The Role of Interaction Patterns with Hybrid Electric Vehicle Eco-Features for Drivers’ Ecodriving Performance

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Abstract

Objective: The objective of the present research was to understand drivers’ interaction patterns with hybrid electric vehicles’ (HEV) eco-features (electric propulsion, regenerative braking, neutral mode) and their relationship to fuel efficiency and driver characteristics (technical system knowledge, ecodriving motivation).

Background: Ecodriving (driving behaviors performed to achieve higher fuel efficiency) has the potential to reduce CO2 emissions caused by road vehicles. Ecodriving in HEVs is particularly challenging due to the systems’ dynamic energy flows. As a result, drivers are likely to show diverse ecodriving behaviors, depending on factors like knowledge and motivation. The eco-features represent an interface for the control of the systems’ energy flows.

Method: A sample of 121 HEV drivers who had constantly logged their fuel consumption prior to the study participated in an online questionnaire.

Results: Drivers’ interaction patterns with the eco-features were related to fuel efficiency. A common factor was identified in an exploratory factor analysis, characterizing the intensity of actively dealing with electric energy, which was also related to fuel efficiency. Driver characteristics were not related to this factor yet they were significant predictors of fuel efficiency.

Conclusion: From the perspective of user-energy interaction, the relationship of the aggregated factor to fuel efficiency emphasizes the central role of drivers’ perception of and interaction with energy conversions in determining HEV ecodriving success.

Application: To arrive at an in-depth understanding of drivers’ ecodriving behaviors that can guide interface design, future research should be concerned with the psychological processes that underlie drivers’ interaction patterns with eco-features.

Keywords: Driver behavior, user-energy interaction, electric propulsion, regenerative braking, neutral mode.

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1 INTRODUCTION

Road transport is one of the major contributors to CO2 emissions caused by energy infrastructure (Davis, Caldeira, & Matthews, 2010). Consequently, energy-efficient vehicles such as hybrid electric vehicles (HEVs) that can reduce road transport CO2 emissions (Bitsche & Gutmann, 2004) have become increasingly widespread (see e.g., Dijk, Orsato, & Kemp, 2013). Yet actual energy efficiency is still associated with the driver: vehicle maintenance or route selection (strategic or tactical ecodriving decisions) constitute significant influences on drivers’ ecological footprint (Sivak & Schoettle, 2012). Likewise, operational ecodriving (Sivak & Schoettle, 2012), comprising all driving behaviors performed to achieve higher energy efficiency (see e.g. Barkenbus, 2010), vastly impacts the real-world energy efficiency of road vehicles (e.g., af Wåhlberg, 2007; Bingham, Walsh, & Carroll, 2012), with the potential for long-term fuel savings of on average 10% (cf. Barkenbus, 2010). Therefore, applying a human factors and ergonomics perspective for understanding patterns in energy efficient driving behavior is fundamental to improving the sustainability of road transport.

Which ecodriving behavior yields optimal energy efficiency particularly depends on drivetrain characteristics, for example the availability of regenerative braking (Cocron et al., 2011; Kuriyama, Yamamoto, & Miyatake, 2010). When compared to conventional combustion vehicles, HEVs contain several additional drivetrain features, such as electric propulsion, regenerative braking and neutral mode (i.e., a driving mode in which the HEV is coasting without energy from the motor/engine and without regenerative braking). These key drivetrain features (hereafter labelled eco-features) enable the driver to control the system’s energy flows, and thus constitute an HEV’s specific user-energy interface. Understanding how driver-interaction with eco-features is related to fuel efficiency therefore constitutes a key contribution to the field of user-energy interaction.

Due to the comparatively complex energy flows in the HEV (McIlroy, Stanton, Harvey, & Robertson, 2013; e.g. bidirectional energy flow), drivers who generally use different sets of ecodriving strategies can have similar energy efficiencies (Franke, Arend, McIlroy, & Stanton, 2016a). However, specific ecodriving strategies that include the usage of eco-features (i.e., interaction patterns with eco-features) tend to be associated with increased or decreased fuel efficiency (Franke et al., 2016a). An important question in this respect is what determines the drivers’ selection of specific interaction patterns. Among other factors focusing on the role of driver characteristics in ecodriving, technical system knowledge and ecodriving motivation (see e.g., Franke et al., 2016a; Franke, Arend, McIlroy, & Stanton, 2016b; Stillwater & Kurani, 2013) have been examined, in particular for HEV drivers. Both tend to be related to the selection of specific ecodriving strategies, in addition to fuel efficiency (Franke et al., 2016a).
et al., 2016a). Consequently, investigating the role of technical system knowledge and ecodriving motivation is considered a relevant topic for understanding driver-interaction with eco-features.

The objective of the present research was to examine (a) which interaction patterns with eco-features are related to energy efficiency (i.e., ecodriving success), and how technical system knowledge and ecodriving motivation are related to (b) inter-individual differences in those interaction patterns and (c) ecodriving success.

2 BACKGROUND

2.1 Driver-Interaction Patterns with Eco-features: A Control-Theoretic Approach

In general, for driving energy efficient HEV drivers have to constantly adapt their behavior, thereby utilizing the eco-features in a certain way. Control-theoretic models constitute a fruitful framework for modelling such continuous interactions (Fuller, 2011; Summala, 2007) and are therefore particularly suited to model drivers’ interaction patterns with eco-features, embedded in the general (eco)driving-task (see Franke et al., 2016a). Control-theoretic models propose that drivers constantly monitor system and environmental variables, and control/adapt their driving behavior by comparing an actual state to a target state (e.g., Fuller, 2005, 2011). Both constitute levels of task difficulty (e.g., a car driving with a certain speed [actual state] is slowed down [controlled] until the preferred speed level [target state] is reached). Transferred to the scenario of a driver-interaction with an eco-feature, the driver will control the system in order to achieve the eco-feature state perceived as energy efficient (e.g., in HEV driving with the combustion engine [actual state], the driver slowly reduces pressure on the gas pedal [control] until the combustion engine is shut off and solely the electric propulsion moves the wheels [target state]).

In control-theoretic models, the individual target state as well as general differences in (eco)driving behavior are assumed to be dependent on the driver (see e.g., Davidse, Hagenzieker, van Wolffelaar, & Brouwer, 2009; Fuller, 2005, 2011). There will be differences between drivers regarding factors such as their motivation (e.g., the importance of the primary goal of driving safely relative to the secondary goal of fuel efficiency, or varying goal priorities due to traffic/roadway demands; e.g., Dogan, Steg, & Delhomme, 2011; Fuller, 2007) or knowledge (e.g., Franke et al., 2016a). Consequently, both are hypothesized to relate to drivers’ interaction patterns with HEV eco-features.

2.2 Energy flows related to HEVs’ eco-features

By controlling the vehicle, drivers influence the energy flows associated with the eco-features. Firstly, electric propulsion (i.e., the driving state when the wheels are moved by the electric motor) allows the
conversion of electric into kinetic energy via the wheels. Secondly, with regenerative braking (i.e., the driving state of energy recovery while the car is decelerating) kinetic energy of the wheels can be converted back into electric energy. Thirdly, the neutral mode (i.e., the driving state of coasting created by the kinetic energy already possessed by the wheels without drivetrain propulsion or employment of regenerative braking) is, compared to other eco-features, associated with maximum utilization of the kinetic energy built up; thus avoiding conversion. Using this perspective of a relationship between driver behavior and energy flows may also contribute to a better understanding of general patterns of user-energy interaction.

3 PRESENT RESEARCH

The objective of the present research was to advance the understanding of user-energy interaction by examining (a) which interaction patterns with eco-features are related to energy efficiency (i.e., ecodriving success) and how technical system knowledge and ecodriving motivation are related to (b) inter-individual differences in those interaction patterns and (c) ecodriving success. To study drivers with day-to-day experience of HEVs’ eco-features, a sample of 121 HEV drivers who had constantly logged their fuel efficiency was recruited.

3.1 Research Questions and Hypotheses

Table 1 provides an overview of the research questions and hypotheses. When the direction of effects could be deduced from literature or theory, hypotheses were directional; when not, hypotheses were non-directional. Directional hypotheses regarding Q2, Q3 and Q4 are based on results from Franke et al. (2016a).

Based on the control-theoretic framework introduced in the section ‘Background’, drivers control each eco-feature to arrive at the target state they perceive efficient. Q1 is therefore concerned with how energy efficient HEV drivers perceive the eco-features.

Typical interaction patterns with HEV eco-features were deduced from an interview study documented in Franke et al. (2016a). These patterns were conceptualized as dimensions (e.g., each deceleration with eco-features can be classified between entirely with neutral mode versus entirely with regenerative braking). To examine a broad range of interaction patterns, two dimensions representing general (i.e., a behavioral tendency to use an eco-feature) as well as two representing specific (i.e., a characteristic driving maneuver) interaction patterns were assessed. General interaction patterns referred to the frequency of using electric propulsion and regenerative braking, whilst specific ones
related to acceleration without versus with utilization of electric propulsion, and deceleration with neutral mode versus with regenerative braking.

In addition to these factors, the relationships of technical system knowledge and ecodriving motivation to interaction patterns with eco-features (Q3), as well as to fuel efficiency (Q4), were also examined. H4c concerns the role of technical system knowledge and ecodriving motivation in determining fuel efficiency. It is expected that their positive influence on fuel efficiency arises as a result of differences in ecodriving behavior (including differences in drivers’ interaction patterns with eco-features). This is the case when both technical system knowledge and ecodriving motivation are related to interaction patterns and their relationship to fuel efficiency weakens when the influence of interaction patterns on fuel efficiency is also taken into account.

**Table 1: Research questions and hypotheses in the present study**

<table>
<thead>
<tr>
<th>Research question</th>
<th>Hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1 How do drivers perceive the energy efficiency of HEV eco-features?</td>
<td>H1 Perceived energy efficiency of each eco-feature is related to technical system knowledge</td>
</tr>
<tr>
<td>Q2 How do interaction pattern dimensions relate to fuel efficiency?</td>
<td>H2a Frequency of using the electric propulsion is related to lower fuel efficiency</td>
</tr>
<tr>
<td></td>
<td>H2b Frequency of regenerative braking is related to fuel efficiency</td>
</tr>
<tr>
<td></td>
<td>H2c Acceleration without vs. with electric propulsion is related to lower fuel efficiency</td>
</tr>
<tr>
<td></td>
<td>H2d Deceleration with neutral mode vs. regenerative braking is related to fuel efficiency</td>
</tr>
<tr>
<td>Q3 How do drivers’ technical system knowledge and ecodriving motivation relate to interaction pattern dimensions?</td>
<td>H3a Technical system knowledge is related to the frequency of using regenerative braking and to deceleration with neutral mode vs. regenerative braking</td>
</tr>
<tr>
<td></td>
<td>H3b Higher technical system knowledge is related to acceleration without the electric propulsion</td>
</tr>
<tr>
<td></td>
<td>H3c Ecodriving motivation is related to frequency of using regenerative braking and to deceleration with neutral mode vs. regenerative braking</td>
</tr>
<tr>
<td></td>
<td>H3d Higher ecodriving motivation is related to higher frequency of using the electric propulsion and acceleration with the electric propulsion</td>
</tr>
<tr>
<td>Q4 How do drivers’ technical system knowledge and ecodriving motivation relate to energy efficiency?</td>
<td>H4a Higher technical system knowledge is related to higher fuel efficiency</td>
</tr>
<tr>
<td></td>
<td>H4b Higher ecodriving motivation is related to higher fuel efficiency</td>
</tr>
<tr>
<td></td>
<td>H4c The relationships of technical system knowledge and ecodriving motivation to fuel efficiency weaken when the relationships of interaction patterns to fuel efficiency are taken into account</td>
</tr>
</tbody>
</table>

*Note.* Directional hypotheses are: H2a, H2c, H2d, H3b, H3d, H4a, H4b, H4c. Non-directional hypotheses are H1, H2b, H2d, H3a, H3c.

4 METHOD

4.1 Participants

To assess hypotheses with 80% power of detecting bivariate correlations $|r| \geq .30$ and $R^2 \geq .10$ in the expected multiple linear regression models with up to 6 predictors (for H4c), a sample size of at least 130 HEV drivers was required (a-priori power analyses calculated with G-Power; Faul, Erdfelder, Buchner, & Lang; 2009). To achieve this, drivers of the Toyota Prius 2, 3 and c were recruited. To reach a sample of experienced drivers who constantly logged their fuel consumption data, recruitment focused on drivers from the online-database spritmonitor.de. Only drivers who had logged their fuel data at least once within six months before the initial contact were recruited (most drivers however logged their fuel consumption regularly on a weekly basis). Drivers who met these criteria were contacted from 10/2015 to 12/2015 with an invitation to participate in an online questionnaire. The study was run from 12/2015 to 01/2016.

The final sample consisted of 121 HEV drivers (93% male; $M_{age} = 48$ years; $SD_{age} = 11$). Of the total number of participants, 20 had previously participated in an interview-study documented in Franke et al. (2016a). Drivers’ had a mean driven distance of 62392 km ($SD = 52324$; range: 5600–250000) with HEVs, accordingly 38769 miles ($SD = 32513$; range: 3480–155343), corresponding to a mean driving experience of 3.3 years ($SD = 2.3$; range: 0.4–16 years). At the time of data collection, 42% of the drivers drove a Prius 3, 30% a Prius c, and 28% the Prius 2 as their primary HEV. With their respective HEV, drivers had a mean driven distance of 57482 km ($SD = 48791$; range: 4000–230000), accordingly 35718 miles ($SD = 30317$; range: 2485–142915).

4.2 Scales and Measures

The same rating scale was used for all items and all scales described below (6-point Likert scale ranging from completely disagree [1] to completely agree [6]). Scales, instructions and items are included in Appendix 1.

4.2.1 Perceived Efficiency of Eco-features

Efficiency evaluation of each eco-feature was assessed based upon two facets: items representing the perceived efficiency of the usage of each eco-feature, and items focusing on the perceived efficiency of the energy dynamics incurred in utilizing the respective eco-feature. Items were deduced from driver statements collected via a previous interview-study (Franke et al., 2016a). Scale reliabilities (Cronbach’s alpha) were sufficient to excellent (electric propulsion: $\alpha = .83$; regenerative braking: $\alpha = .79$; neutral mode: $\alpha = .91$).
4.2.2 Usage Dimensions of Eco-Features

As stated in the section ‘Present Research’, interaction patterns can be conceptualized as ecodriving strategy dimensions. In the questionnaire, participants rated a number of ecodriving strategy dimensions; all assessed with two-item-scales. As general usage dimensions, the frequency of using electric propulsion (usage of electric propulsion; \( \alpha = .75 \)) and the frequency of using regenerative braking (usage of regenerative braking; \( \alpha = .91 \)) were assessed. As specific usage dimensions, acceleration without versus with utilization of the electric propulsion (acceleration; \( \alpha = .75 \)), and similarly deceleration with neutral mode versus with regenerative braking (deceleration; \( \alpha = .84 \)) were assessed.

4.2.3 Knowledge and Motivation

Technical system knowledge (knowledge; three items; \( \alpha = .84 \)) and ecodriving motivation (motivation; two items; \( \alpha = .81 \)) were both assessed using scales developed in previous research (Franke et al., 2016a, 2016b). The knowledge scale (adapted from Franke, Rauh, Günther, Trantow, & Krems, 2015) was developed to represent technical knowledge concerning the HEV and its system dynamics. The motivation scale was designed to represent behavioral intention (i.e., intention to perform energy efficient driving behavior; e.g., Ajzen, 1991; Lauper, Moser, Fischer, Matthies, & Kaufmann-Hayoz, 2015).

4.2.4 Fuel Efficiency

In order to assess the fuel consumption of the drivers as accurately as possible, four indicators were taken into account (see Appendix 1): Drivers estimated their average fuel consumption between April and September 2015 (estimated). Their fuel consumption for the same time period was also calculated from logger data (logged): At the end of the questionnaire, drivers were asked to provide a data file with their logged fuel consumption (users of the spritmonitor.de website can download their individual fuel logs). Logger-data was available from 100 participants (18 drivers decided not to provide logger data; 3 provided data files that did not contain fueling events between April and September 2015). The strong relationship \( (r = .86) \) between estimated and logged fuel consumption indicated that participants’ estimations were sufficiently accurate.

To arrive at a reliable indicator of fuel efficiency, the following steps were performed (parallel to the rationale of Franke et al., 2016a). To account for potential differences in the trip profiles of the drivers (e.g. some participants may drive primarily on urban versus rural routes), two indicators were used: drivers estimated their fuel consumption for an urban (urban) and a rural route (rural)—both with standardized conditions (e.g., weather, other traffic). Furthermore, in order to remove mean fuel
consumption differences between HEV models, the indicators were standardized based on the respective distribution parameters of the whole fleet (taken from spritmonitor.de). Results were inverted so that higher values corresponded to higher fuel efficiency. This was performed for both indicators, resulting in the fuel efficiency indicators (FEI): FEI.urban and FEI.rural. Since both correlated strongly \( r = .64 \), they were aggregated to one factor (FEI.all; \( \alpha = .78; n = 120 \) due to missing data for one participant) which was used for all following analyses.

5 RESULTS

Statistical analyses were based on descriptive statistics, correlation coefficients and linear regression models. Effect sizes were interpreted according to Cohen (1992). Outliers more than three standard deviations from the scale mean (i.e., \( |z| > 3 \)) were identified for the variables evaluation of regenerative braking \( (z = -3.25, \text{thus } n = 120) \), motivation \( (z = -3.12) \) and FEI.all \( (z = -3.11) \), and subsequently excluded. \( P \)-values were two-tailed for non-directional and one-tailed for directional hypotheses (Kimmel, 1957). The significance level used was \( \alpha = .05 \).

5.1 Efficiency Evaluation of HEV Eco-features’ Energy Efficiency (Q1)

In reference to Q1, Fig. 1 depicts key parameters of the three efficiency evaluation distributions (median, quartiles, ranges and frequency distributions). Regenerative braking \( (M = 3.65, SD = 0.66) \) and neutral mode \( (M = 3.68, SD = 1.55) \) were, on average, perceived as slightly more energy-efficient than electric propulsion \( (M = 3.33, SD = 1.09) \). However, all mean evaluations lay between 3 and 4 (i.e., slight disagreement and slight agreement with a positive evaluation). Moreover, the efficiency evaluation of electric propulsion and neutral mode comprised fairly strong inter-individual variance.

![Figure 1. Boxplots and histograms depicting the efficiency evaluations of the eco-features.](Image)
A correlational analysis was performed to further assess Q1 and H1 (see Table 2). Assumptions were tested according to Field (2009). All variables except three were non-normally distributed. Spearman rank correlation coefficients (\(\rho\)) were therefore also computed. Regarding the relationships of knowledge to efficiency evaluations, none were significant and effect-sizes were, at the most, small (H1 rejected). All correlations between different efficiency evaluations were moderate to strong and significant (\(p < .001\)). Efficiency evaluation of electric propulsion was positively related to regenerative braking and negative to neutral mode. The relationship between the efficiency evaluation of regenerative braking and neutral mode was negative.

### Table 2. Correlation matrix of efficiency evaluations, knowledge, motivation and FEI.all

<table>
<thead>
<tr>
<th>Variable</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency evaluation of electric propulsion</td>
<td>-</td>
<td>.48***</td>
<td>- .41***</td>
<td>-.12</td>
<td>.17</td>
<td>-.18*</td>
</tr>
<tr>
<td>Efficiency evaluation of regenerative braking</td>
<td>.43***</td>
<td>-</td>
<td>- .42***</td>
<td>-.02</td>
<td>.14</td>
<td>-.18</td>
</tr>
<tr>
<td>Efficiency evaluation of neutral mode</td>
<td>-.40***</td>
<td>-.39***</td>
<td>-</td>
<td>.14</td>
<td>.06</td>
<td>.15</td>
</tr>
<tr>
<td>Knowledge</td>
<td>-.12</td>
<td>.02</td>
<td>.13</td>
<td>-</td>
<td>-.12</td>
<td>.23*</td>
</tr>
<tr>
<td>Motivation</td>
<td>.13</td>
<td>.09</td>
<td>.06</td>
<td>-.12</td>
<td>-</td>
<td>.19*</td>
</tr>
<tr>
<td>FEI.all</td>
<td>-.21*</td>
<td>-.12</td>
<td>.15</td>
<td>.17</td>
<td>.22*</td>
<td>-</td>
</tr>
</tbody>
</table>

**Notes.** *\(p < .05, \quad **p < .01, \quad ***p < .001;\) All p-values were two-tailed. Coefficients above the diagonal are \(r\); Coefficients below the diagonal are \(\rho\). Correlations of two normal distributed variables are interpreted based on \(r\), otherwise \(\rho\). Here, efficiency evaluation of electric propulsion and FEI.all were normally distributed.

When considered together (Q1), these results imply that the majority of drivers perceived the energy-efficiency of regenerative braking rather mediocly, whereas electric propulsion and neutral mode comprised large variance, thereby implying that despite day-to-day interaction, drivers’ perception of the energy-efficiency of eco-features was considerably diverse. Yet which eco-feature was perceived efficient to what degree was highly interrelated. This can be considered an indication for a common underlying pattern: perceiving electric propulsion as efficient involves perceiving regenerative braking as more efficient and neutral mode as less efficient, and vice versa.

### 5.2 Relation of Usage Dimensions of Eco-Features to Fuel Efficiency (Q2)

To assess Q2, the four usage dimensions of eco-features were correlated with FEI.all (see Table 3). Higher usage of electric propulsion and regenerative braking were both related to lower fuel efficiency (small albeit significant effect; H2a and H2b supported). Accelerating with higher utilization of electric propulsion was moderately to strongly and significantly related to lower fuel efficiency (H2c
supported). Finally, decelerating with regenerative braking opposed to with neutral mode when possible was also slightly related to lower fuel efficiency (H2d supported).

Table 3. Correlation matrix of usage dimensions of eco-features and FEI.all

<table>
<thead>
<tr>
<th>Variables</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Usage of electric propulsion</td>
<td>-</td>
<td>.50***</td>
<td>.42***</td>
<td>.39***</td>
<td>-.22*</td>
<td>.70***</td>
</tr>
<tr>
<td>(2) Usage of regenerative braking</td>
<td>.52***</td>
<td>-</td>
<td>.43***</td>
<td>.79***</td>
<td>-.19*</td>
<td>.86***</td>
</tr>
<tr>
<td>(3) Acceleration</td>
<td>.44***</td>
<td>.42***</td>
<td>-</td>
<td>.39***</td>
<td>-.41***</td>
<td>.69***</td>
</tr>
<tr>
<td>(4) Deceleration</td>
<td>.37***</td>
<td>.73***</td>
<td>.33***</td>
<td>-</td>
<td>-.24**</td>
<td>.83***</td>
</tr>
<tr>
<td>(5) FEI.all</td>
<td>-.24**</td>
<td>-.18*</td>
<td>-.40***</td>
<td>-.18*</td>
<td>-</td>
<td>-.31**</td>
</tr>
<tr>
<td>(8) Intensity of actively dealing with electric energy</td>
<td>.74***</td>
<td>.83***</td>
<td>.72***</td>
<td>.74***</td>
<td>-</td>
<td>-.29**</td>
</tr>
</tbody>
</table>

Notes. *p < .05, **p < .01, ***p < .001; p-values were two-tailed; Coefficients above the diagonal are r; Coefficients below the diagonal are ρ. Correlations of two normal distributed variables are interpreted based on r, otherwise ρ. Here, acceleration and FEI.all were normally distributed.

All interrelations between usage dimensions were positive, moderate to strong and significant (p < .001). All variables thus share common variance and could probably be aggregated to one factor. To assess this, we conducted a principal factor analysis with the usage dimensions. A one-factor-solution was proposed by both Kaiser and scree plot criterion. This factor (eigenvalue = 2.07) explained 52% of the total variance. All factor loadings were higher than .52 and can therefore be considered significant (according to Stevens, 2002). Consequently, based on the one-factor-solution, a mean score (reliability: α = .79) of the four interaction dimensions was computed; termed intensity of actively dealing with electric energy. Drivers scoring higher on this factor use the electric propulsion and regenerative braking more often but neutral mode less frequently, whilst drivers having smaller values prefer applying the neutral mode more often and electric propulsion as well as regenerative braking less frequently.

To ultimately answer Q2, a simple linear regression with the intensity of actively dealing with electric energy as predictor, and FEI.all as criterion, was performed (combining H2a to H2d, H2all resulted: the aggregated factor is related to lower fuel efficiency). Again, assumptions for (simple and multiple) regression analyses were tested according to Field (2009). Results were computed without and with exclusion of outliers/influential cases. Exclusion yielded similar parameter estimates but lower p-values (due to exclusion of residual outliers) and consequently only the conservative solution (without exclusion) is reported in the present research. Firstly, one univariate outlier on the factor was excluded.
(z_{36} = -3.17), thus n = 120 for all following analyses. Intensively dealing with electric energy was negatively, moderately, and significantly related to FEI.all (β = -.31, p = .001, N = 118) and accounted for 9% ($R^2_{adj}$, p = .001) of its variance; thereby supporting H2all.

### 5.3 Relation of Knowledge and Motivation to Interaction Dimensions (Q3)

To examine Q3, correlations and p-values were calculated. Knowledge was not related (all effect sizes were less than small; H3a and H3b rejected) to usage of electric propulsion ($ρ = -.04$, $p = .325$), usage of regenerative braking ($ρ = .00$, $p = .976$), acceleration ($ρ = .06$, $p = .771$) and deceleration ($ρ = -.08$, $p = .362$). Motivation was positively associated to acceleration ($ρ = .16$, $p = .043$), and non-significantly but positively related to usage of electric propulsion ($ρ = .13$, $p = .073$), usage of regenerative braking ($ρ = .11$, $p = .232$) and deceleration ($ρ = .11$, $p = .225$). All effect sizes were small. These results partially support H3c; H3d was rejected.

Furthermore, a multiple regression analysis was performed with knowledge and motivation as predictors of the aggregated factor. Transferring hypotheses from Q3, knowledge was expected to relate negatively, and motivation to relate positively to the intensity of actively dealing with electric energy (H3all). The regression model was non-significant ($R^2_{adj} = .00$, $p = .316$, N = 117). The same applied to the effects of the predictors knowledge ($β = -.05$, $p = .290$) and motivation ($β = .13$, $p = .089$). Although directions were as hypothesized, the effects were only small, and thus, H3all was rejected.

### 5.4 Relation of Knowledge and Motivation to Fuel Efficiency (Q4)

For assessing all hypotheses of Q4, a multiple stepwise regression analysis with knowledge and motivation (step 1) and, additionally, the aggregated factor (step 2) as predictors of FEI.all was performed. As depicted in Table 4, knowledge and motivation had small to moderate positive relationships to fuel efficiency (H4a and H4b supported). When incorporated into the model, the aggregated factor had a medium negative effect on FEI.all. The effects of knowledge and motivation on fuel efficiency did not change by taking into account this additional influence (H4c rejected).
Table 4. Stepwise regression with knowledge, motivation and the aggregated factor (intensity of actively dealing with electric energy) as predictors of FEI.all

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Step 1</th>
<th>Step 2</th>
<th>$R^2_{adj}$</th>
<th>$p$</th>
<th>$R^2_{change}$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge</td>
<td>$B$</td>
<td>.25</td>
<td>.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta$</td>
<td></td>
<td>.25</td>
<td>.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$p$</td>
<td>.007</td>
<td>.008</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motivation</td>
<td>$B$</td>
<td>.25</td>
<td>.29</td>
<td>.09</td>
<td>.002</td>
<td></td>
</tr>
<tr>
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<tr>
<td>Aggregated factor</td>
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<td>- .33</td>
<td>.19</td>
<td>.11</td>
<td>&lt; .001</td>
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Notes. $N = 117$. $B$ is the regression slope of the predictor. P-values refer to the effects in the row/column before.

To receive an indication of the practical significance of the effects on ecodriving, the decrease in fuel consumption, as indicated by regression slopes, was calculated by retransformation of the FEI.all indicator into l/100 km. For all three HEV types, a one-scale point increase in knowledge was associated to a decrease of 0.1 l/100km, accordingly 0.04 gallons/100 miles. One scale-point more in motivation was related to reduced fuel consumption of 0.1 (Prius 2, Prius c) to 0.2 (Prius 3) l/100 km, accordingly 0.04–0.09 gallons/100 miles. Furthermore, fuel-savings of 0.1 (Prius c) to 0.2 (Prius 2, Prius 3) l/100 km, again 0.04–0.09 gallons/100 miles, were associated to a one scale point change towards less intensively dealing with electric energy.

In particular, the aggregated factor comprises large potential for reducing fuel consumption because 88% of the drivers had values larger than the midpoint of the scale (with change towards the lower end being associated with lower fuel consumption). A considerably lower intensity in actively dealing with electric energy (e.g., 3 scale-points) could thus result in fuel savings of roughly 0.4 to 0.5 l/100 km, accordingly 0.17–0.21 gallons/100 miles, which corresponds to $M = 11\%$ ($SD = 2\%$, range: 8–17\%), for those drivers.

6 DISCUSSION

6.1 Summary of results

The objective of the present research was to advance understanding of the role of driver-interaction with HEV eco-features in determining ecodriving success. On average, drivers perceived eco-features neither absolutely energy-efficient nor inefficient. In fact, there were large inter-individual differences in the perceived energy-efficiency of electric propulsion and neutral mode, indicating that despite day-to-day experience, drivers do not develop a common perception of the energy efficiency of HEV eco-
features. A driver’s level of technical system knowledge was not significantly related to the perceived energy-efficiency of eco-features (H1 rejected). More intense utilization of electric propulsion (in general and for acceleration) and regenerative braking (in general and for deceleration, instead of neutral mode) were related to lower fuel efficiency (H2a, H2b, H2c, H2d supported). Eco-feature strategy dimensions were aggregated to one factor representing the intensity of actively dealing with electric energy. This factor was moderately related to lower fuel efficiency (H2all supported). In addition, technical system knowledge was neither related to usage dimensions of eco-features nor to the aggregated factor (H3a and H3b rejected). Ecodriving motivation was not correlated to this factor but related to acceleration with utilization of the electric propulsion (H3c rejected, H3d partly supported). Finally, technical system knowledge and ecodriving motivation both had positive effects on fuel efficiency (H4a and H4b confirmed). These effects remained constant when the influence of the aggregated factor on fuel efficiency was taken into account (H4c rejected).

Due to the statistical analyses finally performed, we reached 92% (for a two-tailed test; respectively 96% for a one-tailed test) power for bivariate correlation coefficients $|r| \geq .30$ and 85% power of finding a significant regression model with three predictors and $R^2 \geq .10$. Thus, the probability that expected effects were not identified here is relatively low (Faul, Erdfelder, Lang, & Buchner, 2007).

6.2 Theoretical Implications

The present results contribute to the understanding of user-energy interaction patterns: the high interrelations between perceived energy-efficiency (Q1) of each eco-feature (i.e., high efficiency evaluation of electric propulsion and regenerative braking is paired to low efficiency evaluation of neutral mode and vice versa) comprise the same tendency as the interrelations between usage dimensions of eco-features (Q2). Both patterns support the existence of the factor representing the intensity of actively dealing with electric energy. Applying the perspective of energy conversions, this factor may be interpreted as follows: Actively dealing with electric energy implies a high degree of energy conversions (active utilization [conversion of electric into kinetic energy] and regeneration [conversion of kinetic into electric energy]), whereas dealing less intensively with electric energy is associated to fewer energy conversions (kinetic energy has to be built up but is then conserved by usage of the neutral mode). These results can hence be seen as indicating something like an “energy conversion fallacy” (i.e., a considerable share of users neglect/underrate the losses incurred in energy conversions in estimating fuel efficiency and overuse eco-features related to a high degree of conversions). A tentative theorizing interpretation of this pattern following the prospect theory (Kahneman & Tversky, 1979, 1984; Tversky & Kahneman, 1992) could be that drivers might interact

with the system in order to achieve higher energy efficiency based on one primary reference energy (here: either electric or kinetic energy). Further studies are necessary to examine these assumptions.

Results from Q2 indicate that eco-feature strategies relate to fuel efficiency, and thus constitute driving behavior facets relevant for ecodriving success. This can therefore be regarded as support for the conceptualization of driver-interaction with eco-features based on control theoretic notions.

Furthermore, technical system knowledge and ecodriving motivation related to fuel efficiency (Q4) which supports the assumption that both have to be included as driver characteristics when conceptualizing ecodriving in HEVs based on a control-theoretic approach (see Franke et al., 2016a). Note that the effects found in the present sample were somewhat smaller than those found by Franke et al. (2016a) for a sample of HEV drivers with above-average fuel efficiency.

It should be noted however that knowledge did not yield significant relationships to perceived efficiency or usage dimensions of eco-features, and motivation was only partly related to the usage dimensions (all except one effect were small and non-significant; Q3). In addition to this, the effect of both on fuel efficiency remained constant when the effect of the aggregated factor on fuel efficiency was also taken into account. Whereas the direction of the small (although non-significant) effects found for ecodriving motivation in Q3 are in line with the present hypotheses, the assumption that knowledge relates to usage dimensions (and thus, the selection of ecodriving strategies related to eco-features; cf. Franke et al., 2016a) was not supported. We see two central possibilities for the interpretation of this: Firstly, the positive effect of knowledge on fuel efficiency might originate from ecodriving strategy aspects not related to general usage or non-usage of eco-features. For instance, former results indicate that speed choices (e.g., variable vs. constant speed) relate to both, knowledge and fuel efficiency (Franke et al., 2016a). Secondly, due to the complexity that HEV eco-features introduce to the drivetrain (e.g., McIlroy et al., 2014), aspects of technical system knowledge could be directly reflected on the operational level of driving (Michon, 1985), in the specific implementation of ecodriving (similar to procedural knowledge, see e.g. Anderson, 1982; McIlroy & Stanton, 2015). If so, hypothesized differences in ecodriving behavior that depend on a driver’s individual knowledge might only be identified by methods providing precise descriptions or observations of the concrete strategy implementations (e.g., assessed in interview, field or driving simulator studies; Stanton et al., 2013; for an example see Pampel, Jamson, Hibberd, & Barnard, 2015).

In summary, it has to be acknowledged that some findings in the present study were not in full accordance with findings in our previous study (Franke et al., 2016a). These differences could be due to sample characteristics, statistical (Schönbrodt & Perugini, 2013) or methodological factors. Further studies are needed for clarification. In addition to this, future research should address the influence of

roadway and traffic demands on ecodriving behavior (e.g., driver’s strategy selection in high-density traffic situations) as well as the factors mediating the relationship between knowledge and fuel efficiency.

6.3 Practical implications

The results from Q4 imply a possibility to gain approximately 11% fuel efficiency for many drivers through modifying interaction patterns towards a higher focus on conserving kinetic energy, and avoiding actively intensifying the conversion of kinetic into electric energy, and vice versa. From the perspective of green ergonomics (Hanson, 2013; Thatcher, 2013), modifying driver behavior via the design of specific system feedback is a particularly fruitful approach to enhance the sustainability of road transport (see e.g. for ecodriving Gilman et al., 2015; Jamson, Hibberd, & Merat, 2015). Instead of magnifying the perceived efficiency of energy conversions (e.g. through arrows exclusively indicating utilization and regeneration of electric energy), the energy interface should visualize the maintenance and loss (e.g. indicated by the size of arrows, or branched arrows with one branch implying losses) of kinetic energy. The potential of this approach however for day-to-day driving and possible negative side effects on safety (Kircher, Fors, & Ahlstrom, 2014) must be examined first. Furthermore, usage of the neutral mode should be encouraged (see Q2), for example by increasing its accessibility (e.g., as gas pedal position).

6.4 Conclusion

The present research provided first quantitative insights into drivers’ interaction with key HEV eco-features. Fuel efficiency, and thus the ultimate sustainability effect of HEVs, was shown to be related to interaction patterns with HEV eco-features. Furthermore, the present research provided first evidence of a general pattern of user-energy interaction that can be condensed into one dimension that classifies drivers based upon their strategy regarding energy conversions or reference energy. The link of this dimension to ecodriving success can be considered as an indication for the practical significance of understanding driver-interaction with eco-features from the perspective of user-energy interaction.
7 KEY POINTS

- Drivers’ interaction patterns with hybrid electric vehicle (HEV) eco-features were related to ecodriving success (fuel efficiency)
- An aggregated factor that represented a general pattern of interacting with HEV eco-features (intensity of actively dealing with electric energy) was related to ecodriving success indicating a fuel saving potential of about 11% (0.4–0.5 l/100km, accordingly 0.17–0.21 gallons/100 miles) for many drivers.
- Technical system knowledge and ecodriving motivation were not related to interaction patterns with HEV eco-features but constituted significant predictors of higher fuel efficiency
- The results emphasize the importance of understanding user-energy interaction in HEVs for achieving an optimal sustainability effect (e.g., by changing system feedback)
8 REFERENCES


9 APPENDIX

Appendix A. Translated Items of all Scales Used in the Present Research

<table>
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<tr>
<th>Scale Label</th>
<th>Item Text</th>
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| Perceived efficiency of electric propulsion | Scale instruction: How do you evaluate the efficiency of the electric propulsion for the average fuel consumption on a longer route?

Items:
The more one drives actively electric, the better it is for the average fuel consumption on the route.
The less one forces the electric propulsion, the more fuel-efficient the vehicle.
Routes I drive electric are virtually gratis.
Routes I drive electric also cost fuel at the end of the day.
To drive fuel-efficiently, the electric propulsion should be fully exploited.

| Perceived efficiency of regenerative braking | Scale instruction: How do you evaluate the efficiency of regenerative braking for the average fuel consumption on a longer route?

Items:
The more one recuperates, the better it is for the average fuel consumption on the route.
The less one deploys regenerative braking in decelerations, the more fuel-efficient.
Through regenerative braking, I basically receive energy as a gift.
Despite regenerative braking, a large amount of kinetic energy is lost in deceleration.
To drive fuel-efficiently, regenerative braking should be fully exploited.

| Perceived efficiency of neutral mode | Scale instruction: How do you evaluate the efficiency of the neutral mode for the average fuel consumption on a longer route?

Items:
The more one rolls in neutral mode, the better it is for the average fuel consumption on the route.
The less one deploys the neutral mode, the more fuel-efficient the vehicle.
Neutral rolling is a waste of energy because I do not recuperate it.
To drive fuel-efficiently, regenerative braking should be fully exploited.

| Usage dimensions of eco-features | Description of the driving situation (the same for all dimensions):

– You are alone on the road with your HEV.
– The weather is sunny and calm/windless with 20°C.
– The car (the engine/motor) is already warm.
– You are familiar with the route.
– The terrain is relatively flat.
– There is little traffic on the route.
– You are on a longer route (> 20km) in an urban area (main- and byroads, with speed limits of 30, 50 and 70 km/h, traffic lights, crossings).

Scale instruction (the same for all dimensions):
When I am on the road with my HEV, I regularly utilize the following strategies (i.e., when I am on the road with my HEV, I try to ...)
Intensity of using electric propulsion
Items:
...drive electric as much as possible.
...drive actively electric as little as possible.

Intensity of using regenerative braking
Items:
...recuperate as often as possible.
...recuperate as seldom as possible.

Acceleration
Items:
...accelerate after traffic lights with the electric propulsion for as long as possible.
...to deploy as little electric energy as possible in acceleration after traffic lights.

Deceleration
Items:
...decelerate without regenerative braking (in the neutral mode) when possible.
...decelerate by using regenerative braking when possible.

Knowledge
Items:
I am familiar with the propulsion technology of hybrid cars (e.g., types and functionality of electric motors).
I am familiar with concepts like energy density and energy conversion efficiency.
I have an idea about how regenerative braking technically works.

Motivation
Items:
I am always striving to drive fuel efficiently.
I often try to drive as efficiently as possible.

Fuel efficiency
Items for estimated fuel consumption:
What was the average fuel consumption you achieved with your currently most-used HEV in the previous summertime (beginning of April to end of September 2015)?

Items for FEI.urban (driving situation the same as for interaction dimensions):
What would be your typical fuel consumption under these conditions?

Items FEI.rural (driving situation the same as for interaction dimensions, except for the last point, which was changed accordingly):
- You are on a longer route (> 20km) in a rural area with country roads and small villages.

What would your typical fuel consumption be under these conditions?
10 BIOGRAPHIES

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Thomas Franke is a post-doc researcher at the Department of Cognitive and Engineering Psychology at Technische Universitat Chemnitz where he received his PhD in psychology in 2014.