How Do Hybrid Electric Vehicle Drivers Acquire Ecodriving Strategy Knowledge?

Thomas Franke[1(✉)], Matthias G. Arend[2], and Neville A. Stanton[3]

[1] Institute for Multimedia and Interactive Systems, Engineering Psychology and Cognitive, Ergonomics, Universität zu Lübeck, Lübeck, Germany
franke@imis.uni-luebeck.de

[2] Department of Psychology, Cognitive and Engineering Psychology, Chemnitz University of Technology, Chemnitz, Germany
matthias-georg.arend@s2013.tu-chemnitz.de

[3] Transportation Research Group, Faculty of Engineering and the Environment, University of Southampton, Southampton, UK
n.stanton@soton.ac.uk

Abstract. Hybrid electric vehicles (HEVs) have the potential to accomplish high energy efficiency (i.e., low fuel consumption) given that drivers apply effective ecodriving control strategies (i.e., ecodriving behavior). However, HEVs have a relatively complex powertrain and therefore require a considerable knowledge acquisition process to enable optimal ecodriving behavior. The objective of the present research was to examine the acquisition of ecodriving strategy knowledge in HEV drivers who are successful in achieving a relatively high energy efficiency. To this end, we recruited 39 HEV drivers with above-average fuel efficiencies and collected interview data on the ecodriving strategy acquisition process. Drivers reported the acquisition of different types of knowledge as important for ecodriving, namely specific strategy knowledge and general technical system knowledge. They acquired this knowledge both with system-interaction (e.g., actively testing specific strategies, continuous monitoring of energy consumption) and without system-interaction (e.g., internet forums, consulting experts). This learning process took drivers on average 6.4 months or 10062 km. The results show the high diversity of the means that HEV drivers use to develop their ecodriving knowledge and the considerable time it takes HEV drivers to develop their ecodriving strategies.

Keywords: Hybrid electric vehicles · Ecodriving · Strategy knowledge · Learning process · Driving behavior

1 Introduction

Road transport is one of the major factors contributing to global CO2 emissions caused by energy infrastructure [7]. Electric vehicles constitute a promising technology that has the potential to reduce road transport CO2 emissions considerably (e.g., [4]). Indeed, electrification of road transport is currently one of the largest technological transformations in the field of sustainable development. However, to make this transformation a success the user factor has to be taken into account in system design.

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That is, each technical system designed to foster sustainability can be characterized by its technical sustainability potential (e.g., maximum possible energy efficiency under realistic usage conditions). Yet, in the end it often depends on user behavior (e.g., an optimal interaction with the system features designed to optimize energy efficiency) whether this potential can actually be realized in everyday usage of the system.

Ecodriving is the term that is commonly used to describe all those driving behaviors that are performed to increase real-world energy efficiency of a road vehicle (e.g. [3, 14, 25, 26, 30]). In electric vehicles, this influence of driver behavior on energy efficiency has been discussed as particularly relevant as research suggests that drivers have a high impact on energy consumption in electric vehicles compared to conventional combustion vehicles [21, 22, 31]. Further, electric powertrains have specific energy dynamics (i.e., powertrain efficiency characteristics, [16]) that make behavioral adaptation necessary to achieve a high energy efficiency. Hence, drivers have to understand these energy efficiency characteristics of the powertrain to adapt their behavior accordingly.

Hybrid electric vehicles (HEVs) represent the most complex electric powertrain and at the same time constitute an increasingly widespread type of electric vehicle [1] which makes it particularly relevant to address potential human factors issues associated with their usage. The complexity of this powertrain mainly results out of the combination of an electric motor and a combustion engine that interact at a fast rate as well as a regenerative braking system that creates a highly dynamic bidirectional energy flow. Those powertrain characteristics can be presumed to require behavioral adaptation [2, 6]. Thus, HEV drivers are likely in particular need of a sufficiently precise understanding of the energy dynamics to perform effective ecodriving strategies in HEV usage (see also [9]). Hence, there is a considerable risk that a substantial part of the sustainability potential of HEVs is lost due to a lack of drivers' understanding of effective ecodriving strategies.

A key challenge from the perspective of green ergonomics [13, 28] therefore is to advance understanding of user-energy interaction in HEVs and how drivers can be best supported in the acquisition of correct mental models and effective ecodriving strategies. One step in this research agenda is to gain a comprehensive understanding of drivers' adaptation to the system and the development of ecodriving strategy knowledge.

The objective of the present research was to examine the acquisition of ecodriving strategy knowledge in HEV drivers. To specifically gain an understanding of successful learning strategies we concentrated on drivers who are particularly successful in optimizing the energy efficiency of their HEVs. To this end, we recruited 39 HEV drivers who achieved an above-average fuel efficiency with their HEV under everyday conditions compared to a population of HEV drivers who regularly logged their fuel consumption data (i.e. all could be assumed to be at least somewhat interested in energy efficiency).

2 Background

Several challenges have to be overcome until a driver can achieve a high energy efficiency with a particular vehicle. From a motivation and volition perspective of goal setting, goal striving and action regulation these can mainly be broken down into three steps. First, drivers need to cognitively represent the goal of ecodriving in an accessible way and evaluate it positively and achievable (i.e., set ecodriving as a salient goal for establishing a basic level of ecodriving motivation). Second, drivers need to pursue the ecodriving goal with high priority in comparison to other attractive (i.e. competing) goals such as time-efficiency, safety, comfort or driving pleasure ([8]; i.e., volitional processes, [18]). However, the largest challenge for drivers that potentially demands the most cognitive resources is the continuous control of goal-directed behavior to increase energy efficiency. Interestingly, while considerable research so far has focused on increasing and sustaining ecodriving motivation (e.g. [17, 26]) there is less research that focusses on the issues of cognitive control of ecodriving behavior on a more microscopic level (for exceptions see e.g., [2, 9, 19]).

Previously, we have suggested that ecodriving efforts can be conceptualized as a control theoretic feedback loop [9] parallel to the increasingly widespread notions in driver behavior models that examine on other facets of driving behavior, typically safe/unsafe driving, from a control theory perspective [11, 12, 27]. With regard to the regulation of ecodriving behavior it can be conceptualized that the control process starts with the perception of relevant environmental variables (i.e., system state and state of environment) to enable the identification of applicable ecodriving strategies in a given situation. Further, drivers should select and finally implement a strategy that is perceived as particularly energy-efficient in a given situation (and fits to other motives/goals such as safety or comfort).

A core component of this framework is the strategy knowledge base that is expected to comprise the drivers' repertoire of strategies (i.e., which ecodriving strategies exist), as well as their subjective conceptualizations of energy efficiency (i.e., which ecodriving strategies are effective and why). A relevant task for advancing understanding of the ecodriving control process is thus, to examine this knowledge base and how it is established (i.e., how ecodriving strategy knowledge is developed).

First research in this area has examined drivers' knowledge and mental models of energy efficiency in driving conventional vehicles [20, 23] showing, for example, that ecodriving knowledge in the general population is rather low [20] yet when asked to drive energy efficient, drivers change their driving behavior (compared to normal driving behavior; [23]). Furthermore, first research in the context adaption to electric vehicle driving has demonstrated that ecodriving knowledge is dynamic and develops with practical driving experience [22, 24], or with specific supporting ecodriving feedback [14, 15]. However, research addressing the question of how exactly drivers acquire this ecodriving knowledge is still lacking, in particular with regard to user-interaction with new and complex powertrains like HEVs.

3 Method

3.1 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., [29]) and most prototypical HEV model. To enable recruitment of drivers who achieved a specific fuel efficiency with their HEV we used the database on www.spritmonitor.de.

From the almost 1500 Prius drivers in the 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.

3.2 Procedure

To collect the required, data 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 interview process.

After introducing the study and gaining informed consent, the interview had the following parts: (P1) ecodriving motivation, (P2) ecodriving strategies, (P3) questions on ecodriving strategy development, false beliefs (i.e. false mental models), and user suggestions for ecodriving support systems (P4) questionnaire parts to assess socio-demographic and experience-related variables. The interview was audio-recorded and transcribed. The present paper focuses on the part of section (P3) of the interview that deals with strategy acquisition (development of ecodriving strategies). Results regarding the other parts of the interview and further details on the methodology have been published in [9, 10].

3.3 Qualitative Data Analysis

We based our qualitative data analysis on thematic analysis [5]. After each interview, the interviewer and the scribe (first and second author) discussed insights and first ideas for possible codes. After familiarization with the data, the initial coding phase led to a list of codes that was relevant to our research question (consequently, only statements referring to the acquisition of knowledge were provided with codes). Afterwards, the coding system was reviewed and discussed, and initial ideas for themes (i.e., thematic clusters) were revised and refined based on the thematic proximity of codes. As only a relatively low level of abstraction of statements was targeted, this phase was less complex than for other topics in psychology (i.e., semantic rather than latent level analysis; [5]). In the final phase, we again went through all transcripts and coded participants' statements with regard to the developed coding systems (i.e., clusters and sub-clusters). Within this phase some final revisions and refinements of the coding system were performed. Hence, all statements of the participants that were relevant to the respective research question were grouped into clusters and sub-clusters. Clusters group similar statements of different participants (i.e., an overarching theme that is addressed by several participants).

4 Results

All percentage values given in the following sections refer to the share of drivers from the whole sample ($N = 39$). Note that percentages must not add up to 100% because one driver can use more than one mean (i.e., no exclusive coding was performed).

To address our research question, how HEV drivers acquire ecodriving strategy knowledge, we posed the following question to drivers: "How did you developed your strategies over time?". This question directly followed the extensive interview section where drivers elaborated on (a) the ecodriving strategies they used in four prototypic situations (driving on the autobahn, city driving, relatively straight rural road with flat terrain, mountainous and winding rural road) as well as (b) their conceptualization about why these strategies were effective in increasing energy efficiency (for results see [9]). Hence, it can be assumed that this elaboration of the ecodriving strategy knowledge base also made the memories about how the ecodriving strategies developed over time more accessible in memory and, therefore, helped drivers to sketch a more comprehensive and precise picture about their ecodriving strategy acquisition.

With regard to results, first, drivers' answers to the interview question were coded as the acquisition of two knowledge types: (a) strategy knowledge (95%) and (b) relevant technical system knowledge (41%). Second, another key distinction that resulted from the data was, whether strategy or technical system knowledge where reported to having been acquired *with interaction* with the HEV (69%) or *without interaction* with the HEV (87%). Hence, this pattern can be structured in a fourfold table. Consequently, a correspondingly structured overview of the main means that drivers used to acquire their ecodriving strategies is depicted in Table 1.

In the following sections, a more detailed view on how drivers acquired strategy and technical system knowledge will be presented. We refer to the fourfold table above for structuring the results. For each of the four categories, descriptions of those categories, sub-topics (i.e., acquisition means) and example statements are given.

4.1 The Acquisition of Strategy Knowledge

In the present study, strategy knowledge can be defined as the knowledge about driving behaviors that are perceived efficient. Obviously, this knowledge does not refer to

Table 1. General overview of acquisition means used to acquire ecodriving knowledge

		Knowledge type	
		Strategy knowledge	Technical system knowledge
Acquisition Means	With system-interaction	Testing Monitoring Incidental learning System trains driver	Testing
	Without system-interaction	Internet forums Expert survey Additional literature Videos Former knowledge	Internet forums Additional literature Videos

Note. This table gives a first overview of the results; more detailed results are presented in the text below.

strategies which undoubtedly have a positive effect on real-world fuel efficiency, but to knowledge about strategies that is deemed efficient by the drivers. As stated above, strategy knowledge has been acquired with and without HEV system-interaction (see Table 1). We consequently present the results in the order of cells of this fourfold table.

Acquisition of Strategy Knowledge with Interaction with the HEV. Many drivers (64.1%) reported that they have acquired strategy knowledge during their trips with the HEV. A crucial role in this respect played the active testing of different strategies which was reported to be used by more than half of the drivers (54%). To infer the efficiency of the strategies tested, the drivers reported to monitor different kinds of system feedback, of which fuel consumption was the most prominent (52%). Yet, there were some differences in regard of which specific fuel consumption criterion drivers monitored: fuel consumption per route (e.g., on the daily route; 28%) fuel consumption in general (e.g., on the basis of tank fillings recorded; 23%) and fuel consumption within very short time periods (e.g., instantaneous fuel consumption; 15%). In this respect, drivers used different kinds of system feedback (e.g., the fuel consumption history display that is provided by the HEV models in the present study) or other helpful applications (e.g., spritmonitor.de website to log the fuel consumption data):

"I drive the same route each day. […] Through the instantaneous fuel consumption as it is currently displayed in the vehicle, I get information and obviously also by the curve [refers to fuel consumption history display]. The higher the resolution, the better. Next, I have been using spritmonitor.de for many, many years and through this I was obviously able to monitor even better and, in terms of fuel … from refueling stop to refueling stop examine, how it develops."(P03)

Furthermore, to test the effectiveness of the specific ecodriving strategy pulse and glide (drivers repeatedly accelerate in a pulse-phase to a target speed, subsequently decrease this speed in the glide phase, see [9]), even specific driving environments and conditions were used to control for further influences:

"And then I obviously conducted a test, at night, with low traffic, the influence of driving only with pulse and glide between 30 and 50 km/h. Lo and behold, I get down to 3.2 l/100 km." (P05)

Beyond fuel consumption, drivers also monitored other kinds of system feedback to acquire strategy knowledge: further feedback provided by the hybrid system (e.g., depiction of the energy flows; 15%) and by additional apps and tools (10%) and sounds (3%). How the feedback by the hybrid system affects ecodriving strategies (e.g. intensity of regenerative braking), is illustrated by the following statement:

"There are the displays in the car which really help me, these are the energy bar display where one can see where the vehicle saves energy, how it also saves energy in braking. When I brake strongly the system recharges less, when I brake less intense, one can see that the energy recovery is a little bit bigger [...]." (P19)

In contrast to the active testing of different strategies, some drivers also mentioned kind of a passive strategy knowledge acquisition process: Drivers reported that strategy effectiveness is better understood through incidental learning by interacting with the HEV (*"it is learning by doing"*, [P09]; 10.3%), or that the system is educating the driver *("I've got the feeling, that the car trains the driver in driving efficiently. Simply because of its functionality"*[P27]; 7.7%).

Acquisition of Strategy Knowledge without Interaction with the HEV. When acquiring strategy knowledge without system-interaction, drivers reported to rely on internet forums (64%), their former knowledge (39%), 'expert' surveys (asking experts, e.g. experienced drivers, about their knowledge; 8%), reading additional literature (e.g., the user manual 8%) or videos (5%).

From the large percentage of drivers using internet forums to acquire strategy knowledge, a considerable share (18%) already informed themselves prior to the purchase. Moreover, for some drivers it could be categorized which specific strategies they had adopted from those forums. Those strategies were pulse and glide (8%), a specific way of accelerating from standstill (5%), using (or rather not using) the B-mode (engine break active, cf. Franke et al., 2016), utilizing electric driving, the adaptive cruise control and neutral coasting in the neutral mode (each 3%). This process of acquiring knowledge through the internet and applying this knowledge to real word driving is reflected in the following statement:

"Then I have learned pulse and glide, in the third phase. I found this strategy not in the manual of Toyota but on the internet and I have to say, this [pulse and glide] poses, to me, the most powerful tool among those strategies I have learned, based on the driving technique. With which one can really influence the fuel consumption most." (P31)

Some drivers also reported that former knowledge played a crucial role in developing HEV strategy knowledge, particularly ecodriving strategies they have already acquired with their former vehicle (26%) and physics knowledge (8%). The former primarily refers to some general ecodriving knowledge applicable to most vehicles, as stated by one driver:

"I guess that I have already developed most of the strategies with my conventional vehicle" (P16)

The latter, physics knowledge, depicts a general influence on the strategy knowledge in a way that strategy effectiveness can be deduced from it, as reflected in the statement of the following driver:

"I was attentive during the physics lessons and I know what consumes energy and what doesn't. So, I know that I need the most energy for accelerating and for constantly gliding at one speed, I only have to overpower the friction and air resistance and I consume relatively few [fuel]." (P12)

Beyond those factors already mentioned, several drivers (26%) perceived personal attributes as important determinants of their acquisition of strategy knowledge. Below them was the fun factor of driving energy efficient (10%), as stated by another driver:

"One more often remembers to drive in that way [energy efficient] because it is fun. So, one is tempted to try ... 'maybe I can reduce my fuel consumption for another 0.2 l/100 km'" (P32)

Other attributes mentioned were trust (i.e., knowledge that the algorithms will control the vehicle most energy efficient; 3%) or the drivers interest in the technology (3%).

4.2 The Acquisition of Technical System Knowledge

The acquisition of technical system knowledge (concerning the HEV system) is a construct that was subject in former research and has proven an important determinant of HEV ecodriving success [2, 9]. Consequently, as drivers did not exclusively rely on reporting the acquisition of strategy knowledge, we also analyzed their reports on the acquisition of this knowledge type. As for strategy knowledge, reports for technical system knowledge referred to acquisition with and without interaction with the system. Thus, results will again be presented in this order.

Acquisition of Technical System Knowledge with Interaction with the HEV. Several drivers (15%) reported that they have acquired strategy knowledge through the interaction with the system. For example, the way system dynamics (e.g., the state of charge) influence how the driving energy is supplied might be understood through interacting with the HEV system:

"I now know how far I may press the accelerator pedal before the combustion engine will turn on, furthermore I also know now that this depends on the state of charge of the battery. It is always less optimal the emptier the battery becomes. And it is more likely that the combustion engine will also turn on. This is taught by the car." (P28)

Acquisition of Technical System Knowledge without Interaction with the HEV. Finally, a total of 13 drivers (33%) reported that they have gained technical system knowledge through sources like internet forums (28%), professional literature (3%) and videos (of the hybrid system; 3%).

"Yes, I am an active member of the Priusfreunde-forum. [...] They also provide the Prius-Wiki, where many technical aspects are explained. This has helped my understanding a lot."(P04)

4.3 Duration of Learning Process

Finally, in addition to the main interview question of strategy acquisition, we asked drivers the sub-question how long it took them to acquire their ecodriving strategies (with regard to time and total distance driven). This information could finally be derived from $N = 38$ participants, because one participant did not provide a clear numerical value. Further three drivers were not aware of a substantial strategy learning process during the time of their HEV usage, meaning they perceived that they had already acquired the ecodriving knowledge they deemed necessary prior to purchasing their HEV (e.g., *"Prior to purchasing the car [...] I had concerned myself certainly for 1.5 years very extensively with the topic of hybrids, thus, purely hypothetical."* [P20] or "*I was attentive during the physics lessons.*" [P12]). Within the sample of the remaining $N = 35$ drivers, the average time it took them to develop their ecodriving strategies, based on the drivers' estimates, was $M = 6.4$ months ($SD = 7.8$, 25th percentile = 2, 75th percentile = 12 months). Moreover, drivers' duration estimates in terms of total distance driven were $M = 10062$ km ($SD = 8785$, 25th percentile = 4000, 75th percentile = 17000 km).

5 Discussion

How and where do HEV drivers learn to optimize the energy efficiency of their vehicles? Is it enough to hear or read some basic rules to become a successful eco-driver, or which learning strategies do HEV drivers really use? This was the question of the present research. The results showed that drivers used a diverse set of means to develop their ecodriving control strategies and that this learning process took them considerable time.

The successful ecodrivers we recruited for our interview study (i.e., drivers with above-average fuel efficiency compared to a sample of HEV drivers who could all be assumed to have a basic interest in their fuel consumption) did not only report the learning of specific rules or strategies to be important for acquiring ecodriving skills, yet also stated that technical system knowledge (e.g., understanding of the technical interplay of the powertrain components) played an important role. Hence, it appears that, to support development of ecodriving skills in novice drivers of HEVs, these drivers should not only be provided with ecodriving tips focused on specific behaviors (i.e., "this behavioral strategy is effective to optimize energy efficiency"). Instead, drivers should also be provided with the necessary background knowledge to understand why these behavioral strategies work (e.g., "there are two states where the combustion engine in your HEV is most efficient and that is why you should target these states which you can do with this strategy", or "air resistance increases exponentially with speed, hence reducing speed on the motorway is very effective"). This could also, for example, make drivers more flexible in applying certain strategies and derive new ones.

Moreover, ecodriving strategy knowledge is developed both while driving as well as without direct system interaction. In particular, the time-consuming active testing and monitoring of certain strategies shows that identifying the optimal ecodriving strategies is not that simple. Variations in environmental conditions (e.g., presence and behavior of other vehicles) make it complex for drivers to clearly trace the success of the application of certain ecodriving strategies. Here, there is a considerable potential of ecodriving support systems such as systems that help to objectively quantify environmental characteristics with relevance for energy consumption (e.g., traffic flow, road conditions, terrain) and depict these along with energy consumption data (e.g., in an energy consumption history display) to aid drivers in disentangling effects of their behavior versus environmental factors on fuel consumptions.

Further, the results of the present study indicated that control and monitoring processes of ecodriving strategy effects are implemented at different time scales, that is, drivers use different aggregations (i.e., reference periods) to check the success of their ecodriving efforts such as the consumption averaged over one trip or one filling of the tank (i.e., one refueling cycle), down to consumption in the last minute or second. These different levels of control have to be considered in system design as well as in theorizing of ecodriving behavior. Future research could be concerned with which monitoring reference periods provide adequate feedback for ecodriving success.

Finally, the process of developing ecodriving knowledge in HEV driving (at least the time that successful ecodrivers need to acquire their level of knowledge) takes considerable time. This echoes the notion that the powertrain of HEVs is complex and energy dynamics are difficult to understand for drivers. Moreover, one can assume that the development of ecodriving strategies is not just a matter of knowing a certain strategy but also acquiring the knowledge how to actually implement this strategy in different situations. Hence, each ecodriving support system that is focused on supporting strategy development should not only be focused on teaching rules and strategies, but also continuously guide drivers' in their efforts to implement these strategies in different driving situations.

All in all, the present study represents a first step to advance understanding of ecodriving strategy development in HEV drivers. Further quantitative studies will be needed to assess the processes and patterns discussed in the present contribution with greater precision and provide further insights into the questions of how achieving optimal energy efficiency and reaching the technical sustainability potential of a system can be facilitated as much as possible for users.

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