Ecodriving in hybrid electric vehicles – exploring challenges for user-energy interaction

Thomas Franke[1]*, Matthias Georg Arend[1], Rich C. McIlroy[2], Neville A. Stanton[2]

[1]Department of Psychology, Cognitive and Engineering Psychology,
Technische Universität Chemnitz, Chemnitz, Germany

[2]Transportation Research Group, Faculty of Engineering and the Environment,
University of Southampton, Southampton, UK

Accepted for publication in
Applied Ergonomics

http://www.journals.elsevier.com/applied-ergonomics/

ABSTRACT

Hybrid electric vehicles (HEVs) can help to reduce transport emissions; however, user behaviour has a significant effect on the energy savings actually achieved in everyday usage. The present research aimed to advance understanding of HEV drivers' ecodriving strategies, and the challenges for optimal user-energy interaction. We conducted interviews with 39 HEV drivers who achieved above-average fuel efficiencies. Regression analyses showed that technical system knowledge and ecodriving motivation were both important predictors for ecodriving efficiency. Qualitative data analyses showed that drivers used a plethora of ecodriving strategies and had diverse conceptualisations of HEV energy efficiency regarding aspects such as the efficiency of actively utilizing electric energy or the efficiency of different acceleration strategies. Drivers also reported several false beliefs regarding HEV energy efficiency that could impair ecodriving efforts. Results indicate that ecodriving support systems should facilitate anticipatory driving and help users locate and maintain drivetrain states of maximum efficiency.

Keywords: Hybrid electric vehicles, Ecodriving, User-energy interaction, Driving behaviour

Highlights:

- We examined ecodriving in HEVs and challenges for optimal user-energy interaction.
- Impact of motivation and knowledge on fuel efficiency varied with environmental complexity.
- There was considerable inter-individual variance in ecodriving strategy selection.
- Drivers had diverse conceptualisations of HEV energy efficiency and named several false beliefs.
- Design guidelines for ecodriving support systems are derived to facilitate ecodriving.

*corresponding author: Thomas Franke | Cognitive & Engineering Psychology | Technische Universität Chemnitz | D-09107 Chemnitz | E-Mail: thomas.franke@psychologie.tu-chemnitz.de

Citation: Franke, T., Arend M. G., McIlroy, R. C., & Stanton, N. A. (2016). Ecodriving in hybrid electric vehicles – exploring challenges for user-energy interaction. *Applied Ergonomics.* http://dx.doi.org/10.1016/j.apergo.2016.01.007

1 INTRODUCTION

Facing the global sustainability challenge of reducing greenhouse gas emissions, electrification of road transport has become a major trend (Dijk et al., 2013), and hybrid electric vehicles (HEVs) in particular are becoming increasingly widespread (Al-Alawi & Bradley, 2013; U.S. Department of Energy, 2015). HEVs are key for sustainable road transport as they can reduce fuel consumption without necessitating complex changes in energy-supply infrastructure (in contrast to plugin or fuel cell electric vehicles). Yet, ultimately, sustainability strongly depends on the actual energy efficiency that users achieve in everyday usage. User behaviour is, therefore, a critical factor with regard to the ultimate effect that such systems have on making the road transport system more sustainable.

Ecodriving has emerged as a term that encompasses all the influences users have on the real-world energy efficiency of a road vehicle (see e.g., Barkenbus, 2010; Jamson et al., 2015a; Sivak & Schoettle, 2012; Stillwater & Kurani, 2013; Young et al., 2011). As well as strategic and tactical ecodriving measures (e.g., optimize tyre pressure, route choice; Sivak & Schoettle, 2012), specific driving behaviours (i.e., operational ecodriving strategies; Sivak & Schoettle, 2012) are a core element of ecodriving. Electric drivetrains have been discussed as particularly challenging (McIlroy et al., 2014; Neumann et al., 2015) due to the novelty of their energy dynamics (e.g., consumption dynamics of electric propulsion, bidirectional energy flow resulting from regenerative braking). HEVs represent the most complex drivetrain in this respect because of the extremely dynamic interplay between the different drivetrain components, and the central role of bidirectional energy flow. Hence, maximising HEV fuel-efficiency can be considered particularly challenging, not only requiring ecodriving motivation, but also a sufficient level of technical system knowledge. From the perspective of green ergonomics (Thatcher, 2013; Hanson, 2013) a key challenge, therefore, is to advance understanding of user-energy interaction and support drivers' ecodriving efforts.

The objective of the present research was to advance understanding of HEV drivers' ecodriving strategies, and the challenges to optimal user-energy interaction. To this end, we recruited 39 HEV drivers with above-average fuel efficiencies (suggesting the performance of eco-driving behaviours) and collected interview data, questionnaire responses, and long-term fuel efficiency recordings. With this research we seek to: (a) identify challenges to, and ways of facilitating ecodriving in HEVs, and (b) advance understanding of user-energy interaction in dynamic systems.

2 BACKGROUND

2.1 User-energy interaction as a core issue of green ergonomics

Users often have a considerable degree of freedom in terms of the way in which they use systems designed with environmental sustainability in mind (see e.g., Thatcher, 2013; Franke et al., 2012). The efficient utilisation of energy resources is often challenging; not only can optimally monitoring and controlling energy resources incur workload and stress (e.g., Jamson et al., 2015b; Franke et al., 2015), but choosing the optimal control strategy can require detailed system understanding (e.g., Revell & Stanton, 2014). These human factors challenges call for system and interface designs that facilitate efficient use of energy resources as much as possible (see also Thatcher, 2013; Hanson, 2013). For progress to be made, however, a comprehensive understanding of the patterns of user-energy interaction is needed. Ecodriving represents an especially pertinent case of user-energy interaction, particularly in the highly dynamic and relatively complex environment of HEVs.

2.2 A conceptual framework of ecodriving behaviour

Although this is typically not acknowledged explicitly in driving style inventories (see e.g., Taubman-Ben-Ari et al., 2004) ecodriving can be conceived as an important dimension of driving style (e.g., McIlroy & Stanton, 2015; Stillwater & Kurani, 2013). It is the dimension that encompasses all those behaviours that drivers perform in order to increase energy efficiency.

We propose here that it is useful to conceptualise ecodriving behaviour from the perspective of control theoretic models of behaviour (e.g., Summala 2007; Fuller, 2005; Franke & Krems, 2013). This is not only in line with recent theorizing in the broader field of driver behaviour models (see Fuller, 2011; Lewis-Evans et al., 2013), but also acknowledges the fact that optimizing fuel efficiency requires constant behavioural adaptation to environmental dynamics. Moreover, we argue that notions of subjective expected utility (SEU; Edwards, 1954) should be integrated into a model of ecodriving behaviour; efficient driving involves decision-making under uncertainty that is targeted towards *achieving* (i.e., optimizing) rather than *satisficing*. Research has shown SEU as a particularly useful concept for such facets of driving (Tränkle & Gelau, 1992). Finally, driving behaviour is always motivated by multiple competing driver goals (e.g., time saving, safety; Summala 2007; Dogan et al., 2011). The relative importance of the ecodriving goal is therefore important to consider. Our conceptual framework is depicted in Figure 1.

We propose that whenever drivers are motivated to drive economically they continuously perform the following activities; (1) monitor system and environmental variables; (2) identify applicable ecodriving strategies (based on pre-existing knowledge; the 'strategy knowledge base', Figure 1) and evaluate them in terms of their SEU; and (3) select the strategy with the highest SEU, along with a certain implementation intensity (i.e., similar to a preferred level of task difficulty; Fuller, 2005) and, consequently, regulate their behaviour in accordance with this strategy (i.e., strategy implementation). The resulting ecodriving behaviours and system/environment dynamics will determine ultimate fuel efficiency.

The strategy knowledge base is expected to comprise drivers' repertoire of strategies, as well as their subjective conceptualisations of energy efficiency. SEU is expected to arise from: (a) the perceived effectiveness of a strategy for increasing energy efficiency in the current situation, and (b) the perceived fit of the strategy with current driving motives (i.e., the target level for ecodriving, time saving, etc.). The final level of fuel efficiency will therefore be influenced by: (a) the match between perceived and objective strategy effectiveness (with technical system knowledge as a central predictor), and (b) the level of ecodriving motivation. The latter will also determine the target intensity of strategy implementation.

In some environments strategy selection can be very simple (where there are few applicable strategies and a stable environment; e.g., flat motorway with little traffic). In other environments selection will be more complex and dynamic (i.e., where there are several applicable strategies and an unstable environment; e.g., typical city driving). While higher environmental complexity may increase demands, strategy selection will generally be a quick process, as drivers will perform many aspects of situation assessment and strategy evaluation automatically.

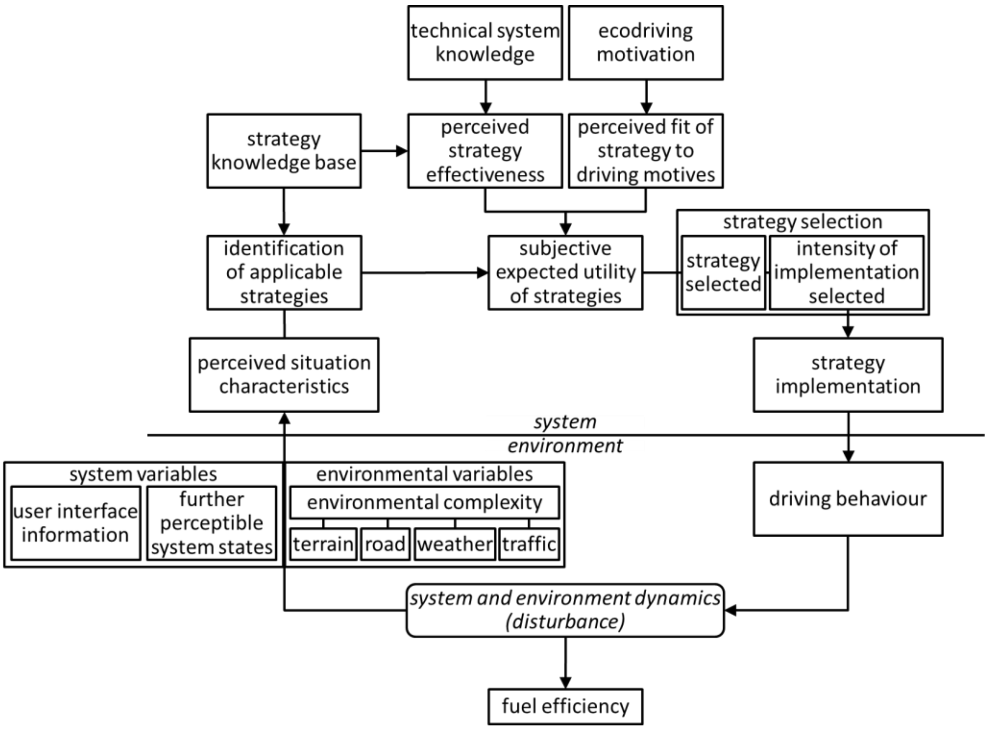

Figure 1. The conceptual framework of adaptive control of ecodriving strategy selection in HEV driving. The depiction shows processes at the trip-level. Long-term relationships between variables are omitted for clarity.

3 PRESENT RESEARCH

The objective of the present research was to advance understanding of HEV drivers' ecodriving strategies, and the challenges to optimal user-energy interaction. We focused on drivers who can be assumed to practise ecodriving, as this sample allowed us to both identify the human factors challenges to optimal ecodriving behaviour (i.e., beyond the basic challenge of motivating drivers to engage in ecodriving behaviours), and to advance our conceptual model (i.e., through studying drivers who may be able to explain their ecodriving strategies).

Given that research in this field is in its relative infancy, we used a mixed-methods approach with quantitative and qualitative analyses. Apart from Q1 (below), the present research is largely exploratory. The following research questions were examined:

Q1 – motivation and knowledge: To what extent can ecodriving motivation and technical system knowledge account for individual differences in ecodriving success (i.e., fuel efficiency)?

Regarding Q1 we hypothesize (H1) that higher ecodriving motivation and higher technical system knowledge are both related to a higher fuel efficiency.

Q2 – strategy selection: Which ecodriving strategies do drivers use, and how do individuals differ in strategy selection?

Q3 – conceptualisations: How do HEV drivers conceptualise HEV energy efficiency (i.e., strategy effectiveness)?

Q4 – false beliefs: Which false beliefs about HEV energy efficiency do drivers have?

Hence, Q2-Q4 assessed characteristics of the strategy knowledge base (see section 2.2).

Q5 – support systems: Which ecodriving support systems could facilitate ecodriving?

4 METHOD

4.1 Participants

We focused recruitment on HEV drivers of the Toyota Prius (2nd gen, 3rd gen, and Prius c [in Germany sold as Yaris Hybrid]), being the most sold (see e.g., U.S Department of Energy, 2015) and most prototypical HEV model. From the almost 1500 Prius drivers in the www.spritmonitor.de database we invited drivers who (a) had an average fuel efficiency above the fleet-average of the vehicle model, (b) were from Germany, Austria, or Switzerland, and (c) had logged their fuel efficiency within the last 3 months. We avoided drivers who appeared to log fuel efficiency inconsistently, and sought to sample drivers across a range of above-average fuel efficiencies (i.e., from "just above-average" to "top of the list”). Ethical approval was sought from and granted by the University of Southampton’s Ethics and Research Governance committee (reference number 17071).

Participants in the resulting sample (*N* = 39) had an average age of *M* = 45 years (*SD* = 10) and an average HEV driving experience of *M* = 74079 km (*SD* = 64513), 92% were male, and 56% had a university degree.

4.2 Procedure

Telephone interviews (including questionnaire sections) were conducted (M_{duration} = 48 min, *SD* = 8). Participants received the interview guideline before the interview and could therefore refer to the documentation as the interviewer went through the questions. The interviewer’s experience with HEV driving (>6 years) facilitated the process.

After introducing the study and gaining informed consent, the interview had the following parts: (P1) ecodriving motivation (also as “icebreaker”), (P2) ecodriving strategies, (P3) further questions on ecodriving support, strategy development, and false beliefs, and (P4) questionnaire to asses socio-demographic and experience-related variables. The interview was audio-recorded and parts P2 and P3 (approx. 75% of the 32h audio material) were transcribed verbatim.

In P2, participants were first asked to give an overview of the ecodriving strategies they used. Afterwards, participants were asked to report on their strategies (in high detail), and on their conceptualisations of strategy effectiveness in four characteristic situations (designed to represent different levels of environmental complexity; see Appendix A for full descriptions): (S1) autobahn (low complexity), (S2) city (high complexity), (S3) rural flat (medium complexity), (S4) rural mountainous (medium complexity).

4.3 Scales and measures

4.3.1 Fuel efficiency indicators

Different fuel efficiency indicators (FEI) were assessed. First, participants exported fuel log data of their current main HEV from the spritmonitor.de database. This data included all refuelling events, comprising the refuelling amount (in litres) and the distance driven (in total 1.9 million km). The data of the last 90 days was extracted (labelled *FEI1.last90d.log*) to standardize for seasonal variations (interviews were conducted in August 2015).

Second, participants’ estimated fuel efficiency for the last 90 days (labelled *FEI2.last90d.est*), and for the four situations (*labelled FEI3.S1.autobahn, FEI4.S2.city, FEI5.S3.ruflat, FEI6.S4.rumount*), were assessed (in litre per 100 km, items displayed in Appendix B). Finally, we computed *FEI7.S.all* as the average of FEI3-FEI6 (i.e., as composite score for the average consumption in the four situations S1-S4, Cronbach's Alpha = .87).

To eliminate the influence of vehicle model we computed the distribution parameters for each HEV model (based on fuel efficiency data from all vehicles of this model in the spritmonitor.de database) and *z*-standardized the FEI-values of each participant on the respective distribution. Finally, all FEI-values were inverted such that higher values corresponded to higher fuel efficiency.

4.3.2 Questionnaire scales

Ecodriving motivation (labelled “motivation” for brevity) was assessed with a 2-item scale (Cronbach’s Alpha = .82) focussing on the motivation aspect of behavioural intention (Ajzen, 1991; items adapted from Neumann, 2016). Technical system knowledge (labelled “knowledge” for brevity) was assessed with a 3-item scale (Cronbach’s Alpha = .84), adapted from Franke et al. (2015). A 6-point Likert scale *completely disagree* to *completely agree* was used (see Appendix B).

4.4 Qualitative data analysis

We based our qualitative data analysis on thematic analysis (Braun & Clarke, 2006) using the MAXQDA 10 software (2011). After each interview, the interviewer and the scribe (first and second author) discussed insights and first ideas for possible codes. After familiarisation with the data, the initial coding phase led to an extensive list of codes that were relevant to the respective research question. Within this phase, ideas for possible overarching themes and ways of grouping the initial codes were developed. Afterwards, the coding system was reviewed and discussed, and initial ideas for themes (i.e., thematic clusters) were revised and refined based on preliminary indicators of prevalence in the data. As only a relatively low level of abstraction of statements was needed (the interview focused on concrete behaviours and beliefs), this phase was less complex than for other topics in psychology (i.e., semantic rather than latent level analysis; Braun & Clarke, 2006). In the final phase we again went through every transcript and coded participants’ statements with regard to the developed coding systems. Within this phase some final revisions and refinements of the coding system were performed.

5 RESULTS

5.1 (Q1) Motivation and knowledge as predictors of fuel efficiency

To test research question Q1 (motivation and knowledge), we conducted multiple linear regression analyses with the motivation and knowledge variables as predictors, and fuel efficiency indicators as criteria.

Assumptions for regression analysis were tested according to Field (2009). Apart from the following two exceptions assumptions were satisfactorily met: First, there were some residual outliers (consequently, analyses were computed with and without these values, in accordance with Urban and Mayerl, 2008). Second, there were problems with normality; the knowledge and motivation variables were therefore transformed (with cube transformation).

In order to avoid any potentially confounding effects that might arise from differences in personal trip profiles (e.g., some participants may drive in heavy traffic more often than others), the fuel efficiency indicators FEI3-FEI7 (i.e., participants' efficiency estimates for the specific standardized situations, see section 4.3.1) were the key variables for the H1-test. However, to receive an indicator for participants' estimation accuracy we first computed the analysis with the fuel log data (FEI1.last90d.log) and the parallel drivers' estimate (FEI2.last90d.est) in comparison (participants gave estimations of efficiency in the interviews [FEI2] before they were asked to provide actual logged data [FEI1]). The analyses showed comparable results for both *actual* (FEI1) and *estimated* (FEI2) fuel efficiency indicators (Table 1). Furthermore, both also correlated strongly ($r_{FEI1FEI2}$ = .88, p < .001). We therefore conclude that there were no problematic biases or large inaccuracies in participants' fuel efficiency estimates.

Table 1.
Motivation and knowledge as predictors of fuel efficiency indicators FEI1-FEI2 (personal route profile)

criterion	predictors	*N*	$r_{zero\ order}$	r_{part}	ß	*p**	R^2_{adj}	*p*
FEI1.last 90d.log	knowledge	39 (36)	.40 (.61)	.41 (.61)	.41 (.62)	.006 (<.001)	.12 (.34)	.039 (<.001)
	motivation	39 (36)	.02 (-.04)	.09 (.02)	.10 (.03)	.270 (.429)		
FEI2.last 90d.est	knowledge	39 (37)	.30 (.44)	.31 (.44)	.31 (.45)	.031 (.003)	.04 (.15)	.169 (.023)
	motivation	39 (37)	.01 (-.04)	.07 (.01)	.07 (.01)	.329 (.482)		

Note. **p*-values that belong to regression weights are one-tailed because of directional hypotheses. Results after outlier exclusion are given in parentheses.

Hypothesis H1 was supported with a significant regression model that accounted for 22% of the variance (see Table 2, FEI7.S.all as a composite score for all four situations). Yet, as the more detailed analyses of the individual situation scores (FEI3-FEI6) show, the relative importance of the two factors appeared to be dependent on environmental complexity; motivation yielded a strong effect for the low complexity situation (FEI3.S1.autobahn), but not for the high complexity situation (FEI4.S2.city). Knowledge yielded the opposite pattern. For the medium complexity situations (FEI5.S3.ruflat and FEI6.S4.rumount) both factors played comparable roles.

Table 2.
Motivation and knowledge as predictors of fuel efficiency indicators FEI3-FEI7 (standardized route profile)

criterion	predictors	N	$r_{\text{zero order}}$	r_{part}	ß	p*	R^2_{adj}	p
FEI7.S.all	knowledge	39 (37)	.32 (.40)	.39 (.44)	.40 (.44)	.005 (.002)	.22 (.25)	.004 (.003)
	motivation	39 (37)	.33 (.32)	.40 (.37)	.41 (.37)	.004 (.007)		
FEI3.S1. autobahn	knowledge	39 (38)	.08 (.08)	.16 (.19)	.17 (.19)	.139 (.095)	.18 (.28)	.012 (.001)
	motivation	39 (38)	.44 (.54)	.46 (.56)	.47 (.57)	.002 (<.001)		
FEI4.S2. city	knowledge	39	.45	.47	.48	.001	.18	.010
	motivation	39	.06	.15	.15	.158		
FEI5.S3. ruflat	knowledge	39 (37)	.25 (.21)	.31 (.32)	.31 (.33)	.023 (.016)	.15 (.25)	.022 (.003)
	motivation	39 (37)	.31 (.44)	.36 (.50)	.37 (.52)	.010 (.001)		
FEI6.S4. rumount	knowledge	39 (35)	.31 (.43)	.36 (.46)	.37 (.46)	.010 (.003)	.16 (.22)	.017 (.008)
	motivation	39 (35)	.26 (.23)	.33 (.28)	.33 (.28)	.017 (.039)		

Note. **p*-values that belong to regression weights are one-tailed because of directional hypotheses. Results after outlier exclusion are given in parentheses. We focus our interpretation on the N = 39 sample (i.e., before outlier exclusion). FEI7.S.all is the average score of FEI3-FEI6.

5.2 (Q2) Ecodriving strategy selection

The interview questions that were used to collect data for qualitative analyses (research questions Q2-Q5) are displayed in Appendix B. In the following we group participants' statements with clusters (abbreviated as *C*) and dimensions (abbreviated as *D*). Clusters group similar statements of different participants (i.e., an overarching theme that is addressed by several participants). Dimensions represent two contrasting sub-clusters, for example differing behavioural strategies that belong to the same cluster (e.g., accelerating gently vs. accelerating quickly up to a target speed). Only clusters with a prevalence of $n \geq 4$ (i.e., 10% of the sample), and only the core dimensions (i.e., where ≥50% of participants could be classified and no class reflected <20%) are described. To simplify switching between tables and text, clusters and dimensions are numbered (e.g. C1) in each section. All percentages displayed in the sections below indicate the proportion of the N = 39 drivers who, for example, mentioned a particular strategy. Prototypical quotes from the transcripts are depicted in Appendix C.

Regarding research question Q2 (strategy selection), drivers described various strategies to achieve high energy efficiency. These were structured with a comprehensive coding system (in total >1770 codings) comprising eight major clusters (labelled as C1-C8; see Table 3).

The first three clusters (C1-C3) summarized ecodriving strategies related to the basic driving manoeuvres of acceleration (e.g., avoiding over-/underload of combustion engine in acceleration), deceleration (e.g., avoiding to use mechanic brakes), and cruising (e.g., gliding with electric assistance).

Clusters C4-C7 included various specific strategies, and C8 included strategies related to anticipatory driving (e.g., scanning for distant traffic lights to increase time available for action). In addition to these strategy clusters a highly prominent topic (mentioned by 82% of the drivers) was the trade-off between ecodriving and other driving goals when selecting strategies (e.g., not delaying other traffic, time constraints). As Table 3 shows, the cluster frequency varied considerably between situations, indicating that strategy selection was highly sensitive to situation characteristics.

Table 3.
Frequency of strategy usage related to the eight strategy clusters (C1-C8) in different driving situations (S1-S4)

cluster	strategies	S1.autobahn	S2.city	S3.ruflat	S4.rumount	all
C1	acceleration	3%	87%	46%	3%	100%
C2	deceleration	15%	82%	67%	10%	100%
C3	cruising	72%	87%	56%	8%	100%
C4	limiting maximum speed	95%	15%	79%	8%	100%
C5	cruise control usage	74%	31%	51%	18%	87%
C6	pulse and glide	10%	18%	21%	0%	38%
C7	strategies for hilly roads	26%	8%	13%	95%	97%
C8	anticipatory driving	15%	56%	21%	26%	100%

Note. Column "all" summarizes strategy usage frequency over S1-S4 and the preceding introductory questions (see Appendix B). Pulse and glide is a strategy where drivers first accelerate (pulse-phase), then subsequently reduce speed with reduced/no pressure on gas pedal (i.e., glide phase, ideally with combustion engine off), then repeat this procedure. Drivers in the present study used various forms and intensities of pulse and glide.

To characterize inter-individual differences in ecodriving strategy selection we expanded our analysis to identify characteristic strategy dimensions. For each situation we went through all clusters looking for sub-clusters where clear groups became visible that seemed to reflect a dimension of ecodriving style (i.e., contrasting sub-clusters). We then explored the relationships between dimensions, knowledge, motivation and fuel efficiency (see Table 4). Due to small group sizes, we focus our interpretations on effect size magnitude and only interpret moderate effects (Cohen's $d \geq .50$; Cohen, 1992).

For the autobahn situation (S1), the core dimension (D1) was limiting speed; 49% reported a target speed of ≤ 100 km/h, 38% >100 km/h. Limiting speed was related to higher fuel efficiency and higher motivation and knowledge (last two effects slightly below .5, see Table 4).

For the city situation (S2), acceleration intensity from standstill was found to be rather fast for some (33%) and rather slow for others (41%; D2). Starting faster was associated with more knowledge and higher fuel efficiency. Related to this, some reported trying to utilize more the combustion engine (28%), others the electric propulsion (26%) when accelerating from standstill (D3). Accelerating with the combustion engine was associated with higher fuel efficiency and knowledge even though accelerating with electric propulsion was related to higher motivation. Finally, regarding cruising (D4), 33% reported exploiting the available electric energy whenever possible (e.g., making the car switch to electric propulsion with certain gas pedal positions), others (51%) tended to not intervene actively, or used electric propulsion only under certain conditions. The first group was more motivated, but obtained lower fuel efficiencies (though the size of this effect was slightly below .5).

For the rural flat situation (S3), 26% reported driving at speed limits (70 and 100 km/h in the situation description) while 36% reported choosing an average speed level near to 70 km/h regardless of the higher speed limit (D5). The second group achieved higher energy efficiency. Regarding speed uniformity, while 21% reported strategies involving varying speed levels (e.g., pulse and glide) 69% reported strategies with more constant/uniform speed (e.g., cruise control usage; D6). The first group had higher knowledge.

For the rural mountainous situation (S4), drivers reported diverse strategies, however, only one clear dimension resulted: while some (59%) preferred decreasing their speed while driving uphill to increase energy efficiency, others (26%) reported keeping the speed (D7). There were no group differences on the three variables.

Table 4.
Relationship between the seven strategy dimensions (D1-D7), motivation, knowledge and fuel efficiency indicators (FEI).

strategy dimension			knowledge		motivation		FEI	
		N	*d*	*p*	*d*	*p*	*d*	*p*
	FEI3.S1.autobahn							
D1	speed limit ≤ 100 km/h vs. speed limit > 100 km/h	19 vs. 15	0.49	.160	0.48	.195	1.74	<.001
	FEI4.S2.city							
D2	accelerating rather fast vs. rather slow from standstill	13 vs. 16	0.55	.157	-0.30	.485	0.63	.105
D3	accelerating with combustion engine vs. with electric propulsion from standstill	11 vs. 10	1.03	.027	-0.63	.175	0.73	.111
D4	not exploiting electric driving vs. exploiting electric driving	20 vs. 13	-0.10	.809	-0.57	.150	0.48	.188
	FEI5.S3.ruflat							
D5	average maximum speed vs. exploiting speed limits	14 vs. 10	-0.21	.644	0.18	.690	0.77	.076
D6	variable speed vs. constant speed	8 vs. 27	0.71	.076	-0.29	.516	0.18	.654
	FEI6.S5.rumount							
D7	decreasing vs. keeping speed for going up the hill	23 vs. 10	-0.01	1.000	0.00	1.000	0.30	.435

Note. *N* refers to first vs. second group of the dimension. Cohens' *d* was computed (Cohen, 1977). Because of varying group sizes we used a permutation test (Hothorn et al., 2008) to compute *p*-values; *p*-values are two-tailed.

5.3 (Q3) Drivers’ conceptualisations of HEV energy efficiency

The final coding system for research question 3 (conceptualisations) consisted of six major clusters focusing on system-related conceptualisations of HEV energy efficiency (see Table 5). Apart from these system-related conceptualisations, 77% of drivers also explained energy efficiency based on their physical knowledge, naming concepts such as kinetic energy (21%) and air resistance (51%) as factors influencing strategy effectiveness.

Table 5.
Clusters of system-related conceptualisations of HEV energy efficiency

cluster	cluster label: conceptualisation of …	% of drivers
C1	combustion engine energy efficiency	56%
C2	electric propulsion energy efficiency	59%
C3	recuperation energy efficiency	85%
C4	drivetrain components interaction energy efficiency	72%
C5	automated drivetrain control mechanisms	26%
C6	display-based conceptualisation of energy efficiency	31%

Regarding cluster C1 drivers used concepts such as technical combustion efficiency levels (23%), rpm-levels (23%), or motor load ranges (13%) to describe which engine states they perceived as (in)efficient. Several drivers (23%) referred to certain engine states as *inefficient,* such as partial (13%) and very high (13%) motor load ranges. Many drivers (36%) described certain engine states between under- and overload as efficient (inverse u-shaped efficiency relationship), while others (13%) named a lower load to be more efficient (a negative linear efficiency relationship). This was the identified first dimension (D1) within the Q3 analysis. As Table 6 shows, drivers who expressed the u-shaped (rather than linear) efficiency conceptualisation obtained higher fuel efficiency (effect size slightly below .5), and were more knowledgeable.

Regarding C2 many drivers (38%) perceived electric propulsion positively (e.g., ‘when I drive electric I consume less fuel’). Others (21%) were more critical, however, as they understood that electrical energy would have to be regained via an inefficient process (i.e., generated by the combustion engine). As Table 6 shows (under D2) the first group had less knowledge and more motivation.

Regarding C3 many (36%) expressed that regenerative braking allowed them to regain energy and reuse it later. However, drivers differed in the extent to which they mentioned recuperation potential; many (46%) emphasized that energy can only be recovered partially (i.e., substantial energy conversion losses), whereas others did not identify this limitation (33%). The perception of limitations was related to more knowledge and less motivation (D3, see Table 6).

Regarding C4, drivers discussed different aspects of the dynamic interaction of HEV drivetrain components as contributing to energy efficiency. Many (38%) reported the system's ability to shut down the combustion engine as an opportunity for energy savings. Some described the advantage of the system's ability to utilise electric propulsion when the combustion engine would be in an inefficient underload-state (10%), or that the battery can be charged by combustion-engine surplus (15%). No dimension resulted for C4.

Regarding C5, drivers regarded the automated drivetrain control mechanisms (i.e., algorithms that the system uses for deciding when to use which drivetrain component in which way) as key for energy efficiency, suggesting reliance on this automation to be an efficient strategy. Comparing this group with the rest of the sample (i.e., drivers who did not explicitly state such system reliance, D5, see Table 6) yielded only weak effects (i.e., system reliance only weakly related to lower energy efficiency).

Finally, regarding C6, 31% of the drivers specifically expressed display-level conceptualisations of energy efficiency. In other words, they explicitly stated for certain strategies, that they knew their behaviour to be efficient as the displays told them as such (i.e., they based their conceptualisation of strategy effectiveness explicitly on system feedback). Drivers were assigned to this category if they clearly expressed this explanation for at least one strategy. Comparing this group with the part of the sample which expressed more in-depth system-related conceptualisations (D6) showed a strong effect for knowledge, but only a weak effect for motivation and energy efficiency (see Table 6).

Table 6.
Relationship between the six energy-efficiency dimensions (D1-D6), motivation, knowledge and fuel efficiency indicators (FEI)

dimension	conceptualisation dimension		knowledge		motivation		FEI7.S.all	
		N	*d*	*p*	*d*	*p*	*d*	*p*
D1	inverse-u-shaped efficiency vs. linear efficiency	14 vs. 5	1.36	.016	0.29	.642	0.48	.382
D2	electric driving inefficient vs. efficient	8 vs. 15	0.85	.070	-0.94	.044	0.24	.595
D3	energy recovery without vs. with limitations	13 vs. 18	-0.62	.111	0.63	.105	0.19	.605
D5	not system reliant vs. system reliant	29 vs. 10	-0.22	.605	0.23	.564	0.36	.329
D6	not feedback-based vs. feedback-based	21 vs. 12	1.53	<.001	-0.45	.254	0.37	.320

Note. *N* refers to the first vs. the second group of the dimension. Cohens' *d* was computed (Cohen, 1977). Because of varying group sizes we used a permutation test (Hothorn et al., 2008) to compute *p*-values, *p*-values are two-tailed. For C4 there was no clear dimension, hence there is no D4. FEI7.S.all is the average score of FEI3-FEI6.

5.4 (Q4) False beliefs regarding HEV energy efficiency

To address research question 4 (false beliefs), we directly asked participants about the false beliefs (i.e., false conceptualisations of HEV energy efficiency) they had experienced themselves, or had noticed in other drivers. Most (92%) reported such false beliefs, with 26% reporting to have previously held false beliefs themselves. The clusters are depicted in Table 7. Apart from these specific false beliefs, several drivers (18%) generally emphasized that many HEV drivers had no accurate knowledge (or no knowledge at all) regarding specific drivetrain functionality, and that this could make it difficult to establish correct beliefs regarding energy efficiency.

Table 7.
Clusters of false beliefs about HEV energy efficiency

cluster	Cluster label	% of drivers
C1	electric energy utilization	44%
C1.1	"maximizing utilization of electric energy is good"	38%
C1.2	"using the EV-mode is good"	23%
C2	acceleration	36%
C2.1	"slow acceleration is good"	21%
C2.2	...."very harsh acceleration is good" (power mode, electric boost, full throttle)	15%
C3	"using the B-mode for deceleration is good"	15%
C4	"using cruise control is good"	10%
C5	"HEV is efficient irrespective of route type" (e.g., also on autobahn, short trips)	10%

Note. The B-mode is one of the four basic driving modes in the Toyota HEV (i.e., R, N, D, and B). The B-mode activates engine braking (i.e., slows car by spinning the combustion engine).

Regarding C1, participants stated that many drivers mistakenly overused electric propulsion, forgetting that this increased the requirement on the combustion engine to recharge the battery. Some (10%) also reported to have previously held this false belief before realizing that this impaired fuel economy.

Regarding C2, participants stressed that many drivers believed, erroneously, that very slow accelerations would be efficient, while others would wrongly accelerate as harshly as possible following the common ecodriving advice of "accelerate quickly". Both groups missed the point of an optimum efficiency point for acceleration that was relatively brisk, but not too excessive.

Regarding C3, participants reported that they knew that many drivers falsely understood the B-mode as a more effective regenerative braking mode, whereas in reality the perceived heightened deceleration is due to increased combustion engine drag.

Regarding C4, several participants stated that maximizing cruise control usage was a false strategy, as the vehicle cannot optimize the energy flows as well as a driver can.

Finally, regarding C5, participants reported that many inexperienced HEV drivers had misconceptions about HEVs being highly efficient generally, for instance for short trips (neglecting that HEVs also have an inefficient warm-up phase) or at autobahn speeds (where the advantage of the HEV drivetrain is not particularly high).

Beyond these major clusters individual drivers also named several further false beliefs (though at lower than 10% prevalence), such as “recuperation also works efficiently in strong decelerations” (i.e., neglecting regenerative braking limits; 8%) or “the AC needs much additional energy” (5%).

5.5 (Q5) Suggestions for ecodriving support systems to facilitate ecodriving

Most drivers (92%) had specific ideas for ecodriving support systems to facilitate ecodriving. The seven resulting major clusters are depicted in Table 8. Apart from these suggestions, 31% explicitly stated their general satisfaction with the ecodriving support currently provided by the vehicle. In order to also include less frequent suggestions we lowered our threshold for describing sub-clusters to 5% prevalence.

Table 8.
Cluster of suggestions to facilitate ecodriving by enhanced system support

cluster	cluster label	% of drivers
C1	systems to facilitate anticipatory driving	36%
C2	concurrent tracking feedback to facilitate targeting optimal system states	26%
C3	simple motivating feedback on eco-efficiency of driving style	26%
C4	changes in display layout	28%
C5	training approaches	23%
C6	various further suggested system parameters to display	36%
C7	various further ideas for assistant functions	33%

Regarding C1, drivers stated that a major challenge for optimal anticipation when driving was to predict the road ahead (particularly on unfamiliar routes). Several (23%) suggested that an ecodriving support system should provide information on the distance to, and properties of relevant upcoming road events (ascents/descents, congestion, traffic lights, reductions in speed limits). This augmented view of the road ahead would help drivers to adapt their strategy selections, and to fine-tune ecodriving behaviours. Several drivers (21%) suggested that the vehicle could also partly execute such anticipatory adaptations autonomously (i.e., highly automated driving and energy management functions), for example with an “eco cruise control” that exerts energy efficient longitudinal control based on driver inputs, or by controlling the charge level of the battery according to upcoming descents/ascents.

Regarding C2, drivers suggested that certain critical system states should be more clearly displayed (e.g., the point of maximum efficiency of the combustion engine, the neutral point at which there is zero energy flow in the system, the point at which regenerative braking is optimal, or a point just before that at which the combustion engine turns on), and that targeting these points should be facilitated. Several (18%) suggested the inclusion of detailed haptic/tactile feedback on the pedals that would help drivers to easily locate and maintain these critical points, without needing to look at a visual indicator. Furthermore, some (10%) suggested to either enlarge the pedal region that reflected the neutral point, or to add the option of deactivating regenerative braking on the gas pedal completely (for example with a switch).

Regarding C3, drivers suggested an additional ‘simple motivating feedback’ (see Table 8), for example with colours or symbols, that informed drivers when their behaviours have particularly strong negative or positive impacts on efficiency. Drivers stated that this would be particularly helpful for beginners, yet would also reassure more experienced ecodrivers (i.e., like a system that monitors drivers’ errors).

Regarding C4, drivers expressed a desire for several changes in the ecodriving display layout, such as fewer displays (10%), a less frequent need to switch between displays (8%, i.e., one integrated ecodriving display), the ability to shift relevant displays closer to the central gaze direction (8%, i.e., because of the need of continuous monitoring), and the ability to freely configure the displays themselves (5%).

Regarding C5, although not necessarily an in-vehicle ecodriving support system, many users stated the importance of instructing and training drivers regarding correct ecodriving strategies and accurate system understanding. Some (10%) also imagined this to be part of the user-interface (e.g., like a tutorial mode that was active during familiarisation with the vehicle).

Regarding C6, drivers reported a desire to have several additional system variables displayed that would help reduce uncertainties in strategy selection and implementation, for example combustion engine rpm (15%), energy consumption by the AC (8%), system temperature (8%), and battery charge/discharge current (8%). Moreover, some drivers (10%) expressed a wish for a more meaningful aggregation of average consumption history (e.g., avoid distortion by time-based intervals), and some drivers (8%) stated a desire for more precise information on momentary fuel consumption (i.e., not simply a bar display up to 10 l/100 km).

Regarding C7, few drivers suggested including a number of other ecodriving support systems, such as an automatic vehicle grill (5%, i.e. to shorten vehicle warm-up phase), or cruise control at 25 km/h (5%, i.e. to facilitate cruising in low-speed zones).

6 DISCUSSION

6.1 Summary of results

The objective of the present research was to advance understanding of HEV drivers' ecodriving strategies, and the challenges to optimal user-energy interaction. As expected (under hypothesis H1), motivation and knowledge explained sizeable variance (22%) in fuel efficiency, with their relative contributions varying with environmental complexity. Regarding the exploratory research questions (Q2-Q5), several core strategy dimensions were identified that were partly related to motivation, knowledge and fuel efficiency (Q2 – strategy selection). Furthermore, drivers expressed diverse conceptualisations of HEV energy efficiency (e.g., efficiency of utilizing electric propulsion; Q3), and reported various common false beliefs that lead to inefficient strategies (e.g., inefficient acceleration strategies; Q4). Finally, drivers suggested various ecodriving support systems (e.g., systems for facilitating anticipatory driving; Q5). The following sections describe the results with respect to theoretical and practical implications.

6.2 Theoretical implications

Results from research questions Q1-Q4 provided first support for notions of our conceptual framework. The fact that ecodriving motivation and technical system knowledge both explained sizeable variance in fuel efficiency (Q1 results) underlines their relevance in guiding efficient ecodriving behaviour. The variation of strategy selection across situations (Q2 results) indicates that drivers integrate perceived situation characteristics in strategy selection. Environmental complexity seems to be a relevant dimension in this respect. The present findings revealed that, with higher complexity, knowledge becomes more, and motivation less important for ecodriving efficiency (see Q1 results). However, the present study only provides first evidence. Further replication is needed to test the robustness of this effect. A key question in this respect regards the facets of the situation characteristics (e.g., dynamic instability of the situation versus amount and discriminability of applicable strategies) that ultimately drive environmental complexity in the context of user-energy interaction. To identify the dimensions of environmental characteristics that systematically interact with patterns and processes in user-energy interaction would be a key contribution to a general model of user-energy interaction. Examining the ways in which knowledge can protect against high environmental complexity (e.g., in preventing slips or mistakes; Reason, 1990; Stanton & Salmon, 2009) is another important field. Related to this, future research should also examine which specific facets of technical knowledge support optimal HEV ecodriving (Q3 results provide a possible starting point).

Moreover, the results of Q2 show large individual differences in strategy selection, giving some support to the idea that there are several individual factors that influence strategy selection. The relationships with motivation and knowledge (see Table 4) support this perspective, and the relationships of strategy selection to fuel efficiency (see Table 4) further demonstrate the relevance of strategy selection as a core component of the model. In addition, results for the autobahn situation in Table 4 give a first indication for the relevance of the 'intensity of implementation' component of the model (i.e., it is not just the type of strategy, but also the intensity of application that can make a difference).

Finally, results of Q3 (conceptualisations) and Q4 (false beliefs), in addition to those for Q2 (strategy selection), show the relevance of the 'strategy knowledge base' component of the model. Drivers expressed a large number of different conceptualisations of HEV energy efficiency (Q3), and identified various false beliefs (Q4) that could affect fuel economy. This indicates that more complex knowledge representations (e.g., mental models; Wilson & Rutherford, 1989) are an important component to consider when explaining eco-driving behaviour.

Although our conceptual model received initial support from the results, further specification of components could increase its predictive power. While effective strategy selection is crucial, considerable variance in driving behaviour may also be explained by lower-level strategy implementation (so far just one box in our framework, see Figure 1). Drivers reported strategies such as "anticipatory driving" and "optimize regenerative braking", yet no strategy dimensions resulted. It might be that only driving simulator or on-road studies with eye-tracking and data logging can uncover further dynamics in these strategies, for example by quantifying the anticipatory distance to test its relevance for energy efficiency. Further cognitive skills and processes, like perceptual speed (i.e., inspection time; Matas et al., 2014) or situation awareness (Durso & Sethumadhavan, 2008; Salmon et al., 2012), could play additional roles here.

Finally, our research provides a preliminary indication for certain decision biases in user-energy interaction. For example, results regarding Q2-Q4 suggest that there might be something like an "energy conversion fallacy"; many drivers were not aware of the considerable losses incurred when converting energy, and often reported over-utilization of electric propulsion (Q2) and regenerative braking, overvaluing their energy efficiency (Q3).

Furthermore, different heuristics and biases could be present (Tversky & Kahneman, 1974; see e.g. Schouten et al, 2014) in user-energy interaction in dynamic systems, for example effects related to anchoring (Kahneman, 2003), sunk costs (Arkes & Blumer, 1985), framing, mental accounting, or further biases related to prospect theory (Kahneman & Tversky, 1984). Identifying these effects would be a valuable contribution to a general framework of user-energy interaction. This becomes especially appealing when we consider that ecodriving can be described as decision-making under uncertainty that proceeds in a highly dynamic fashion, whereby discrete decision-making events overlap with continuous tracking.

6.3 Design implications

The large variety of drivers' suggestions for advanced ecodriving support systems in HEVs (results of research question Q5) emphasised the great potential for facilitating ecodriving. The following general design guidelines are derived from these results.

6.3.1 Design guideline 1 – comprehensive feedback

In developing ecodriving support systems, four key types of user-interface information appear crucial; (1) predictive information (for supporting adaptation to upcoming road events); (2) concurrent tracking feedback (to support the targeting of optimally efficient drivetrain states); (3) real-time performance feedback (i.e., indicators of momentary energy efficiency); and (4) aggregated performance feedback (i.e., aggregated indicators of energy efficiency). A comprehensive ecodriving support system needs to incorporate all four components, as incomplete information can create biases in drivers' ecodriving strategies (e.g., targeting sub-optimal system states, excessive focus on momentary consumption). Designing aggregated feedback is particularly challenging because different aggregations are meaningful in different situations (e.g., kilometres vs. minutes, size of aggregation/reference period). Adding context information (e.g., related elevation/speed profile) can be helpful. However, this also increases display complexity.

6.3.2 Design guideline 2 – ease of perception

Given that ecodriving behaviour needs to be controlled at a high pace, system design should maximise ease of perception and minimise distraction. For instance, drivers suggested haptic presentation for concurrent tracking feedback (for a similar view see Birrell et al., 2013), enabling peripheral monitoring of momentary performance feedback, and generally shifting ecodriving information to the central gaze direction.

6.3.3 Design guideline 3 – strategy acquisition support

To avoid false beliefs/strategies, ecodriving support systems should support efficient strategy acquisition. Our data suggested two opportunities in particular; (a) a tutor system that provides explicit advice on correct strategies, and the reasons for strategy effectiveness; or (b) a system that communicates this advice implicitly via the interface information described above, thereby supporting trial-and-error learning. If following approach (b), thorough interface testing must be conducted to ensure that drivers can easily discover efficient strategies, and that false beliefs are ruled out (see results of Q3 and Q4 for challenges to this approach).

6.3.4 Design guideline 4 – automated functions

Automated driving functions can facilitate certain aspects of ecodriving (e.g., optimal acceleration/deceleration trajectories). However, ecodriving is always a balance of different driver motives and current situation characteristics (see results of Q2), and some drivers already expressed their dissatisfaction with the design of current simple system interventions. Shared control (see e.g., Petermeijer et al., 2014) may be a fruitful approach, for example an adaptive eco cruise control (eco-ACC) for efficient longitudinal control that allows drivers to influence key parameters (e.g., the intensity of energy efficiency optimization, system flexibility to change speed) so that automated vehicle control matches drivers' momentary preferences.

6.3.5 Design guideline 5 – system transparency display

A display that shows drivetrain dynamics (e.g., energy flows) can be beneficial for ecodriving. Some drivers argued that a precise understanding of the drivetrain functionality would be helpful in preventing false strategies (Q4), and several drivers requested more information on system states (Q5). However, identifying the optimal level of system transparency, and how to present this in an easily understandable way, requires further research.

6.3.6 Design guideline 6 – configurability

Finally, driver diversity has to be considered. First, drivers of different levels of system understanding (or technical knowledge or ecodriving skill) will have different information needs. Second, differences in strategy preferences (e.g., based on drivers' general driving styles) can also lead to different information needs (e.g., a strategy-orientation towards maximizing cruise control usage vs. a strategy of constantly switching between optimal engine states). For an optimal ecodriving support system, some level of adaptability (e.g., the option to switch between basic vs. advanced ecodriving support) is necessary.

6.4 Conclusion

The present study showed that, even in a sample of HEV drivers who all hold relatively high ecodriving motivations, individual differences in applied ecodriving strategies are still substantial. Moreover, various false beliefs, alongside large individual differences in the way HEV energy efficiency is conceptualised, were identified. Our conceptual framework received initial support from the findings; however, several avenues for further advancement were identified.

The present research demonstrates that system understanding is necessary for energy efficiency, but that motivated ecodrivers do not necessarily develop efficient strategies (i.e., ecodriving motivation does not guarantee ecodriving success). Simply providing drivers with a technology that has the *potential* for high energy savings is not sufficient; the systems must be developed in a way that facilitates energy efficient behaviours. The achievement of the system's efficiency *potential* must not be an unnecessarily complex or demanding task. In this respect, the present study collected numerous suggestions for the design of systems that facilitate ecodriving.

It could be argued that facilitating efficient user-energy interaction (i.e., sustainability-by-design, increasing usability of the user-energy interaction) is a particularly powerful approach for the support of sustainable behaviours, as it would enable all those with basic motivation to utilize energy resource efficiently (i.e., this might partly bypass the need to establish strong positive attitudes towards environmentally friendly behaviours). This underlines the potential of green ergonomics (Thatcher, 2013). The ultimate goal of green ergonomics is to develop a general theory of user behaviour in low-resource systems (i.e., resource efficient systems); the present study is one step in this long-term agenda.

7 ACKNOWLEDGEMENTS

This research was supported by a DAAD grant to the first author and an ERASMUS+ grant to the second author. We gratefully thank Prof. Dr. Josef Krems for providing parts of the research infrastructure; Juliane Ketzer, Christian Rosomm, Diana Steinhoff, and Sabine Wollenberg for their assistance with processing the interview data; and Christiane Attig for assistance in manuscript preparation.

8 REFERENCES

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, *50*, 179–211. doi:10.1016/0749-5978(91)90020-T

Al-Alawi, B. M., & Bradley, T. H. (2013). Review of hybrid, plug-in hybrid, and electric vehicle market modeling studies. *Renewable and Sustainable Energy Reviews*, *21*, 190–203. doi:10.1016/j.rser.2012.12.048

Arkes, H. R., & Blumer, C. (1985). The psychology of sunk cost. *Organizational Behavior and Human Decision Processes*, *35*, 124–140. doi:10.1016/0749-5978(85)90049-4

Barkenbus, J. N. (2010). Eco-driving: An overlooked climate change initiative. *Energy Policy*, *38*, 762–769. doi:10.1016/j.enpol.2009.10.021

Birrell, S. A., Young, M. S., & Weldon, A. M. (2013). Vibrotactile pedals: Provision of haptic feedback to support economical driving. *Ergonomics*, *56*, 282–292. doi:10.1080/00140139.2012.760750

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*, 77–101. doi:10.1191/1478088706qp063oa

Cohen, J. (1992). A power primer. *Quantitative Methods in Psychology*, *112*, 155–159. doi:10.1037/0033-2909.112.1.155

Cohen, J. (1977). *Statistical power analysis for the behavioral sciences* (Rev. Ed.). New York, NY: Academic Press, Inc.

Dijk, M., Orsato, R. J., & Kemp, R. (2013). The emergence of an electric mobility trajectory. *Energy Policy*, *52*, 135–145. doi:10.1016/j.enpol.2012.04.024

Dogan, E., Steg, L., & Delhomme, P. (2011). The influence of multiple goals on driving behavior: The case of safety, time saving, and fuel saving. *Accident Analysis and Prevention*, *43*(5), 1635–1643. doi:10.1016/j.aap.2011.03.002

Durso, F. T., & Sethumadhavan, A. (2008). Situation awareness: Understanding dynamic environments. *Human Factors*, *50*, 442–448. doi:10.1518/001872008X288448

Edwards, W. (1954). The theory of decision making. *Psychological Bulletin*, *51*, 380–417. doi:10.1037/h0053870

Field, A. P. (2009). *Discovering statistics using SPSS*. London, United Kingdom: Sage Publications.

Franke, T., Bühler, F., Cocron, P., Neumann, I., & Krems, J. F. (2012). Enhancing sustainability of electric vehicles: A field study approach to understanding user acceptance and behaviour. In M.

Sullman & L. Dorn (Eds.), *Advances in traffic psychology* (pp. 295–306). Farnham, United Kingdom: Ashgate.

Franke, T., & Krems, J. F. (2013). Understanding charging behaviour of electric vehicle users. *Transportation Research Part F*, *21*, 75–89. doi:10.1016/j.trf.2013.09.002

Franke, T., Rauh, N., Günther, M., Trantow, M., & Krems, J. F. (2015). Which factors can protect against range stress in everyday usage of battery electric vehicles? Towards enhancing sustainability of electric mobility systems. *Human Factors*. http://dx.doi.org/10.1177/0018720815614702

Fuller, R. (2005). Towards a general theory of driver behaviour. *Accident Analysis and Prevention*, *37*, 461–472. doi:10.1016/j.aap.2004.11.003

Fuller, R. (2011). Driver control theory: From task difficulty homeostasis to risk homeostasis. In B. E. Porter (Ed.), *Handbook of Traffic Psychology* (pp. 13–26). London, United Kingdom: Academic Press.

Hanson, M. A. (2013). Green ergonomics: Challenges and opportunities. *Ergonomics, 56*, 399–408. doi:10.1080/00140139.2012.751457

Hothorn, T., Hornik, K., van de Wiel, M., & Zeileis, A. (2008). Implementing a class of permutation tests: The coin package. *Journal of Statistical Software*, *28*(8), 1–23.

Jamson, S., Brouwer, R., & Seewald, P. (2015a). Technologies to support green driving [Special issue]. *Transportation Research Part C, 58*(D), 629–782.

Jamson, S. L., Hibberd, D. L., & Jamson, A. H. (2015b). Drivers' ability to learn eco-driving skills; effects on fuel efficient and safe driving behaviour. *Transportation Research Part C*, *58*, 657–668. doi:10.1016/j.trc.2015.02.004

Kahneman, D. (2003). A perspective on judgment and choice: Mapping bounded rationality. *The American Psychologist*, *58*, 697–720. doi:10.1037/0003-066X.58.9.697

Kahneman, D., & Tversky, A. (1984). Choices, values, and frames. *The American Psychologist*, *39*, 341–350. doi:10.1037/0003-066X.39.4.341

Lewis-Evans, B., de Waard, D., & Brookhuis, K. A. (2013). Contemporary models of behavioural adaptation. In C. M. Rudin-Brown & S. L. Jamson (Eds.), *Behavioural adaptation and road safety* (pp. 35–60). Boca Ranton, FL: Taylor & Francis.

Matas, N. A., Nettelbeck, T., & Burns, N. R. (2014). Cognitive and visual predictors of UFOV performance in older adults. *Accident Analysis & Prevention*, *70*, 74–83. http://doi.org/10.1016/j.aap.2014.03.011

MAXQDA 10 [Computer software]. (2011). Marburg, Germany: VERBI Software – Consult – Sozialforschung.

McIlroy, R. C., & Stanton, N. A. (2015). A decision ladder analysis of eco-driving: The first step towards fuel-efficient driving behaviour. *Ergonomics*, *58*, 866–882. doi:10.1080/00140139.2014.997807

McIlroy, R. C., & Stanton, N. A., Harvey, C. (2014). Getting drivers to do the right thing: A review of the potential for safely reducing energy consumption through design. *IET Intelligent Transport Systems*, *8*, 388–397. doi:10.1049/iet-its.2012.0190

Neumann (2016). Energy Efficiency in Battery Electric Vehicle Use - Implications for the Driver Interface, the Driving Task, and Motivational Aspects. (doctoral dissertation).

Neumann, I., Franke, T., Cocron, P., Bühler, F., & Krems, J. F. (2015). Eco-driving strategies in battery electric vehicle use – how do drivers adapt over time? *IET Intelligent Transport Systems*, *9*, 746–753. doi:10.1049/iet-its.2014.0221

Petermeijer, S. M., Abbink, D. A., & de Winter, J. C. F. (2014). Should drivers be operating within an automation-free bandwidth? Evaluating haptic steering support systems with different levels of authority. *Human Factors*, *57*, 5–20. doi:10.1177/0018720814563602

Reason, J. (1990). *Human Error*. Cambridge, United Kingdom: Cambridge University Press.

Revell, K. M. A., & Stanton, N. A. (2014). Case studies of mental models in home heat control: Searching for feedback, valve, timer and switch theories. *Applied Ergonomics*, *45*, 363–378. doi:10.1016/j.apergo.2013.05.001

Salmon, P. M., Stanton, N. A., Young, K. L. (2012). Situation awareness on the road: Review, theoretical and methodological issues, and future directions. *Theoretical Issues in Ergonomics Science*, *13*, 472–492. doi: 10.1080/1463922X.2010.539289

Schouten, T. M., Bolderdijk, J. W., & Steg, L. (2014). Framing car fuel efficiency: Linearity heuristic for fuel consumption and fuel-efficiency ratings. *Energy Efficiency*, *7*, 891–901. doi:10.1007/s12053-014-9260-z

Sivak, M., & Schoettle, B. (2012). Eco-driving: Strategic, tactical, and operational decisions of the driver that influence vehicle fuel economy. *Transport Policy*, *22*, 96–99. doi:10.1016/j.tranpol.2012.05.010

Stanton, N. A., & Salmon, P. M. (2009). Human error taxonomies applied to driving: A generic driver error taxonomy and its implications for intelligent transport systems. *Safety Science*, *47*, 227–237. doi:10.1016/j.ssci.2008.03.006

Stillwater, T., & Kurani, K. S. (2013). Drivers discuss ecodriving feedback: Goal setting, framing, and anchoring motivate new behaviors. *Transportation Research Part F*, *19*, 85–96. doi:10.1016/j.trf.2013.03.007

Summala, H. (2007). Towards understanding motivational and emotional factors in driver behaviour: Ccomfort through satisficing. In P. C. Cacciabue (Ed.), *Modelling Driver Behaviour in Automotive Environments* (pp. 189–207). London, United Kingdom: Springer.

Taubman-Ben-Ari, O., Mikulincer, M., & Gillath, O. (2004). The multidimensional driving style inventory—scale construct and validation. *Accident Analysis & Prevention*, *36*, 323–332. doi:10.1016/S0001-4575(03)00010-1

Thatcher, A. (2013). Green ergonomics: Definition and scope. *Ergonomics*, *56*, 389–398. doi:10.1080/00140139.2012.718371

Tränkle, U., & Gelau, C. (1992). Maximization of subjective expected utility or risk control? Experimental tests of risk homeostasis theory. *Ergonomics*, *35*, 7–23. doi:10.1080/00140139208967794

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *Science*, *185*(4157), 1124–1131. doi:10.1126/science.185.4157.1124

Urban, D., & Mayerl, J. (2008). *Regressionsanalyse: Theorie, Technik und Anwendung*. Wiesbaden, Germany: VS Verlag für Sozialwissenschaften.

U.S. Department of Energy (2015). U.S. HEV Sales by Model. Retrieved from http://www.afdc.energy.gov/data/10301

Wilson, J., & Rutherford, A. (1989). Mental Models: Theory and Application in Human Factors. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *31*(6), 617–634. doi:10.1177/001872088903100601

Young, M. S., Birrell, S. A., & Stanton, N. A. (2011). Safe driving in a green world: A review of driver performance benchmarks and technologies to support “smart” driving. *Applied Ergonomics*, *42*, 533–539. doi:10.1016/j.apergo.2010.08.012

9 APPENDIX

9.1 Appendix A

Appendix A.

Description for situations S1 to S4

interview-part	text in interview manual
general introduction	Let us assume for all the following driving situations that you are driving alone with your Prius. The weather is sunny and calm, at 20°C. There is relatively little traffic on the route. You are familiar with the route. Let us assume that you want to drive as energy-efficient as possible.
situation 1 (S1): autobahn	Imagine driving on a three-lane motorway, there are no speed limits and the terrain is rather flat.
situation 2 (S2): city	Imagine driving in the city (light traffic) on major and secondary roads with intersections and traffic lights.
situation 3 (S3): rural flat	Imagine driving on a relatively straight and flat country road (federal road with speed limits between 70 and 100 km/h)
situation 4 (S4): rural mountainous	Imagine driving on a rather winding country road, the terrain is mountainous (longer route sections up- and downhill).

9.2 Appendix B

Appendix B.
Interview questions administered to address research questions Q1-Q5

	interview questions
Q1	<u>*Item for FEI2:*</u> Which average fuel consumption do you currently achieve with your most used hybrid car? Please refer this to the last 3 month. <u>*Item for FEI3-FEI6 (preceded by situation description, see Appendix A):*</u> What would be a typical average consumption for you under these conditions? <u>*Items for ecodriving motivation:*</u> i1: I am always striving to drive particularly fuel efficient. i2: I try to drive as efficient as possible. <u>*Items for system background knowledge:*</u> i1: I am familiar with the propulsion technology of hybrid cars (e.g., types and functionality of electric motors). i2: I am familiar with concepts like energy density and energy conversion efficiency. i3: I have an idea about how regenerative braking technically works.
Q2	Definition: A strategy is a concrete behaviour that you use while driving to reduce fuel consumption. <u>*First introductory question:*</u> What are the strategies that you use to reduce fuel consumption while driving? Could you give us a summary? <u>*Question asked for each of the four situations S1-S4:*</u> What are you doing in this situation in order to drive as efficient as possible?
Q3	<u>*Question asked for each of the four situations S1-S4:*</u> From your perspective, why does this strategy lead (especially with a hybrid car) to the reduction of energy-consumption? *(The Q3-Coding system was developed based on answers to this question. Finally, answers to the Q2-questions for S1-S4 were reviewed to identify all statements on energy efficiency conceptualisation to be included in the analysis)*
Q4	With increasing experience users often develop certain conceptualizations about how the hybrid drivetrain works. This means conceptualizations about how the drivetrain components work together and how the drivetrain system can be affected in order to drive fuel-efficient. Sometimes, however, one realizes that certain conceptualisations of the functionality of the system are imprecise or incorrect and may lead to suboptimal ecodriving strategies. What could be some false conceptualisations regarding the functionality of the hybrid drivetrain that negatively affect fuel-efficient driving?
Q5	How could the implementation of your strategies been made even easier with displays or other system feedback? How could energy-efficient driving with a hybrid car be made even easier through improved information/support of the driver by vehicle?

9.3 Appendix C

Appendix C.

Exemplary quotations per research question (Q) and cluster/dimension (C/D)

Q	cluster/ dimension	quote
Q2	D1 (autobahn; speed limit ≤ 100 km/h vs. speed limit > 100 km/h)	"I drive in the rightmost lane. I set the cruise control to, as energy-saving as possible, to 80 quite precisely, according to speedometer, and let the car do the rest." (P34)
		"I would seek a speed, that would get me ahead but which is still not excessively fuel consuming, so somewhere around 120 probably, and I would set the cruise control." (P25)
Q2	D2 (city; accelerating rather fast vs. rather slow from standstill)	"I try to accelerate as ..., well, three quarters throttle control is what I have annotated, as fast as possible to the required speed, that is 50 km/h in town..." (P19)
		"Start as slowly as possible. I mean not hit the gas pedal to get away quickly, but to start slowly, as long as I can stay in EV-mode and slowly increase speed, I would say." (P23)
Q2	D3 (city; accelerating with combustion engine vs. with electric propulsion from standstill)	"And another strategy: While accelerating I try not to press the gas pedal fully, but to accelerate smoothly. So that it has more time to catch that spot, where the hybrid only uses the combustion engine alone for driving. When the spare energy flows into the battery and when it does not have to consume energy from the battery. But, this spot is hard to catch actually." (P25)
		"But normally I would use the EV-button and set the car in motion until 40, 45 km/h and then I switch off the EV-button and then it drives again without combustion engine." (P32)
Q2	D4 (city; not exploiting electric driving vs. exploiting electric driving)	„Every time when the speed is rather around 50 then actually little electric driving but rather accelerate with petrol and then let it roll." (P17)
		"In sections, where I often have to take turns consecutively, I would try to, to drive electric as much as it works." (P31)
Q2	D5 (rural flat; average maximum speed vs. exploiting speed limits)	"It doesn't really matter if I arrive 10 minutes earlier or later. Then even at a speed limit of 100 I let the cruise control stay at 70. Because I know after 5 km the speed limit of 100 is repealed, and then it says 70 again. And then I simply let it roll. And then I put up with someone overtaking me." (P14)
		"Well, now I am really on the move with a constant speed more or less. Sometimes 70, sometimes 100, as you know." (P02)
Q2	D6 (rural flat; variable speed vs. constant speed)	"If the speed limit is currently 70, I would use Pulse and Glide between 60 and 70 km/h. Hence this reducing throttle and then accelerating again until speed is built up again" (P05)
		"I would switch cruise control on and keep the speed." (P25)
Q2	D7 (rural mountainous; decreasing vs. keeping speed for going up the hill)	"But if I really was on my own on the road, I would decelerate the car, this time without cruise control, because it's easier, it consumes less then. Because when I rush the car up the hill with full throttle, of course it would not be in accordance with energy saving." (P30)
		"driving up the hill as constant as possible, without full throttle, and braking as carefully as possible to charge the battery downhill" (P01)
Q3	C1 (combustion	"Exactly, with the… that [combustion] engine actually is not very energy-efficient at part-load-operational range. Therefore I either just keep it accelerating and let it work at a good power-output and torque …, or I just let it roll."

Citation: Franke, T., Arend M. G., McIlroy, R. C., & Stanton, N. A. (2016). Ecodriving in hybrid electric vehicles – exploring challenges for user-energy interaction. *Applied Ergonomics.*

	engine energy efficiency)	(P27)
Q3	C2 (electric propulsion energy efficiency)	"Well, like I said, the more electric power I can get out of the vehicle, the better. That's quite clear" (P36)
Q3	C3 (recuperation energy efficiency)	"Here, the benefit of the hybrid-system is, that it is – at least partly – able to transform the energy, the potential energy or the kinetic energy into a re-usable form while driving downhill. And I can just use it again on the uphill drives." (P04)
Q3	C4 (drivetrain components interaction energy efficiency)	"That is, large sections when you drive with an extremely bad degree of efficiency of maybe 5% or maybe barely 10% at best are deactivated completely and are substituted for the electrical operation mode." (P21)
Q3	C5 (automated drivetrain control mechanisms)	"That is, I set the wheel's rotational speed. The computer knows how to provide this speed optimally, that is, electrically powered and or by means of generating more energy." (P21)
Q3	C6 (display-based conceptuali-sation of energy efficiency)	"I rely on that eco-display and the average consumption display in the car. These two displays are decisive." (P11)
Q4	C1.1 ("maximizing utilization of electric energy is good")	"Well, driving electrically powered as much as possible, that would be a wrong conclusion. What I did not consider is that the motor-management system consumes very much more energy; when it drops below the last two lines and then it has to recharge. Then the consumption rises really, really high for a relatively long period of time and that's annoying, especially, when it happens in those phases, when you could drive in an optimum way with hybrid, but the battery is just down." (P31)
Q4	C1.2 ("using the EV-mode is good")	"Yes, that was in the early stages, that I was very proud of the electric mode of operation and when I tried to drive electrically with the EV-mode. That's of no use at all. Basically because it needs to charge later on somewhere, unless it fits with the route." (P25)
Q4	C2.1 ("slow acceleration is good")	"Well, the first thing I can imagine is that many people think, that slow driving and energy-saving driving is the same thing. That means, they accelerate like "lalalala hm hm" like very careful in electric mode. Well accelerating with electric energy is a nice thing, but: when the hybrid battery is down eventually, the motor needs to generate more energy. And the more fuel it consumes as well to charge the battery again." (P30)
Q4	C2.2 ("very harsh acceleration is good")	"When people think, they always have to accelerate really fast, because only then the electric motor is assisting. This is fundamentally wrong. It uses the electric motor in the eco-area [referring to eco-display] as well. I can tell that from the charge rate. Partly up to 10 amperes. The higher the charge, that is the charge state of the battery, the more it wants to get rid of during the drive. I would generally never use power mode." (P39)
Q4	C3 ("using the B-mode for deceleration is good")	"A wrong impression, which emerged again and again while the Prius for example, when I drive downhill with B, then it is more fuel-efficient, because I recuperate more often and I regain more energy. So that is definitively wrong in that case." (P05)
Q4	C4 ("using cruise control is good")	"Well I personally do not believe that a cruise control helps to save gas. I simply believe that if you have a certain understanding of how such a motor works, that you will do better than a stupid fixed adjustment of speed." (P21)

Citation: Franke, T., Arend M. G., McIlroy, R. C., & Stanton, N. A. (2016). Ecodriving in hybrid electric vehicles – exploring challenges for user-energy interaction. *Applied Ergonomics.*

Q4	C5 ("HEV is efficient irrespective of route type")	"Well I only know that there are situations, where the hybrid propulsion works rather badly. I mean, when someone has the notion that he lives somewhere in the mountains. Well he would be rather worse off with a hybrid drivetrain, than with a diesel. That would be a wrong conception of a hybrid. I mean that one believes, that it is the best option in all situations." (P09)
Q5	C1 (systems to facilitate anticipatory driving)	"I would need a topographical navigation-system, which tells me on unfamiliar routes now you are going to go uphill or downhill. Which provides me with traffic messages for the nearby area. Like there is a traffic jam in the next two kilometres. These are all the things that I know on my home route, but that I don't know on unknown routes. That is why I manage to save fuel very well. When I am unfamiliar, I don't manage so well. So a navigation system with information about the environment could facilitate a reaction to things in the near future. So that the car knows what will happen next." (P01)
Q5	C2 (concurrent tracking feedback to facilitate targeting optimal system states)	"That is the ideal operating point. It could be visualized by a display or by a tangible notch on the pedal. This is what I would like, for example. A counterpressure on the pedal, so I realize, okay if I go further the electric motor will shut off or the combustion engine kicks in. So that I do not depend on watching out for it visually. This would help many people, who are not so good at multi-tasking. They would simply feel it somehow and would not be distracted from the traffic. So a notch on the pedal for the spot of optimum combustion would be good as well. Because you would simply feel it." (P17)
Q5	C3 (simple motivating feedback on eco-efficiency of driving style)	"For example for beginners it would be good to have a display that's like "yes excellent, you are driving very energy efficient right now"; or if you drive too wildly or inconsiderately "Watch out now, back off a little bit." (P30)
Q5	C4 (changes in display layout)	"You can do it [improve it] by configuring the head-up display correspondingly. That the meters are simply better to read or that this energy flow chart is projected on the windshield, that you can possibly also alter the display content of the projection on the windshield." (P18)
Q5	C5 (training approaches)	"I would consider a training mode. Like I have with computer games. When I start a new game, I often do not quite understand how the whole controls are working and so I have to learn it. These kind of things can be integrated in the car and it could tell like "I'm driving in tutorial mode right now". And after 100 kilometres I can switch it off or it turns off by itself." (P01)
Q5	C6 (various further suggested system parameters to display)	"Maybe you could show the disadvantage of consumption by the air conditioning compressor, so that you would see some numerical values, when the air condition is switched on, to what extent it eventually makes a difference. Because you simply do not have an overview about this." (P07)
Q5	C7 (various further ideas for assistant functions)	"Like if the cruise control was not only working from 40 km/h. In the city we often have speed limits of 30 km/h, it would be good here if it could be switched on at 25 kmh. That is always cumbersome, it doesn't work below 40." (P19)