ECO-DRIVING STRATEGIES IN BATTERY ELECTRIC VEHICLE USE – HOW DO DRIVERS ADAPT OVER TIME?

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ABSTRACT: Eco-driving is of high importance when driving battery electric vehicles (BEVs) in terms of prolonging the vehicle's limited range. A longitudinal field study with 40 participants was conducted to examine which eco-driving strategies users know before and after driving a BEV for 3 months. Furthermore, participant’s knowledge regarding eco-driving strategies with BEVs versus internal combustion engine vehicles (ICEVs) was compared. After 3 months of BEV usage, a driving test was applied in order to investigate the strategies drivers apply to drive energy efficiently and to estimate the effectiveness of these strategies. Results reveal that reported eco-driving strategies for BEVs and ICEVs differ significantly. Users reported significantly more BEV eco-driving strategies after experiencing the BEV for 3 months than before. Furthermore, drivers were able to significantly reduce energy consumption by applying eco-driving strategies in the driving test. Reported eco-driving strategies proofed to be effective. The results imply that eco-driving strategies for ICEVs have to be adapted for BEV eco-driving and that drivers gain a deeper understanding of factors that influence energy consumption by experiencing the BEV for a longer period of time. Based on the results, support of the driver through training or assistance systems is recommended.

Keywords: battery electric vehicle, eco-driving, field study, driver behaviour, adaptation, energy consumption.

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1. INTRODUCTION

Given the goal of reducing CO₂-emissions in the transportation sector, the implementation of ‘green solutions’ has gained importance in recent years. On the one hand, there are many technical developments that aim to make individual mobility efficient, like producing fuel efficient cars with smart technologies. On the other hand, the driver himself has the potential to save energy, for instance, by applying an energy saving driving style or choosing energy efficient routes (e.g., [1]). With respect to battery electric vehicles (BEVs), which are supposed to be an inherently ‘green’ transportation technology, reducing energy consumption confers an additional benefit compared to conventional vehicles in terms of prolonging the limited range. Given the limited battery capacity and relatively long charging durations, an energy efficient driving style might lead to a longer usable range per charge [2, 3]. Bingham, Walsh and Carroll [4] found that the energy consumption (i.e., range) of a BEV can vary by about 30% depending on driving style. Furthermore, BEVs are equipped with a regenerative braking system which enables the driver to actively regain energy in deceleration manoeuvres. This is also one of the reasons why results of studies examining eco-driving with internal combustion engine vehicles (ICEVs) cannot readily be transferred to BEVs [5].

Eco-driving with conventional vehicles has been studied in depth (e.g., [6, 7]), but research on eco-driving strategies when driving a BEV are rare and focus predominantly on technical issues (e.g., [4]). In the present contribution eco-driving in BEVs is approached from a user perspective. More specifically, the objectives of the current research are (1) to investigate the eco-driving strategies drivers know before and after BEV experience and (2) how these differ, and thus have to be adjusted, from eco-driving strategies reported for ICEVs. Furthermore, the question is addressed, (3) whether drivers apply the stated strategies when asked to drive energy efficiently and (4) whether the strategies are effective in terms of eco-driving. Finally, the question is raised, (5) if experienced drivers are able to reduce BEV energy consumption if intended.

2. BACKGROUND

2.1 Knowledge acquisition - the adaptation to BEVs

When starting to use a BEV instead of an ICEV, a learning process is initiated in which the driver gets accustomed to the new driving features (e.g., low noise emission, regenerative braking) and to the challenges of the BEV (e.g., limited range, restricted charging opportunities). There is some research investigating different facets of this learning and adaptation process to BEV usage. For instance, Cocron et
al. [8] examined the adaptation process regarding the usage of regenerative braking and found relatively short adaptation intervals of 50 km BEV driving with only few and adjustable problems. Vilimek, Keinath and Schwalm [9] mentioned a change in user behaviour from daily charging to several times a week. The learning process regarding energy efficient driving might be mostly related to the adaptation to the limited range of the BEV. In this regard, Franke et al. [10] reported an increase of optimal range utilization after integrating a BEV in daily routine. Furthermore, Pichelmann, Franke and Krems [11] found this adaptation period to be completed after about 3 months, whereas the concrete strategies and processes behind this adaptation still remained unclear. There are also some findings concerning a change of driving style towards less aggressive, and thus energy efficient, driving. BEV drivers reported to somehow adapt their driving towards a less speeding and less aggressive driving style during a 5 months period of BEV usage [12]. Helmbrecht et al. [13] found an adaptation in terms of a smoother acceleration and deceleration in BEV driving compared to ICEV driving after 5 months of BEV experience. Overall, the before mentioned studies provide strong evidence that drivers adapt to BEVs when starting to use these vehicles instead of ICEVs which underlines the importance of this research topic.

The OECD Scientific Expert Group [14] defined behavioural adaptations as “those behaviours which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change. Behavioural adaptations occur as road users respond to changes in the road transport system such that their personal needs are achieved as a result.” [p.23]. Given the BEV with its new features, including the limited range (i.e., the change in the system), and the mobility needs of users (i.e., driver needs), that sometimes exceed the given resources, eco-driving would be a behavioural adaptation to fulfil or at least better fit the driver’s mobility needs. In literature, adaptation processes are often linked to learning. For instance, Anderson [15] considers learning as “the mechanism by which organisms can adapt to a changing and non-predictable environment” [p. 3]. Accordingly, the learning process that takes place during the first months of BEV driving can lead to a successful adaptation to the BEV. During this process drivers gain knowledge regarding the BEV energy consumption and influencing factors. Research on training [16] as well as on pro-environmental behaviour [17] indicates that the knowledge of strategies is an important precondition for (energy saving) behaviour.

The present study examines the transition and, if necessary, the adjustment of drivers’ knowledge regarding ICEV to BEV eco-driving when experiencing the BEV for 3 months.
2.2 Eco-driving in BEV use

In general, BEV eco-driving is regarded as particularly valuable, also in comparison to energy efficient driving with ICEVs, because it offers the opportunity to prolong the limited range per charge. As also found for ICEVs, there is potential to save energy when applying a less aggressive driving style during BEV driving [4]. Furthermore, it is argued that, because of the regenerative braking, the fuel economy of electrical driven vehicles is much more sensitive to the driver’s driving style than that of ICEVs [18]. In parallel to results of research on ICEVs (e.g., [19]), some findings on energy consumption of BEVs imply that the reduction of energy consumption could be supported by eco-driving applications [20, 21]. However, such research predominantly focuses on performance measures and does not or only marginally take the user perspective into account. Additionally, there are some hints from current research that prior knowledge and experience in eco-driving might result in better eco-driving performance [22, 23]. Walsh et al. [22] examined the impact of driving style on BEV energy consumption on a driving cycle with 6 participants, who differed with regard to their driving styles. When driving as subjects’ would usually do, the most efficient driver turned out to be an eco-driving expert. Similarly, Knowles, Scott and Baglee [23] found an advanced eco-driver to perform best amongst 11 test drivers in terms of energy efficiency. However, in these studies knowledge was neither manipulated nor explicitly examined. Additionally, both studies investigated eco-driving with only few participants without long term BEV experience.

Literature provides different conceptualisations of the construct eco-driving. Sivak and Schoettle [24] have a very broad definition of “eco-driving include[ing] those strategic decisions (e.g., vehicle selection and maintenance), tactical decisions (e.g., route selection), and operational decisions (e.g., driver behaviour) that improve vehicle fuel economy” [p.96]. For the current study, we use the term eco-driving in a more narrow sense focusing on ‘operational decisions’ meaning strategies a driver could apply in order to drive more energy efficiently; ‘strategic’ and ‘tactical decisions’ are of minor importance here.

3. RESEARCH OBJECTIVES

In the present contribution, the learning process when adapting from ICEV to BEV driving is addressed focussing on eco-driving strategies. Current research implies that BEV energy consumption is somehow influenced by specific driver behaviour [4]. As knowledge of a specific behaviour is known to be an important precondition for this behaviour [16, 17], the drivers’ knowledge regarding BEV eco-driving strategies is examined. Additionally, eco-driving strategies known for ICEVs and BEVs are compared to illustrate a
possible adaptation to BEV eco-driving. Specifically, the following research questions were addressed:

1. **Knowledge**: Which strategies do drivers know to drive energy efficiently with BEVs before and after hands-on experience with a BEV?

2. **Knowledge**: How do reported eco-driving strategies with a BEV differ from strategies with ICEVs?

Besides the knowledge of eco-driving strategies, it is crucial for BEV drivers to be able to apply those strategies when intended, for instance, when the BEV is low on charge. Furthermore, the validity of strategies, and thus a real energy saving potential, as well as the ability to actively reduce energy consumption can be seen as important requirements for a successful adaptation process. For these reasons, the present study investigates the following research questions:

3. **Behaviour**: Do drivers apply reported strategies when instructed to drive energy efficiently?

4. **Effectiveness**: Are reported strategies really effective when implemented while driving?

5. **Performance**: Are BEV experienced drivers able to reduce their energy consumption compared to normal driving when instructed to drive energy efficiently?

### 4. METHOD

#### 4.1 Participants

A sample of 40 users was selected to use the BEV for 6 months in a private household setting (for more details regarding the selection process see [25]). The 35 men and 5 women had a mean age of 49.9 years ($SD = 10.19$) and held their driving license, on average, for 31.0 years ($SD = 9.94$). The majority of the participants (80%) were experienced ICEV drivers with an annual mileage of about 10,000 to 30,000 km. The sample was well educated, 72.5% held a university degree. Some of the users (40%) stated that they had already driven some kind of electric vehicle (hybrid and/or BEV) before. Yet, most of them (81.3%) had tested such a vehicle only for a short test drive. One participant dropped out after 3 months of BEV driving (second point of data collection).

#### 4.2 Field trial

The current research was part of the second BEV user study of a large scale field trial in the metropolitan area of Berlin [26, 27], embedded within a series of international field studies [28]. Data were collected three times throughout the study: when receiving the BEV (T0), after 3 months (T1) and after 6 months (T2) of BEV driving. At these three points of data collection participants completed questionnaires and answered structured interview questions. For the current contribution data were collected at T0 and T1.


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A converted MINI Cooper with a range of around 170 km under normal driving conditions was used as the test BEV for the study. The test vehicle was an automatic transmission car. The implemented regenerative braking system returned energy to the battery whenever drivers lifted their foot from the accelerator by applying decelerations up to \(-2.25\, \text{m/s}^2\). The two-seater contained some BEV-specific gauges: the state of charge (SOC) display, the remaining range display, the average consumption display and the instantaneous power meter.

### 4.3 Driving test

After 3 months of BEV usage, a driving test was implemented. Participants were instructed to drive a certain route of about 4 km length in urban traffic for two times (Figure 1). The route was chosen because it represented a typical urban traffic setting, which was assumed to be experienced most often by users of the current study and which is also discussed as the most promising use case for BEVs (e.g., [13, 29]). The route alternated between one- and two-lane driving and had a high number of intersections (with and without traffic lights). As usual in German urban areas, the speed was limited to 50 km/h, partly to 30 km/h. The subjects were accompanied by an investigator who could record deviations from the given route. The instructions for the two rounds within the driving test were as follows:

1. “Please drive the given route as you would normally do. We use this test drive for calibration of data loggers.” (condition normal)
2. “Please drive the given route as energy efficient as possible. Please drive in a way which does not obstruct traffic.” (condition eco)

The sequence of the two rounds was not counterbalanced as also found in other studies [20, 21], because it was important to collect the normal driving behaviour of the participants before asking for eco-driving. It was expected that if drivers were already instructed to drive energy efficiently in the first round and know about the research interest, it would somehow influence their ‘normal’ driving in the second round. For both rounds of the driving test several variables (information from the displays) were recorded via protocols (date, time, battery temperature, SOC and remaining range) at the beginning and the end of each round. Additionally, remarks about considerable events or hazards, like suddenly crossing pedestrians, could have been noted. Events that usually occur in urban traffic and that could provoke braking events, like red traffic lights or a braking car in front, were not assessed during the test drive. It was assumed that those events correspond to some extent to the evaluated traffic density and would occur roughly evenly amongst users and test drives.
In order to control for different traffic conditions, subjects were asked to rate the traffic density after each round on a more fine-grained scale (0, 1, ..., 9, 10), where only the end points of the scale were labelled (1 – “no traffic at all” and 10 – “very high traffic”). The traffic densities for both rounds of the driving test was rated rather medium ($M_{\text{normal}} = 4.22, M_{\text{eco}} = 4.08$) and did not differ significantly from each other, $t(36) = 0.67; p = .508$. Deviations from the given route were not detected.

### 4.4 Data Collection

#### 4.4.1 Knowledge acquisition regarding eco-driving strategies in BEV and ICEV driving

In order to examine which BEV eco-driving strategies participants knew, the following open-ended question was addressed after a short test drive with the BEV (T0) and after 3 months of BEV driving (T1): “Which strategies do you know to actively prolong the BEV’s range?” (“...to drive energy efficiently with the BEV?”) at T1). For a comparison of known strategies across both power-trains, the same question was applied with regard to the usually driven ICEV (T0): “Which strategies do you know to drive energy efficiently with the ICEV?” All answers to these questions were recorded and transcribed; afterwards the statements were coded.
using inductive category development according to Mayring [30]. A system of categories, developed by reviewing the material several times while defining and re-defining categories, was applied to all answers. As most statements were clearly formulated, minimal effort was required to clarify interpretation. In order to control for possible bias that might occur during the coding process, 50% of the material was independently coded by two involved researchers. Based on the codings of both researchers the interrater reliability (κ) was calculated according to Cohen [31],

\[
κ = \frac{(p_a - p_e)}{(1 - p_e)},
\]

where \(p_a\) is the proportion of agreed on judgements of both coders and \(p_e\) is the probability of agreement by chance. Results reveal an ‘almost perfect’ interrater reliability (BEV strategies: \(κ = .96\); ICEV strategies: \(κ = .87\); [32]). After the coding process was completed, the frequency of each assigned category was analyzed.

4.4.2 Indicators for eco-driving behaviour

Each BEV was equipped with an on-board data logger which continuously recorded parameters from the CAN bus. Pre-processed logger data were provided by the car manufacturer. All parameters were aggregated per 1 km. During the driving test, data were collected for 37 participants; due to technical reasons logger data for two participants was not available.

The following parameters were analysed regarding the applied eco-driving strategies (behaviour): (a) mean acceleration, (b) variance of acceleration, (c) mean speed, (d) mean regenerative power (z-standardised), (e) net total energy consumption (z-standardised), (f) energy consumption without auxiliary features (z-standardised), (g) power of auxiliary features (heater and air conditioning). In order to produce an externally valid scenario, the usage of auxiliary features was not standardised for participants throughout the driving test. Besides, the usage of auxiliary features is known to significantly influence energy consumption [4]. In order to prevent from data distortion and to realistically describe the effects of driving-related strategies, like driven speed and acceleration, we used energy consumption without the consumption of auxiliary features (labelled as ‘energy consumption’) throughout the analysis (except for analysis regarding the strategy ‘usage of auxiliary features’ in section 5.2.4).

4.4.3 Indicators for effectiveness

In order to control for potential influence, the battery temperature and the state of charge in the beginning of both drives were also taken into account. As the data revealed a correlation of battery temperature and energy consumption, this influence was statistically controlled via partial correlation. Thus, the effectiveness
of each eco-driving strategy was calculated via the partial correlation of energy consumption and the specific eco-driving behaviour parameter.

4.4.4 Indicator for eco-driving performance

Furthermore, the energy consumption (z-standardised) of both rounds of the driving test (normal vs. eco) was compared to analyse whether participants were able to drive energy efficiently when instructed to do so (performance).

5. RESULTS

5.1 Knowledge acquisition regarding eco-driving strategies

Drivers reported several strategies for improving driving efficiency with BEVs. Amongst others, they stated that avoiding high speeds, choosing an anticipatory driving style, avoiding auxiliary functions (e.g., air conditioning, radio), using regenerative braking and choosing the most energy efficient route to the destination would save energy while driving (see Table 1). Reported eco-driving strategies for BEVs were similar for both points of data collection. However, in order to investigate whether or not the proportion of participants mentioning a specific category to save energy with the BEV changed significantly over time or differed between BEV and ICEV, the McNemar test was calculated for each strategy. All mentioned strategies as well as results of all comparisons are presented in Table 1. The analysis revealed that the impact of experience was significant for the following reported BEV eco-driving strategies: avoiding auxiliary loads and accelerating moderately.

Comparing the strategies stated for BEV and ICEV eco-driving, it became apparent that the most often mentioned ICEV eco-driving strategy (75% of participants), use highest gear possible, is not applicable in BEV eco-driving. This is the same for the avoidance of idling, which was reported by 27.5% of the participants. The drivers understood that these strategies were not applicable due to the specific characteristics of the BEV (e.g., automatic transmission). Further, based on the results of the McNemar test, proportions of stated strategies for ICEVs were significantly higher for the BEV regarding avoidance of auxiliary functions at T1, and usage of regenerative braking or avoidance of braking\(^1\) for T0 and T1. The proportions of stated eco-driving strategies for ICEVs were significantly higher in comparison to BEVs

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\(^1\) ICEVs are not equipped with regenerative braking. The engine brake, which is used during the avoidance of braking, is regarded as its ICEV equivalent. Additionally, the BEV category ‘usage of regenerative braking’ was also linked to the avoidance of braking by the users. For these reasons the category ‘avoidance of braking’ was considered for comparison with ‘usage of regenerative braking’.


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regarding *letting the car roll* or *sailing*\(^2\) at T1, *optimal tires and tire pressure* at T1 and *minimisation of load* at T1.

In addition to the changes for each specific eco-driving strategy, we investigated the sum of all strategies stated at T0 and T1 per participant. As the data violated the assumption of normal distribution, the Wilcoxon test was calculated revealing significant differences, \(z = -2.25; p = .024; r = -.25\). Results show that drivers reported significantly more strategies after driving the BEV for 3 months (\(Mdn = 4\)) than after the first test drive with the BEV (\(Mdn = 3\)). Whereas subjects stated significantly less strategies with a BEV in comparison to strategies with an ICEV (\(Mdn = 4\)) at T0, \(z = -2.14; p = .033; r = -.24\), this significant difference disappeared after 3 months of BEV usage, \(z = -0.22; p = .823; r = -.02\) (Figure 2).

\[Figure 2.\] Sum of reported eco-driving strategies for ICEV (T0) and BEV (T0 & T1; Medians, error bars represent IQR)

\(^2\) Sailing is described as a state of the vehicle, in which deceleration is only caused by driving resistances [33]. In ICEVs this state is derived through pressing the clutch or driving in neutral, known as ‘letting the car roll’. With regard to BEVs, sailing is the result of holding the gas pedal on a certain point while neither decelerating nor accelerating the BEV. Hence, both concepts are regarded to be more or less equivalent and therefore compared.

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**Date:** 14.01.2015
Table 1: Comparison of reported strategies for ICEV eco-driving at T0 and BEV eco-driving at T0 and T1

<table>
<thead>
<tr>
<th>Eco-driving strategy</th>
<th>Percentage of participants</th>
<th>BEV\textsubscript{T0} vs. BEV\textsubscript{T1}</th>
<th>ICEV\textsubscript{T0} vs. BEV\textsubscript{T0}</th>
<th>ICEV\textsubscript{T0} vs. BEV\textsubscript{T1}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BEV\textsubscript{T0}</td>
<td>BEV\textsubscript{T1}</td>
<td>ICEV\textsubscript{T0}</td>
</tr>
<tr>
<td>Avoid high speeds</td>
<td>47.5</td>
<td>35.0</td>
<td>35.0</td>
<td>( .332)\textsuperscript{a}</td>
</tr>
<tr>
<td>Accelerate moderately</td>
<td>52.2</td>
<td>77.5</td>
<td>45.0</td>
<td>( .031)\textsuperscript{a}</td>
</tr>
<tr>
<td>Drive evenly (speed &amp; acceleration)</td>
<td>17.5</td>
<td>20.0</td>
<td>15.0</td>
<td>( 1.000)\textsuperscript{a}</td>
</tr>
<tr>
<td>Use regenerative braking/ avoid braking</td>
<td>62.5</td>
<td>72.5</td>
<td>22.5</td>
<td>( .454)\textsuperscript{a}</td>
</tr>
<tr>
<td>Choose anticipatory driving style</td>
<td>47.5</td>
<td>52.5</td>
<td>42.5</td>
<td>( .832)\textsuperscript{a}</td>
</tr>
<tr>
<td>Avoid auxiliary functions</td>
<td>55.0</td>
<td>77.5</td>
<td>40.0</td>
<td>( .022)\textsuperscript{a}</td>
</tr>
<tr>
<td>Drive in a way that the instantaneous power meter indicates low energy consumption</td>
<td>7.5</td>
<td>7.5</td>
<td>2.5</td>
<td>( 1.000)\textsuperscript{a}</td>
</tr>
<tr>
<td>Let the car roll (sailing)</td>
<td>0</td>
<td>5.0</td>
<td>17.5</td>
<td>( .500)\textsuperscript{a}</td>
</tr>
<tr>
<td>Choose the most energy efficient route to destination</td>
<td>5.0</td>
<td>7.5</td>
<td>0.0</td>
<td>( 1.000)\textsuperscript{a}</td>
</tr>
<tr>
<td>Choose optimal tires/ tire pressure</td>
<td>10.0</td>
<td>5.0</td>
<td>25.0</td>
<td>( .625)\textsuperscript{a}</td>
</tr>
<tr>
<td>Minimise load</td>
<td>20.0</td>
<td>10.0</td>
<td>27.5</td>
<td>( .289)\textsuperscript{a}</td>
</tr>
<tr>
<td>Avoid short distances</td>
<td>0.0</td>
<td>0.0</td>
<td>10.0</td>
<td>( -)</td>
</tr>
</tbody>
</table>

\textit{Note.} \( N = 40 \); Categories were included if greater than or equal to 5% of the participants reported it at any time of data collection and if strategies could be applied for BEV and ICEV; \textsuperscript{a} exact McNemar test was calculated; \textsuperscript{b} effect size calculation according to Green and Salkind [34].

\textbf{Citation:} Neumann, I., Franke, T., Cocron, P., Bühler, F., & Krems, J.F. (in press). Eco-driving strategies in battery electric vehicle use – how do drivers adapt over time? \textit{IET Intelligent Transport Systems.}

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5.2 Driving behaviour and effectiveness of eco-driving strategies

As far as feasible, the stated eco-driving strategies were assigned to objective indicators of driving behaviour recorded by the data loggers. Table 2 provides an overview about the strategies and assigned indicators, which are analysed in the following sections.

Table 2. Stated eco-driving strategies and assigned indicators of driving behaviour

<table>
<thead>
<tr>
<th>Eco-driving strategy (interview)</th>
<th>Indicator of driving behaviour (data logger)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoid high speeds</td>
<td>Mean speed (km/h)</td>
</tr>
<tr>
<td>Accelerate moderately</td>
<td>Mean acceleration (m/s²); SD acceleration</td>
</tr>
<tr>
<td>Use regenerative braking/ avoid braking</td>
<td>Mean power of regenerative braking (kW)</td>
</tr>
<tr>
<td>Avoid auxiliary functions</td>
<td>Usage of auxiliary features (yes/ no)</td>
</tr>
</tbody>
</table>

5.2.1 Speed

The analysis of the logger data showed a significant speed reduction for eco-driving in comparison to normal driving, \( t(36) = 2.08, \; p = .044 \), with a medium effect size, \( d = 0.34 \) (Figure 3). Nevertheless, the partial correlation with energy consumption revealed only small and non-significant correlations (Table 3) implying less efficiency of this strategy at least on urban routes.

Table 3. Partial correlations of energy consumption and driving parameters for normal and eco-driving

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Consumption</td>
<td>normal</td>
<td>-0.28 ns</td>
<td>0.65***</td>
<td>0.52**</td>
<td>-0.56***</td>
</tr>
<tr>
<td>without auxiliary</td>
<td>eco</td>
<td>-0.08 ns</td>
<td>0.70***</td>
<td>0.55**</td>
<td>-0.50**</td>
</tr>
<tr>
<td>features</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Mean speed</td>
<td>normal</td>
<td>-0.26 ns</td>
<td>-0.10 ns</td>
<td>-0.31 ns</td>
<td></td>
</tr>
<tr>
<td>(km/h)</td>
<td>eco</td>
<td>0.30 ns</td>
<td>0.38*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Mean positive</td>
<td>normal</td>
<td></td>
<td>0.87***</td>
<td>-0.34*</td>
<td></td>
</tr>
<tr>
<td>acceleration</td>
<td>eco</td>
<td></td>
<td>0.91***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(m/s²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. SD acceleration</td>
<td>normal</td>
<td></td>
<td></td>
<td>-0.32 ns</td>
<td></td>
</tr>
<tr>
<td>(m/s²)</td>
<td>eco</td>
<td></td>
<td></td>
<td>-0.52**</td>
<td></td>
</tr>
<tr>
<td>5. Mean regenerative power</td>
<td>normal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>eco</td>
<td></td>
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</table>

Note. ns = not significant (\( p \geq .05 \)), *\( p < .05 \), **\( p < .01 \), ***\( p < .001 \)
5.2.2 Acceleration

Drivers accelerated significantly less when instructed to drive energy efficiently in comparison to normal driving, $t(36) = 8.22, p < .001, d = 1.35$ (Figure 4). Positive and strong partial correlations for both test conditions reveal a high effectiveness of reduced positive acceleration in terms of eco-driving (Table 3).

Drivers reduced the variance of positive acceleration in the energy efficient test condition, $t(36) = 9.68, p < .001, d = 1.59$. The effectiveness of this strategy is underlined by strongly positive partial correlations between the standard deviation of positive acceleration and energy consumption (Table 3).


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5.2.3 Regenerative braking

The analysis of the averaged recaptured energy showed significantly less energy recapture for the eco-driving compared to the normal driving condition, \( t(36) = -5.64; p < .001; d = 0.93 \) (Figure 6). Besides, the regenerative power correlates strongly negative with energy consumption (Table 3) meaning an increased consumption with higher regenerated power. Although this might seem paradoxical at the first sight, this effect is explained when looking at the medium to strong negative correlations of regenerative power and acceleration (Table 3). There is no energy recapture without acceleration and thus energy consumption. In order to recapture energy through regenerative braking, the driver has to accelerate (i.e., consume energy) beforehand. Hence, the optimum driving pattern in terms of eco-driving appears to be a moderate and constant usage of the accelerator pedal, as also mentioned elsewhere [13], trying to regain only as much energy as necessary during deceleration manoeuvres and to accelerate smoothly.

Figure 5. Standard deviation of positive acceleration for normal and eco-driving.
5.2.4 Usage of auxiliary features

As usage of auxiliary features was not standardized during the driving test, all participants were free to use the heater and air conditioning as they wanted. The analysis of the logger data revealed that the majority of participants (about 65%) did not use any auxiliary feature throughout both test conditions. In turn, about 35% of the subjects had the opportunity to switch off these features. Results reveal that only about 31% of those participants who had auxiliary features activated during normal driving actively switched off auxiliary features before or while the eco-driving round, approximately 69% of them did not. Strongly positive and significant correlations between power of auxiliary features and energy consumption (including auxiliary features) imply a high effectiveness of the strategy to avoid auxiliary features in order to reduce energy consumption ($r_{\text{eco}} = .56$, $p < .001$; $r_{\text{normal}} = .53$, $p < .001$).

5.3 Eco-driving performance

In order to analyse whether drivers were able to save energy when instructed to apply eco-driving strategies, a repeated-measures ANCOVA was calculated with difference of mean battery temperature as covariate and instruction (normal vs. eco) as within factor. The results reveal a significantly reduced energy consumption for eco-driving in comparison to normal driving, $F(1,35) = 37.66; p < .001$; $\eta_p^2 = 0.52$ (Figure 7).

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Figure 6. Mean regenerated power (z-standardised) for normal and eco-driving.
6. DISCUSSION

Two of the main objectives of the present research were to (1) examine participants' knowledge regarding energy efficient driving strategies for BEVs in comparison to ICEVs, and to (2) evaluate whether any experience effects occur regarding BEV eco-driving strategies. The comparison of stated eco-driving strategies for the two drive trains made obvious that drivers understand that some important and often mentioned strategies for ICEVs are not applicable or do not make sense in BEV driving. For instance, the strategy to shift up as soon as possible, a well known and educated rule for eco-driving (e.g., [7]), cannot be applied to BEV driving. As a consequence, people have to adapt to some extent to BEVs and cannot just apply what they know from ICEV eco-driving. That there is somehow an adaptation process, or at least gained knowledge regarding eco-driving strategies is supported by the result that the number of reported strategies differed significantly between ICEV and BEV at T0, but were about equal after 3 months of BEV experience. That means, after experiencing the BEV for several months, drivers knew significantly more BEV eco-driving strategies than before BEV usage and about as many strategies as for an ICEV. Although the stated BEV eco-driving strategies did not substantially differ in their content before and after 3 months of BEV usage, some strategies are mentioned by a higher proportion of drivers. Specifically, the avoidance of auxiliary functions, such as air conditioning or radio, and a moderate acceleration style were reported more often after a longer period of BEV-use. These strategies proofed to be effective in terms of energy saving in this study.

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and have also been found in previous research based on driving data [4]. This in turn implies that drivers
develop a deeper understanding of BEV energy consumption and learn which factors have a high impact on
the energy efficiency of a BEV. This expertise is, at least in part, based on experiencing driving the car for a
longer period of time.

Further research questions were addressed within a driving test implemented after 3 months of BEV driving.
On the one hand, it was investigated whether (3) drivers applied the stated strategies in their driving behaviour
when instructed to drive energy efficiently with the BEV and (4) whether these strategies are effective in terms
of saving energy. On the other hand, (5) the overall performance of eco-driving was addressed in terms of
energy consumption during the driving test. The analysis of logger data revealed a significant reduction of
energy consumption for the eco-drive condition compared to normal driving. That means drivers were able to
actively reduce energy consumption of the BEV after several months of BEV usage which might be the result
of a successful adaptation process. These results are in line with current research which implies that energy
consumption is influenced by specific driver behaviour [4]. Investigating whether drivers applied the stated
eco-driving strategies (for those strategies that were collected via data loggers), results of the driving test
revealed that drivers significantly reduced speed, accelerated more smoothly and regained less power
through regenerative braking during eco-driving in comparison to normal driving. Only one third of those
participants who had the chance to switch off auxiliary features did so for the eco-driving run. However, as the
usage of these features was not standardised throughout the driving test, the logged data are a rather weak
behavioural indicator. In this regard more controlled research is needed examining the driver’s behaviour
given a standardised preset of auxiliary features. The drivers’ behavioural strategies, except speed reduction,
were shown to be effective in terms of eco-driving as they all strongly correlate with energy consumption. The
implied minor effectiveness of speed reduction must be interpreted in the light of the limited speed profile of
the urban test route ranging between 0 and 50 km/h. It could be assumed that reductions from higher speeds
would result in higher correlations with energy consumption of the BEV. With regard to regenerative braking
(implemented on the gas pedal of the BEV), results revealed that a moderate usage of regenerative braking
seems to be more effective in terms of energy consumption for the whole trip. With a smooth usage of the
accelerator pedal, and thus evenly driving behaviour, the driver contributes best to an energy efficient driving
style.

One might raise the question why users do not already drive energy efficiently during normal driving (i.e., in
the first round). One possible explanation is that driving behaviour is regulated by different driver motives and

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goals (e.g., [35]). Related to this assumption Franke et al. [2] introduced the construct of competent and performant range in the context of BEV driving. The authors [2] define competent range as expression of the individual eco-driving ability, which is for instance applied in situations when low on charge. Performant range (i.e., range achieved in normal everyday driving) is “usually obtained by each user based on his eco-driving-related motivational strengths and habits” (p.370). Hence, the gap between normal and eco-driving might be explained by each driver’s motivation to drive energy efficiently (i.e., the gap between performant and competent range).

Further, it would be interesting to investigate whether drivers adapt to BEV driving by applying a generally more energy efficient driving style when compared to ICEV driving. There is some evidence from BEV research pointing in this direction. For instance, the process of adapting to regenerative braking was found to be characterized through a more extensive usage of this system over time [8]. Helmbrecht et al. [13] found smoother accelerating and decelerating in BEV driving compared to ICEV driving, which in turn is assumed to contribute to energy efficiency. However, specific questions regarding the adaptation process still remain open, like for instance: a) Is there an adaptation towards a ‘BEV-specific’ driving style? b) If so, how can such a process be characterised? c) How do eco-driving strategies develop with BEV experience? For that reason, it would be valuable to apply an additional driving test already at BEV handover (T0) in order to investigate the adaptation process in-depth by comparing the driving behaviour before and after BEV experience. The implementation of a control group consisting of a matched sample of inexperienced drivers after BEV experience (T1) might be a reasonable alternative that controls for external and temporal influences (e.g., outside temperature, specifics of the route).

As participants of the study could be assumed to be a sample of early adopters, which are highly educated, have extensive driving experience and are highly motivated to interact with the limited range, especially in terms of eco-driving, the reported eco-driving performance might represent an upper level of achievable energy efficiency. The investigation of eco-driving ability and expertise for different driver groups could be subject of further research.

7. CONCLUSIONS

This contribution combines subjective and objective data regarding BEV eco-driving and sheds light on the learning process novice BEV drivers undergo regarding knowledge of eco-driving strategies. Further, it examines the strategies applied by BEV experienced users in order to drive energy efficiently. Although not all
route profiles are examined regarding energy efficient driving behaviour, the most important use case - BEV driving on urban roads [13, 29] - is investigated here. Results reveal that drivers have to adjust the eco-driving strategies they know from ICEVs to BEVs and gain deeper knowledge regarding energy efficient BEV driving behaviour. Furthermore, BEV users are able to apply reported eco-driving strategies and thus reduce the energy consumption of the BEV if necessary. As energy efficient driving behaviour and knowledge are potential factors to prolong range and thus might also reduce range anxiety, they are significant factors in everyday and more efficient BEV usage. In this regard, it could be helpful to incorporate additional information into the interface of the BEV in order to support the driver in the adaptation process and in understanding energy consumption, and thereby range prolonging factors, on the first BEV drive. This conclusion is also supported by findings that even experienced drivers require additional feedback regarding energy consumption and consider additional information or assistance for eco-driving as useful [36].

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9. REFERENCES


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