, 55+), however, this would interfere with counterbalancing. Given the small sample size in this study, participants will only be recruited from the 25-39 age bracket. This avoids the lowest and highest age groups that are more often associated with an elevated crash risk (McCartt et. al., 2009) as well as older drivers who may be slower to learn and adopt new technology. Participants would be compensated at a rate of $15 per hour for approximately 2-3 hours, pro-rated at $2 per 8 minutes.

4.3.7 Questionnaires

Several questionnaires will be used to measure constructs both for RQ2 as well as exploratory analysis. All questionnaires would be created electronically in Qualtrics and offered to participants using a tablet.

Two questionnaires, both completed after each test drive, are together intended to measure drivers' subjective opinions of each display. The System Acceptance Questionnaire is a popular instrument for measuring how useful and satisfying a device or technology is deemed to be, with each on a separate scale (Van Der Laan et. al., 1997). The Intrinsic Motivation Inventory measures a participant's interest and enjoyment of an activity on a single scale (McAuley et. al., 1989). Overall, this gives three measures for comparing the displays according to drivers' opinions: useful, satisfying, and interesting/enjoyable to use.

The remaining questionnaires, as well as the post-test interview, are included purely for exploratory analysis and to inform future research. The Perceived Driving Style questionnaire (Appendix C) is an updated version of the Driving Style questionnaire from Study 1. The Regulatory Focus Questionnaire (Higgins et. al., 2001) and General Regulatory Focus Scale (Lockwood et. al., 2002) are both designed to measure regulatory focus on two independent scales, promotion and prevention. The Environmental Attitude Inventory (Milfont & Duckitt, 2010) measures general attitudes toward the environment, nature, and conservation. Another environmental attitude scale, the Dragons of Inaction Psychological Barriers Scale (Lacroix et. al., 2019), instead asks about willingness to engage in a particular activity or task related to the environment. Each of these measures could reveal moderating effects on the impact of the coffee-cup display. Large correlations could suggest opportunities to improve the display or tailor it for different drivers.

4.4 Experiment Procedure

Each experiment session has a single participant complete the sequence of simulator drives and questionnaires in 2-3 hours. This procedure is described in three stages: Training, Data Collection, and Debrief.

4.4.1 Training

Each study session begins by providing all important information to the participant about the experiment and obtaining their informed consent. The participant is then given instructions on operating the driving simulator and performs two practice drives of the test course to familiarize themselves with the simulator and intervention displays. In the first training drive, they are not shown any intervention display and are asked to focus on getting used to the vehicle controls and learning the route. In the second training drive, the four intervention displays are shown for 90 seconds each in the same counterbalanced order as that participant will see the displays during the experiment. During this second drive, the participant has an opportunity to see how each display responds to their vehicle movements. The participant is told what each display shows (vehicle acceleration or fuel consumption), but not why it is being shown nor how they should respond to the displays.

4.4.2 Data Collection

The participant then begins the data collection stage during which they complete four simulator drives on the same route, one for each experimental condition in a randomly assigned counterbalanced order (matching the order in training). The participant is instructed to drive in a manner as similar as possible to how they would drive normally, as per the following script:

> "In each of the following four drives, imagine you are commuting to work. Please drive naturally, in the way that is normal for you, without exceptional caution or recklessness. Use the presented displays as you deem appropriate. Please refrain from gross traffic violations such as collisions, excessive speeding, or leaving the roadway. The speed limit for the whole route is 65 km/hr."

At the conclusion of each test drive, the participant completes the System Acceptance Questionnaire and Intrinsic Motivation Inventory, considering the intervention display they just experienced. At no time during the experiment will the topic of efficient driving, fuel consumption, carbon dioxide emissions, or environmental considerations be mentioned by the investigator, aside from stating what the fuel consumption display shows.

4.4.3 Debrief

Following their last simulator condition, participants complete five more questionnaires, the Regulatory Focus Questionnaire, General Regulatory Focus Scale, Perceived Driving Style questionnaire, Environmental Attitudes Inventory, and Dragons of Inaction Psychological Barriers Scale. Lastly, the participant is asked a series of questions in an interview format designed to obtain qualitative long-form responses to inform future research (Appendix D). The participant is then paid their compensation and debriefed about the purpose of the study, after which the study session is over.

4.5 Proof-of-Method Pilot Test

The experiment outlined in this chapter could not be conducted due to the COVID-19 pandemic. Despite this, I performed a proof-of-method pilot test to determine how well the performance measures could be detected using the experimental design described above. At the stage in development when the pilot took place, the simulation environment was completed in TMT, but the environment had not yet been populated with agents in the form of other vehicles and pedestrians, nor the triggered events planned for measuring pedal reaction time. The objective of the pilot was to measure the simulator outputs for three trial drives of the route, each performed with a different driving style (i.e. Smooth, Moderate, and Dynamic), and compare the results. The full experiment would only be effective if the driver's experience of driving more smoothly translates to detectable differences in acceleration and fuel consumption measures. The distinct techniques used in each trial are described in Table 5. Besides these changes in driving style technique, all drives were completed in as similar a manner as possible.

Table 5. Pilot test trials definitions according to display and driving style used

Trial	Display	Technique
Smooth	Open Cup	Accelerate and decelerate as quickly as possible without ever spilling the cup
Dynamic	Open Cup	Accelerate and decelerate only as quickly as necessary to spill liquid at each take-off and stop
Moderate	Fuel Consumption	Drive somewhere in between the styles of Smooth and Dynamic, in whatever way feels most natural

4.5.1 Pilot Procedure

Each trial drive was a complete navigation of the route shown in Figure 16, with a full stop at each of the seven marked intersections as well as at the end. A cruising speed of approximately 65 km/h was targeted in all trials, though it was held more consistently in the Smooth trial and with greater variability in the Dynamic trial. The open cup display was used as a reference in the Smooth and Dynamic trials to define an appropriate acceleration for starts and stops. During the Smooth trial, accelerations were as high as possible without ever spilling liquid from the cup. During the Dynamic trial, all accelerations to and from a standstill caused the liquid to spill from the cup but remained within reasonable levels for driving on a public road. For the Moderate trial, the fuel consumption display was used instead so that the cup could not be referred to for quantifying acceleration intensity. Instead, I targeted a driving style that subjectively felt to be about halfway between the Smooth and Dynamic trials.

4.5.2 Pilot Results

Cumulative results from the pilot test are shown in Table 6, with the percentage difference of each measure shown in Figure 17. Cumulative acceleration was quantified in three different ways, in most cases considering positive and negative values separately. Mean positive and negative acceleration is the absolute value of the average of all acceleration values above or below 0, with small values corresponding to smoother driving. Peak positive and negative acceleration is the single largest value at each extreme. Acceleration standard deviation considers the variability of the measure for both positive and negative values combined, with small values corresponding to smoother driving. Total fuel consumed is computed from instantaneous fuel consumption and the distance covered between each data point. Since it is derived from fuel consumption, the percentage difference between trials is identical to average fuel consumption. For all measures except total trip time, the Dynamic trial had the highest values by at least 5% and the Smooth trial the lowest values by at least 5%. This suggests the experiment measurement methods are sensitive enough to detect changes in driving style if the intervention displays cause a change in driver behaviour.

Table 6. Overall measures of acceleration, fuel consumption, and trip time for pilot test using Smooth, Moderate, and Dynamic driving styles

Measure	Smooth	Moderate	Dynamic
Mean Positive Acceleration [m/s2]	0.40	0.51	0.64
Mean Negative Acceleration [m/s2]	0.55	0.63	0.66
Peak Positive Acceleration [m/s2]	2.1	3.5	3.7
Peak Negative Acceleration [m/s2]	2.9	3.6	5.1
Acceleration Standard Deviation [m/s2]	0.70	0.90	1.17
Total Fuel Consumed [L]	0.30	0.32	0.34
Average Fuel Consumption [L/100km]	5.3	5.6	6.0
Total Trip Time [m:ss]	8:10	7:22	7:00

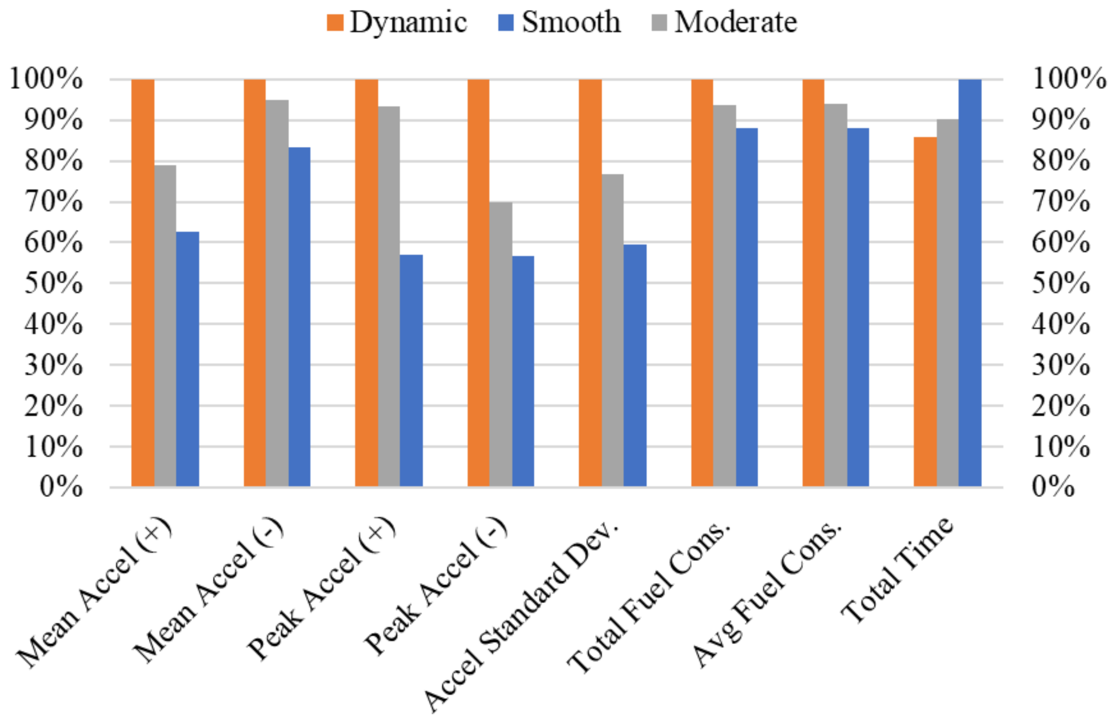


Figure 17. Percentage comparisons for overall measures of acceleration, fuel consumption, and trip time for pilot test using Smooth, Moderate, and Dynamic driving styles

Average fuel consumption was between 5.3 and 6.0 L/100km for the three trials, which is lower than the reported city average of 8-11 for a Chevrolet Malibu. This is unsurprising since many factors that affect fuel consumption are unaccounted for with the methods used here, and because fuel consumption was underestimated at low velocities. Despite these differences, the three trials can still be effectively compared since inaccuracies should remain generally consistent across all drives.

The total trip time demonstrates the cost of adopting a smooth driving style in extending the trip duration. This is an expected consequence of consistently reducing acceleration, but it is difficult to quantify the subjective trade-off of conserved fuel to lost time. Figure 18 shows a plot of consumed fuel over time for each of the trial drives. The end of each line corresponds to the values for Total Fuel Consumed and Total Trip Time in Table 6 and shows the accumulated fuel use throughout the trials. Based on these three simulator trial drives, the fuel savings achieved by using a smoother driving style are approximately proportional to the added trip time. In practice, the trade-off will depend on a variety of route factors including traffic.

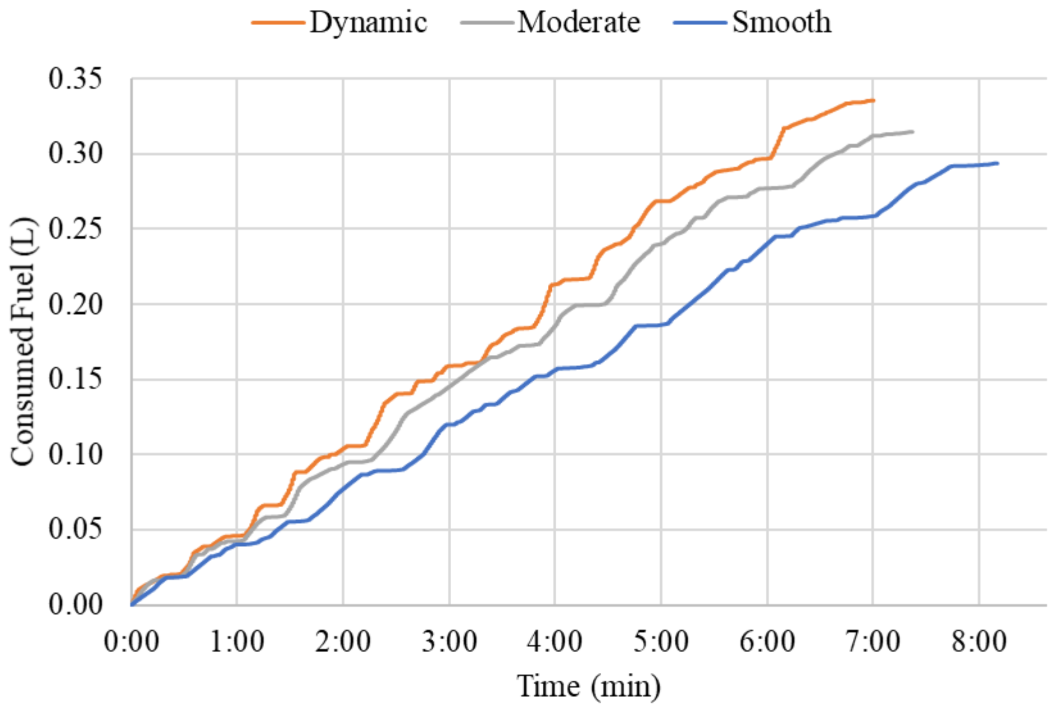


Figure 18. Consumed fuel over time for each driving style during pilot trials

The complete velocity, acceleration, throttle, and fuel consumption curves for all three trials are shown as a function of distance in Figure 19. Velocities were approximately equal during each segment of the route, though slightly lower velocities for the Smooth trial may have contributed to an unusually longer trip time. Acceleration values follow an expected pattern and negative peaks have consistently larger absolute values than positive peaks for all driving styles. Throttle use is noticeably higher for the Dynamic trial than both other trials and shows more of a pulsing technique, which was intentional. Fuel consumption has very large momentary spikes at each take-off for the Dynamic trial. These values should be compared to actual peak fuel consumption values for the engine to ensure they are not inaccurately inflating the fuel measures. Detailed BSFC plots for each trial are shown and explained in Appendix E.

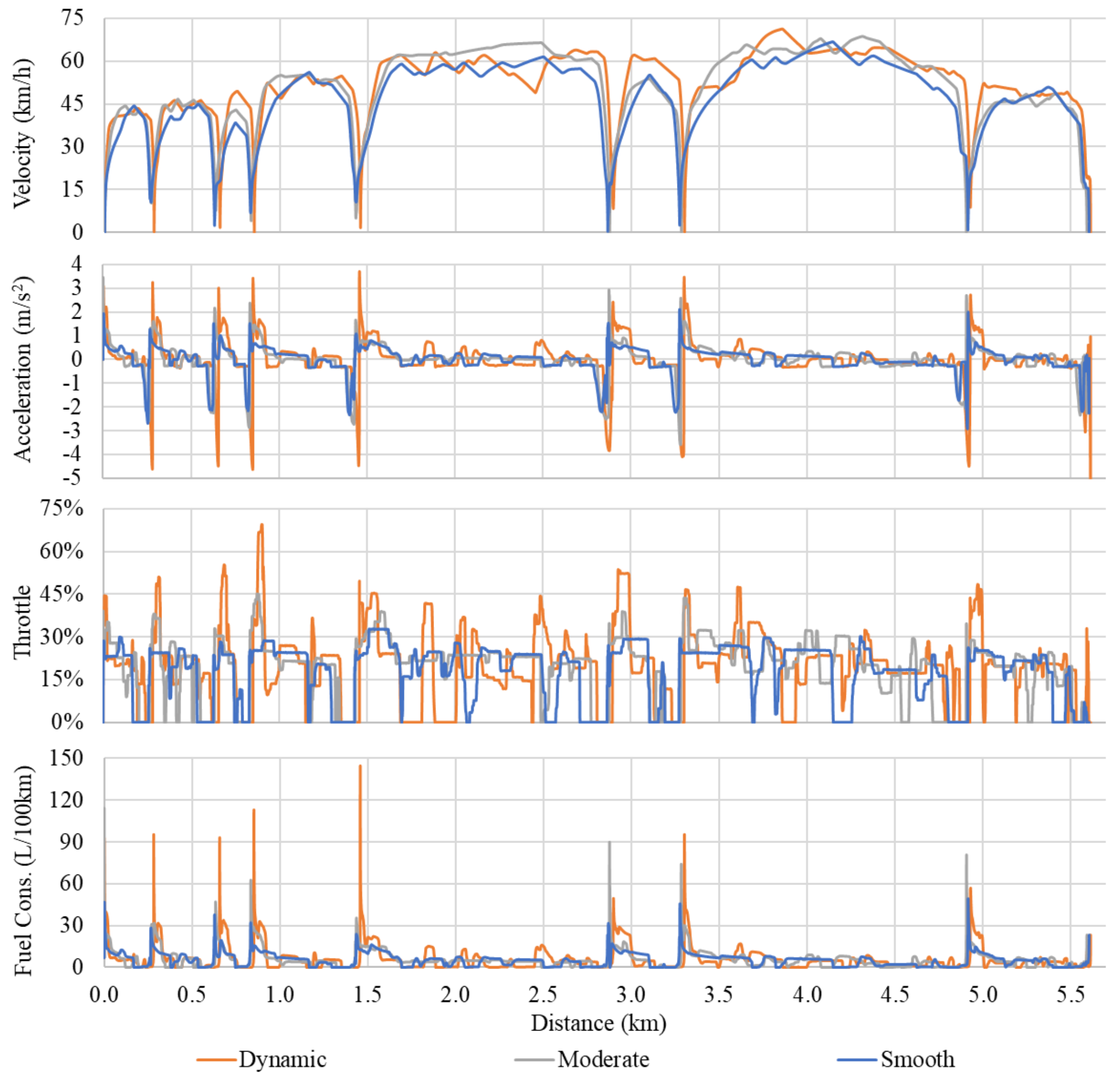


Figure 19. Simulator output data for vehicle velocity, acceleration, throttle, and computed fuel consumption over distance along route for pilot test

The pilot test successfully demonstrated that drives of different styles can be clearly distinguished using the data generated by the simulator. Cumulative results for acceleration and fuel consumption also agreed, suggesting that smoother driving in the simulator does result in lower total computed fuel consumption. Further, it was a successful test of the open cup and fuel consumption prototype displays integrated into the miniSim driving simulator.

4.6 Conclusion

Study 2 was intended to answer four research questions. First, to directly evaluate changes in driving behaviour in response to the coffee-cup display using measured acceleration and fuel consumption. Control conditions would allow comparison to a standard instantaneous fuel consumption gauge and two variants of the coffee-cup display that selectively suppress the theorized intuitive and engaging aspects. Second, to understand drivers' subjective opinions of how useful and enjoyable each display is, suggesting its likelihood to be adopted in the market and accepted by users. The last two research questions investigate driver distraction as a result of using the coffee-cup display. This is done according to standard guidelines for eye glance durations away from the roadway and increases in pedal reaction time to sudden braking events.

While Study 2 could not be completed, a full experiment was developed with four functional prototype displays. A closed variant of the coffee-cup display is intended to be less engaging and an overflow variant is intended to be less intuitive, while both provide equivalent information to the open cup display. An instantaneous fuel consumption gauge was developed that computes accurate values using simulator output data and the brake specific fuel consumption matrix for the simulated engine. A simulator route imitating a short suburban commute with many intersections was created to facilitate the detection of changes in driving style. A proof-of-method pilot was completed to verify that differences in experienced driving style correspond to measurable differences in acceleration and fuel consumption output by the simulator. Since the majority of development work is complete, this study could be quickly resumed and completed by another researcher.

Conclusion and Future Work

The research explored in this thesis has sought to develop and test a practical and illustrative example of a behaviour changing design solution for influencing the consumer class to adopt a meaningful waste-reducing habit. In the process, it was helpful to introduce the concept of "motive substitution" to describe a behavioural design technique that has many existing examples but is not well represented in the behaviour change literature. This technique of designing an alternate task to motivate users as a substitute for the less motivating original task was examined in detail through a case study in energy efficient driving.

Eco-driving practices, especially a smoother driving style characterized by low accelerations, can reduce vehicle energy use and emissions by approximately 5-10%. Driving more smoothly demands little effort and has few compromises, but most drivers are not sufficiently motivated to take the initiative and make it a habit. Considerable research has been done on in-vehicle eco-driving displays over the past two decades, but very few studies have taken a motivational approach to intervention design as opposed to informational. Applying motive substitution, I developed a display that aims to engage drivers and effectively motivate them to practice eco-driving while also aiding them in performing the correct behaviours. A display showing a coffee cup that sloshes in response to the motion of the vehicle is intended to allow drivers to use skill-based behaviour and thus predominantly reflexive processing to moderate their driving style without becoming distracted.

Study 1 investigated the associative and contextual elements of the coffee-cup display that are hypothesized to make it intuitive for drivers. An online survey with 92 participants showed that a diversity of drivers may perceive the coffee-cup display to be more effective than an acceleration dial gauge display that lacks the associative element. Study 2 was developed to test behavioural impacts of the display directly in a driving simulator. The experiment was designed to evaluate the coffee-cup display's effectiveness to reduce acceleration intensity and fuel consumption, subjective opinions of drivers toward the display, and the display's impact on driver eye glances and reaction times. Four functional prototypes were created: the primary open-cup display, a less engaging closed-cup display, a less intuitive overflow-cup display, and a standard instantaneous fuel consumption display. A proof-of-method pilot test suggested that different driving styles could be detected using measures of acceleration and fuel consumption and that both measures change together with driving style. The full experiment could not be conducted due to the COVID-19 pandemic but is documented such that it can be completed by a future investigator.

There are many other interesting directions to explore in future work beyond the simulator study, from further investigation of motive substitution as a design for behaviour change technique to a field study evaluating the coffee-cup display. Within the scope of eco-driving, the coffee-cup could be compared to other display designs that also apply motive substitution or other techniques for engaging and motivating drivers. Displays showing instantaneous information could also be compared to those that show averaged or cumulative information, or a combination of the two. Ideally, an intervention like the coffee-cup display would be evaluated in a longitudinal field study with the displays installed in participants' vehicles. This would offer the most accurate indication of the behaviour changing potential of the intervention in relation to efficient driving, but the potential for distracted driving must also be considered. Looking beyond the scope of eco-driving, motive substitution may be a helpful design strategy to address other pro-environmental behaviours through greater engagement of users. Further research is first needed to clarify the concept of motive substitution and define its boundaries. The effectiveness of the interventions is worth comparing to alternate strategies, and its utility as a concept generation technique could be studied with student and professional designers.

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Appendices

Appendix A – Study 1: Survey on Driving Style

The survey was constructed using Qualtrics, but it has been reproduced here for reference. Explanatory annotations that were not present in the survey are included in square brackets.

Q1: Please enter your MTurk Worker ID.

Q2: Do you hold a valid driver's license?
● Full license; ● Learner's permit; ● Intermediate/provisional license; ● Don't hold a valid license at this time;

Q3: How many years of driving experience do you have? (including period with learner's permit)
● 0 - 2 years; ● 2 – 5 years; ● 5 – 10 years; ● 10 + years;

Q4: How often have you typically driven during the last 6 months?
● Daily, or almost (4+ hours most days); ● Daily, or almost (2 - 4 hours most days); ● Daily, or almost (0 - 2 hours most days); ● Weekly (3 - 4 times most weeks); ● Weekly (1 - 2 times most weeks); ● Less than once per week;

[Participants could only continue if they did not answer "Learner's permit" or "Don't hold a valid license at this time" to Q2, "0 - 2 years" to Q3, and "Less than once per week" to Q4.]
Q5: Please indicate your sex:
● Female; ● Male; ● Other: ________; ● Prefer not to answer;

Q6: Please indicate your age:
● 18 - 24; ● 25 - 34; ● 35 - 44; ● 45 - 54; ● 55 - 64; ● 65 or older; ● Prefer not to answer;

Q7: Indicate how well each of the following statements describe your typical driving style:
● Not at all; ● Slightly well; ● Somewhat well; ● Moderately well; ● Very well; ● Extremely well;
[Question order was randomized.]
Q7.1: I accelerate out of intersections faster than other vehicles
Q7.2: I approach red lights and other stops faster than other vehicles
Q7.3: I drive as fast as safely possible
Q7.4: I often push the accelerator or brake all the way down
Q7.5: Loose items in my car often shift backward and forward as I drive
Q7.6: I often feel the force of the vehicle pushing me forward or holding me back
Q7.7: I take every safe opportunity to get ahead in traffic and adjust my speed as needed
Q7.8: I would change my driving style if I was low on fuel and unsure about making it to the station
Q7.9: My driving style would be more accurately called "dynamic" than "smooth"
Q7.10: My driving style would be more accurately called "sporty" than "relaxed"

Q8: Is your driving style more like car X or car Y?

[Figure 7 shows a single frame from the 20 second animation that was auto-played and looped. Car X accelerates and brakes harshly, and car Y moves with more gentle movements. Participants responded with a 6-point slider from Car X to Car Y]
Car X ● 1; ● 2; ● 3; ● 4; ● 5; ● 6; Car Y

Q9: Why do you typically drive with the style that you do? (select all that apply)
● It feels safer; ● It's more enjoyable; ● I arrive faster; ● It's more fuel efficient; ● Traffic conditions require it;
● Road conditions require it; ● It's better for my car; ● It's what I learned/what I'm used to; ● I don't know; ● Other: ________;

Q10: We will refer to car X's style as "Dynamic" and car Y's style as "Smooth"
[The same animation as Q8 was played again. Participants could not proceed until they made the correct matching of car and style to confirm understanding.]
Car X: ● Dynamic; ● Smooth; Car Y: ● Dynamic; ● Smooth;

Q11: Below are four sample frames of some animated interfaces. Imagine each were displayed on your vehicle dash, animated to respond to the forward-backward motion of the vehicle. How effective would each of these displays be in influencing you to drive more smoothly or dynamically than you typically do?
[Participants were presented the displays as shown in Figure 6 in randomized order, with a response prompted for each display.]
● Very effective for driving more smoothly; ● Moderately effective for driving more smoothly;
● Slightly effective for driving more smoothly; ● No effect; ● Slightly effective for driving more dynamically;
● Moderately effective for driving more dynamically; ● Very effective for driving more dynamically;

Q12: What do you like or not like about these displays? [Text entry]

Q13: Does the vehicle you typically drive have a driving efficiency display?
● Yes (instantaneous MPG, gal/100mi, L/100km); ● Yes (other type of display); ● No; ● I don't know;

[Q14-16 were only presented to participants who answered "Yes" to Q13]

Q14: How effective do you think your current vehicle's display is at influencing you to drive more efficiently than you would otherwise?
● Not effective at all; ● Slightly effective; ● Somewhat effective; ● Moderately effective; ● Very effective;
● Extremely effective;

Q15: Relative to your existing display, how effective do you think these new displays would be at influencing you to drive more efficiently?
[Participants were presented the displays as shown in Figure 6 again in randomized order, with a response prompted for each display.]

● Much more effective; ● Moderately more effective; ● Slightly more effective; ● Slightly less effective;
● Moderately less effective; ● Much less effective;

Q16: Is there a particular type of efficiency display you would like to have? [Text entry]

[Q17 was only presented to participants who answered “Yes (other type of display)” to Q13]

Q17: What vehicle do you drive that has the efficiency display you indicated?
● Make; ● Model; ● Year;

Q18: Indicate how well each of the following statements describe you:
● Not at all; ● Slightly well; ● Somewhat well; ● Moderately well; ● Very well; ● Extremely well;
[Question order was randomized, except for position of the attention check, Q18.5.]
Q18.1: I would be willing to drive more smoothly than I do now
Q18.2: I make a conscious effort to drive energy efficiently
Q18.3: I believe a smooth driving style is significantly more energy efficient than a dynamic one
Q18.4: Environmental sustainability and preventing climate change are important to me
Q18.5: Please select "Slightly well"
Q18.6: I make an effort to reduce my personal environmental impacts
Q18.7: I believe efficient driving is a worthwhile way to reduce environmental impacts

Q19: Do you have any comments or ideas regarding this survey? Your feedback is appreciated! [Text entry]

Appendix B – Study 2: Screening Questionnaire

1. What is your level of proficiency in English?
    a. Native or full proficiency
    b. Working proficiency
    c. Limited proficiency
    d. Elementary proficiency
2. What is your sex?
    a. Female
    b. Male
    c. Other
    d. Prefer not to answer
3. What is your age?
    a. 18 – 24
    b. 25 – 34
    c. 35 – 44
    d. 45 – 54
    e. 55 – 64
    f. 65 or older
4. What valid government-issued driver's license do you currently hold?
    a. Full driver's license (Ontario G or equivalent)
    b. Provisional license (Ontario G2 or equivalent)
    c. Learner's license (Ontario G1 or equivalent)
    d. Other: ___________
    e. I do not currently have a valid government-issued driver's license
5. How many years of driving experience do you have?
    a. 0 – 2 years
    b. 3 – 5 years
    c. 6 – 10 years
    d. 11 – 20 years
    e. 21 years or more
6. How often have you typically driven during the last 6 months?
    a. Almost daily, over 3 hours most days
    b. Almost daily, 1 – 3 hours most days
    c. Almost daily, under 1 hour most days
    d. A few times per week, over 10 hours most weeks
    e. A few times per week, 3 – 10 hours most weeks
    f. A few times per week, under 3 hours most weeks
    g. Once a month or more, but not weekly
    h. Once a year or more, but not monthly
7. Do you drive for work?
    a. Ride share
    b. Delivery
    c. House calls

   d. Other – mostly rural or highway
   e. Other – mostly urban
   f. No
8. Have you ever driven in a driving simulator?
   a. Never
   b. Once or twice
   c. Numerous times
9. If you have used a driving simulator before, have you ever experienced nausea, dizziness, headache, general malaise, or other symptoms?
   a. Not applicable
   b. Never
   c. Sometimes
   d. Frequently
10. Do you experience migraine headaches?
    a. Never or rarely
    b. Sometimes
    c. Frequently
11. Are you generally prone to motion sickness, such as in moving vehicles or when using a virtual reality headset?
    a. Never or rarely
    b. Sometimes
    c. Frequently
12. Are you pregnant?
    a. Yes
    b. No
13. Have you travelled outside of Canada this year? If so, please indicate when and where most recently.
    a. No
    b. Yes Month: ___________ Country: ________________
14. Have you experienced any symptoms associated with COVID-19 in the past month?
    a. Yes
    b. No

Scoring:
Candidates who provide the following answers will be (or may be) considered eligible for the study. Preference will be given to candidates who help achieve a more gender and age balanced sample.

1: a, b; 4: a, b, (d); 5: b, c, d, e; 6: a-f; 9: a, b; 10: a, (b); 11: a, (b); 12: b; 13: a, (b); 14: b

Appendix C – Study 2: Perceived Driving Style Questionnaire

For each of the following questions, indicate how accurately the statement describes your typical driving style.

Scale:

1. Very inaccurate
2. Moderately inaccurate
3. Slightly inaccurate
4. Slightly accurate
5. Moderately accurate
6. Very accurate

Questions:

1. I accelerate out of intersections faster than other vehicles
2. I approach red lights and other stops faster than other vehicles
3. I take every safe opportunity to get ahead in traffic and adjust my speed as needed
4. I drive as fast as safely possible
5. I often push the accelerator or brake all the way down
6. Loose items in my car often shift backward and forward as I drive
7. I often feel the force of the vehicle pushing me forward or holding me back
8. My driving style would be more accurately called "dynamic" than "smooth"
9. My driving style would be more accurately called "sporty" than "relaxed"

Scoring:
Each item is scored from 1 (very inaccurate) to 6 (very accurate). The “Driving Smoothness” measure is defined as the mean score of items 1 through 9.

Appendix D – Study 2: Post-Test Interview

1. How would you describe your driving style?
2. Why do you typically drive with the style that you do?
3. How willing and/or able would you be to change your driving style?
4. Does the vehicle you typically drive have a driving efficiency display that you know of?
5. What type of display is it?
6. How regularly do you refer to this display while driving?
7. How do you think that display influences your driving behaviour?
   OR
8. How do you think the instantaneous fuel consumption display would influence your driving behaviour?
9. How accurately did you find the coffee-cup-style displays to reflect vehicle motion?
10. How do you think the coffee-cup-style displays in this study would influence your driving behaviour?
11. Did you find any of the displays overly distracting?
12. What do you like or not like about these displays, and what would you change?
13. How would you feel about having the open coffee-cup display embedded in your car's dashboard display?
14. Do you have any comments or ideas regarding this study or the displays presented?

Appendix E – Study 2: Proof-of-Method Brake Specific Fuel Consumption Results

Brake Specific Fuel Consumption has units of grams-per-kilowatt-hour and can be computed using the engine speed and torque specified for each row and column of the fuel rate matrix.

$$\text{BSFC}\left(\frac{\text{g}}{\text{kW h}}\right) = \frac{\text{Fuel Rate}\left(\frac{\text{g}}{\text{s}}\right) \times 3.6\left(\frac{\text{s} \cdot \text{N m} \cdot \text{min}^{-1}}{\text{kW h}}\right)}{\text{Torque}(\text{N m}) \times \text{Engine Speed}(\text{rpm})}$$

For each plot below, the black contour lines represent the brake specific fuel consumption map for the Chevrolet Malibu 2.5L I4 engine (EPA, 2016). When the engine speed and torque are at levels corresponding to the lowest values of grams per kilo-watt-hour, the engine is generating the most power per unit of fuel used. The coloured contour overlay is the region the engine operated in during the pilot trial of the given driving style. Darker colours represent a greater number of data points recorded at those engine states meaning the engine spent more time operating at that level of speed and torque.

It plots show that the simulator engine operates in a slightly more efficient region during the Dynamic drive and is least efficient with the Smooth drive. However, the total fuel consumed is still lower for the Smooth drive and highest for the Dynamic drive. This is because power efficiency does not directly translate to fuel efficiency. This test was particularly interesting because of the discrepancy between so-called “Japanese” and “German” style eco-driving (Hiraoka, 2009; Matsumoto, 2014). The results support the claim that a smoother driving style will result in lower fuel use even if it causes the engine to operate in a less power-efficient state.

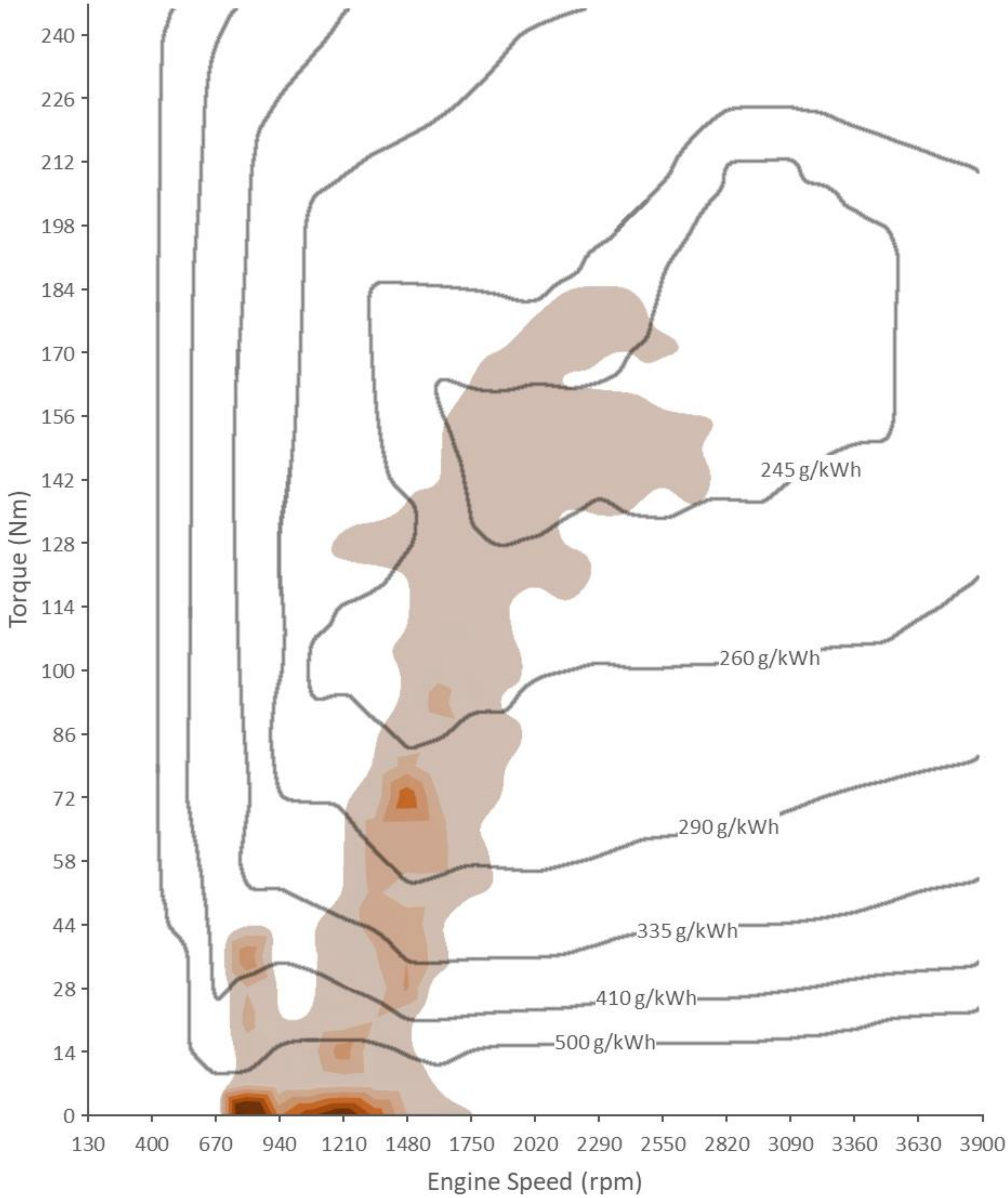

Figure E1. BSFC map for pilot test using Dynamic driving style with a Chevrolet Malibu 2.5L I4 engine (dark colours represent more time operating at the engine state)

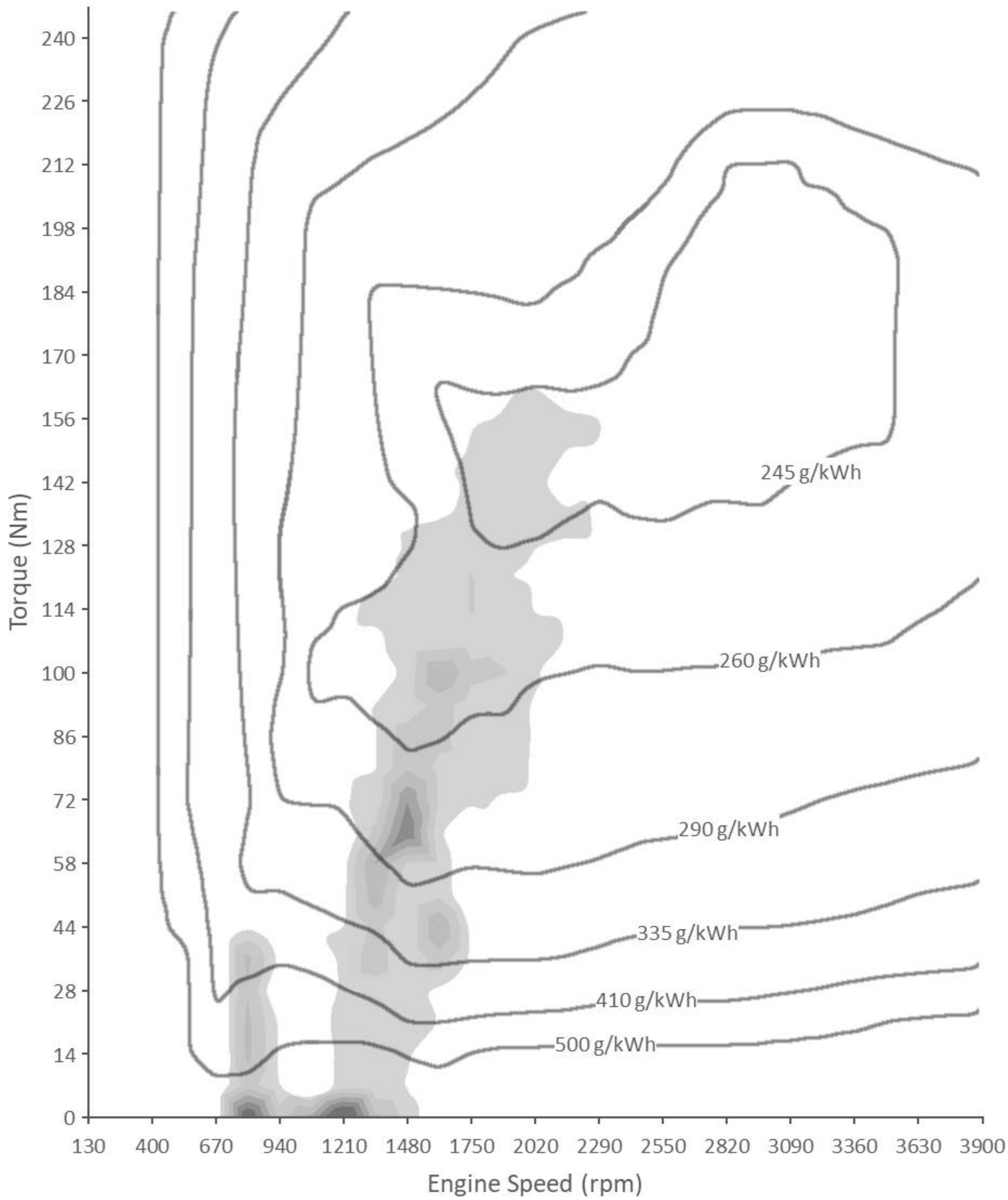

Figure E2. BSFC map for pilot test using Moderate driving style with a Chevrolet Malibu 2.5L I4 engine (dark colours represent more time operating at the engine state)

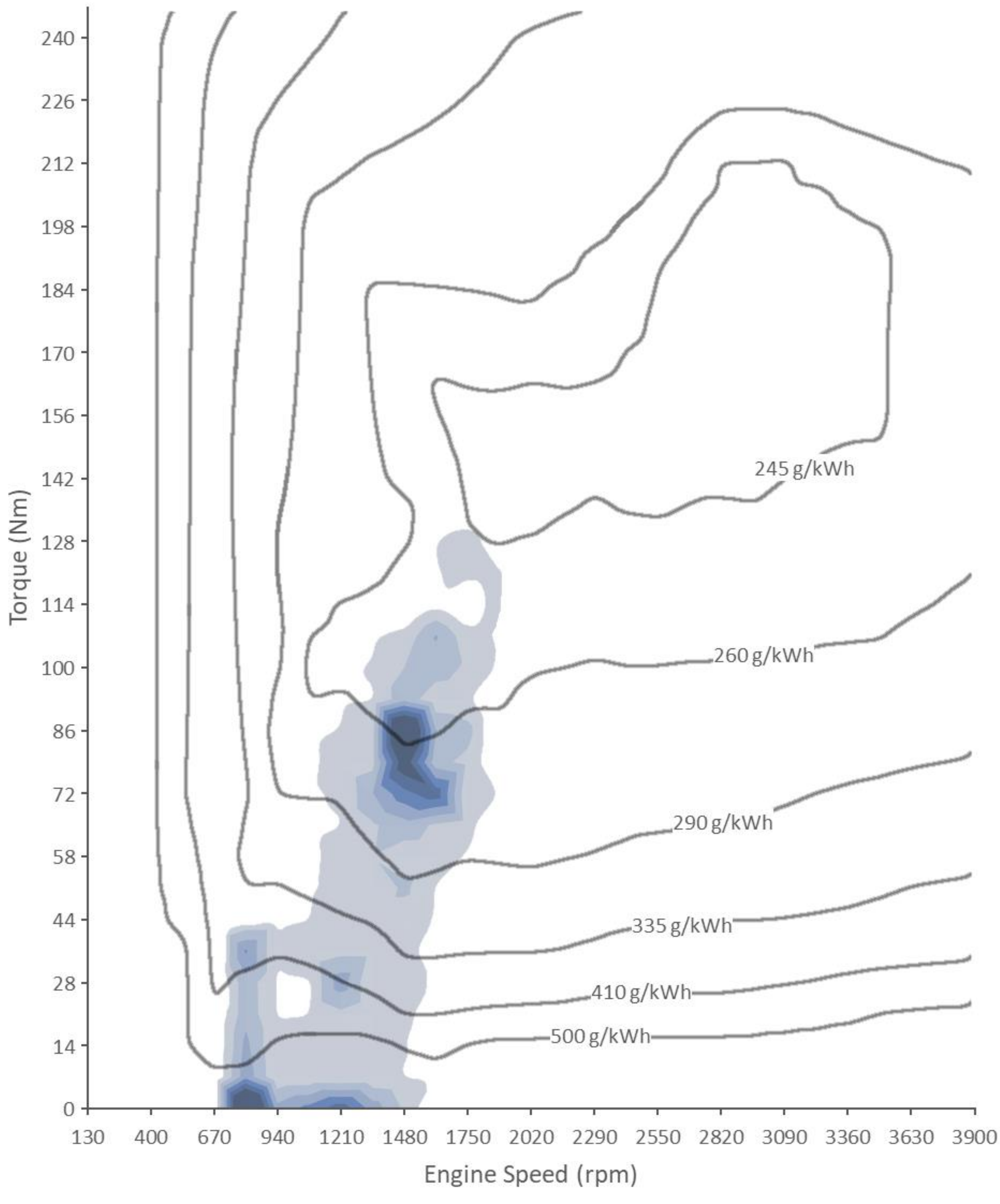

Figure E3. BSFC map for pilot test using Smooth driving style with a Chevrolet Malibu 2.5L I4 engine (dark colours represent more time operating at the engine state)