Abstract—The gradual introduction of fully electrically powered vehicles into the market has extended the opportunities for sustainable mobility and a new technological era. In this paper we investigate the changes in driver behavior patterns compared with patterns of traditional vehicles with combustion engines after having acquired the necessary adjustments needed for driving an electric vehicle. We aim to expound upon the differences present in driving habits after the individual has become adjusted to the driving patterns of an electric vehicle. Results showed that there is a significant difference in the driving habits of an internal combustion vehicle and that of an electric vehicle. Particularly a development from stronger accelerating and decelerating within the first experiences with electric vehicles to a more calm driving after 5 months of experience was noticeable in acceleration and braking maneuvers. Additionally, results for constant driving proved that interaction with electric vehicles with one-pedal driving capability is not a barrier for efficient driving with constant velocity.

Index Terms—Electric Vehicles, Driving Behavior, Driving Efficiency, Driving Patterns, Acceleration, Deceleration

I. INTRODUCTION

Electric vehicles (EVs) are a promising alternative for future individual mobility to vehicles with Internal Combustion Engine (ICEs). The gradual introduction of completely electrically powered vehicles into the market allows us to become closer to an era of sustainable mobility, in which the dependence on fossil fuels can be significantly reduced and road traffic emissions minimized [1], [2]. If the energy used to build and to operate EVs is additionally provided by renewable energy sources, electric mobility is 100% emission-free.

As energy efficiency has a considerable impact on battery energy consumption and therefore on the driving range [3] and at the same time the automobile industry is quickly adopting electro-mobility technologies, it is important to determine and to support driving patterns that lead to energy efficiency. Soon plug-in electric vehicles as well as pure battery-electric vehicles will become widespread due to coming cost reductions through advances in battery technology and higher production volumes [4]. Additionally, the different technological characteristics of electric vehicles, that instead of being composed by an internal combustion engine and fuel tank have a high-voltage battery, and an electric motor among other components, make driving an electric vehicle a unique experience. This experience is even enhanced by regenerative braking, i.e. the electric motors functions as a generator during deceleration maneuvers. The car can be slowed down remarkably even until almost to a standstill while at the same time regenerating energy into the high-voltage system. This driving experience might be reflected in the driving patterns.

Therefore, in this paper we investigate driving patterns with electric vehicles and seek to determine the driving habits acquired during a certain period of time driving an EV in comparison to ICEs, analyzing the following research questions:

1) What are the differences in driving behavior between EVs and ICEs in the first contact and after completed acclimation to electric driving?
2) Does driving experience with electric vehicles cause changes in driving behavior with EVs and ICEs?
3) Is driving behavior changed towards improved anticipatory driving?

The key contributions of this paper are as follows:
- We investigate if the driving habits related to combustion vehicles are affected by a new driving behavior learned through the driving of EVs.
- We study if the continuous use of EVs leads to a change in driving behavior patterns.
- We present detailed results related to the effect of driving electric vehicles on anticipatory driving.

The remainder of this paper is organized as follows.
In the next section we review the state-of-the-art electric vehicle studies that relate to driving patterns and regenerative braking systems. In sections III and IV we describe in detail the methodology. Section V presents our results. Finally, section VI concludes the paper.

II. STATE OF THE ART OF RELATED TECHNOLOGIES

The effects of driving behavior on the level of emissions and fuel consumption have been analyzed in several works. As can be expected, it has been shown that aggressive driving behavior results in high emissions and fuel consumption rates, while calm, reserved driving results in lower emissions and fuel consumption [5]. Driving pattern factors such as speed and acceleration levels depend on driving behavior and are determinant in the estimation of emissions and vehicle fuel consumption [6], [7], [8].

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Energy consumption regarding electric vehicles has been investigated in several works [9], [10]. For example, the authors in [11] showed that energy consumption can be reduced if the driving behavior follows specific patterns, such as smooth acceleration and deceleration, and average speed reduction on highways and country roads. The application of efficient driving strategies in urban scenarios still proposes difficulties. Examining and comparing the long-term influence of driving habits of an electrically powered vehicle with that of the driving habits of a petrol fueled have never been investigated with real EV customers in any previous works, being the novelty of this study especially the focus on the driver interaction with the vehicle specific longitudinal driving dynamics. A methodology with this finality was already outlined in [12] but detailed results have not been provided so far. In this paper we analyze driving pattern factors such as speed and acceleration levels prior to and after acquisition of driving habits with an electric vehicle relying on the above mentioned methodology. We then outline conclusions regarding driving behavior with combustion vehicles.

A. Electric Vehicles Learning Process

Driving dynamics characteristics of electric vehicles differ from combustion vehicles. One aspect is the EVs’ constant torque characteristic, which allows maximum acceleration independently from the e-engine’s rpm. Supported by the possibility of regenerative braking, this enables very direct longitudinal vehicle dynamics which are new to drivers of conventional ICES. In this context, different works have investigated driving behavior and energy consumption [13], [14] and concluded that energy consumption very much depends upon driving profiles.

To create a greater sense of familiarity with the foreignness of driving an electric vehicle, a certain amount of time is required to grow accustomed to the differences. Preliminary studies have shown that electro mobility drivers go through a learning process to properly adapt to the specifics of electric mobility [15]. Learning efficiently and effectively handle the novelties of regenerative braking, charging and range through the everyday use of an electric vehicle is essential in utilizing its unique characteristics and achieve an optimized driving behavior and user experience [16], [17]. The model in [18] classifies the learning procedure in three different phases:

- discovery, in which the driver grows familiar with a new driving feel, braking procedure and battery range and charge.
- translation, in which the new electric vehicle characteristics are evaluated by the driver
- application, in which the acquired knowledge and driving experience is transferred to habitual use, thus consolidating new driving patterns.

The fact that acclimation to EVs is accompanied by a complex learning process makes it necessary to capture two snapshots of daily driving behavior in order to adequately answer the research questions of this study. Therefore the first experiment is set up prior to the learning phase and the second one after some months, when the learning process is supposed to be completed.

B. Energy Recovering in Electric Vehicles

It has been proved that most of the energy saved by hybrid electric vehicles occurs through a regenerative braking system [19], [20]. Motion decrease is achieved through the transfer of the energy to the load [21]. As electric vehicles hold specific variations concerning the battery capacity and charging time, the capability of generating electrical load is currently one of the major research topics in the field and related technologies are quickly been developed. Increased driving efficiency is being investigated with different energy systems through ultracapacitor systems and appropriate control strategies to attain minimal loss of energy and degradation of the battery [22], [23], [24].

Additionally, as regenerative braking affects not only energy consumption but also driving patterns, previous work has also been dedicated to user interactions with this braking system. Generally there are two different interaction concepts to implement the regenerative braking into an EV. In one concept the energy recovery is part of the conventional mechanical brake pedal. In this case the driver does not have to learn any new interaction patterns, but is generally lacking in aptitude of the regenerative braking patterns.

The other concept is to implement the regenerative braking into the accelerator pedal. For slowing down by regenerative braking the driver has to release this pedal. When the accelerator pedal is fully released, the vehicle will decelerate with the maximum of regenerative braking power. If this is not strong enough, the conventional mechanical brake pedal has to be used to gain the necessary additional braking power.

According to [25] the second concept increases driving efficiency as the driver might do almost all decelerations without using the mechanical brake. The electric test vehicle of the presented study - the MINI E - also uses this second concept with the regenerative braking implemented into the accelerator pedal.

While the MINI E features a quite strong regenerative braking system allowing decelerations up to -2.3 m/s², typical regenerative braking maneuvers like stopping at a red traffic light without using the friction brake are also possible with weaker function versions. Customers of the BMW ActiveE, a conversion electric vehicle based on a BMW 1 series coupé with a deceleration of up to -1.8 m/s², when lifting the foot from the accelerator pedal, likewise reported making strategic use of this option, liked the feature and rated the strength of the regenerative braking near optimal [26].

The authors in [27] investigated the learning process related to this unfamiliar interaction concept and showed the adaptation process to be relatively quick for new EV drivers. Some minor adaptation difficulties were reported, but could easily be remedied through an individual adaptation to different levels of deceleration. However, maximizing coasting times by anticipatory driving would be the theoretical optimum, but requires desire and ability on the part of the driver.
C. Anticipatory Driving

According to [28] supporting the driver in anticipatory driving is a lauded approach in increasing driving efficiency of ICEs. In [29] it has been shown that avoiding unnecessary accelerations and using the vehicles present kinetic energy by extended coasting increases driving efficiency significantly. As regenerative braking is also limited by technical efficiency factors, anticipatory driving is an important strategy employed to increase driving efficiency in EV as well.

III. Experimental Design

The presented study was part of a larger set of MINI E field trials which were initiated by the BMW Group to prepare innovations in the field of electro mobility [30]. The objective of this study was to compare the driving behavior with EVs and ICEs upon initial contact and after the finalized acclimation. In order to cover and explore the complex learning procedures in their entirety, a long term study with electric test vehicles was propositioned and executed. A central aspect of the study was to mimic a real life scenario as close as possible. Therefore the MINI electric test vehicles of this study were leased by the customer themselves or their respective companies for five months. Thereby the participants gaining electric driving experience in their daily mobility patterns. Data reported in this paper was collected at two different points in time at supervised driving experiments on a standardized reference route.

The first driving experiment took place prior to acquiring driving habits with EVs. A second experiment took place after the five month period of daily driving with MINI E electric test vehicle.

The MINI E electric test vehicles were built in 2009 relying on a modified version of a MINI Cooper. With a peak power of 150 kW and a range of 140 to 160 km, they belong to the most extended EVs currently in operation. The regenerative braking is implemented into the accelerator pedal. When this pedal is completely released the MINI E decelerates with a negative acceleration of $-2.3 \text{ m/s}^2$. The top speed limitation of the MINI E’s is of 152 km/h. A display called “power meter” (Figure 1) informs the driver of the current power flow of the e-machine system.

Each driving test was performed on a standardized real traffic test circuit. Each test subject drove two laps, one with a MINI E electric test vehicle and the next with an ICE vehicle. The order of these two laps was permuted with the subjects to compensate for the effects of inner-test learning procedures. Figure 2 shows the test procedure.

The driving experiments in this study should be representative for average daily driving habits. Therefore they were conducted on a real traffic test circuit which covered typical road types in an average ratio. 8.6 km of the 31 km track were leading through urban areas, 10.6 km over country roads and 11.6 km over highways ensuring that various common traffic situations, which ranged from simple road intersections or short highway trips to multi-lane traffic light junctions, were included.

By selecting this road scenario which is principally comparable to that of similar field trials [31] we aimed to generate a high sample of accelerating and decelerating patterns that are determinant in the estimation of driving behavior.

The analysis of driving metrics for the whole test circuit characterizes driving patterns to obtain an overarching picture of driving behavior. However a detailed insight into road type specific driving patterns is only available by selecting the five characteristic track segments as shown in Figure 3.
The figure specifies the number of lanes, speed limit and number of kilometers of each trip starting with an urban scenario with a speed limit of 60 km/h and driving then through an arterial road with two lanes, an urban road with a speed limit of 30 km/h, a highway and ending at a country road with one lane.

IV. DATA COLLECTION AND ANALYSIS

In the two experiments prior and after the EV long term usage we collected driving data from a data sample of 40 test subjects 77.5% males, 22.5% females, mean age = 42.9 (SD = 10.2). All of them were experienced drivers with an average annual mileage of 23,000 km (SD = 15,000 km). However, at the time of the first driving test, none of them had previous experience with EVs. At the second experiment the participants had an average driving experience of about 2,500 km with the MINI E.

Driving dynamics data were collected through smartphones (iPhone 4) that were mounted on the ICEs’ and EVs’ windshields. The position of the device was fixed with its z-axis exactly parallel to the respective vehicle’s longitudinal axis. Figure 4 illustrates the setting.

Vehicles longitudinal acceleration and deceleration were recorded through the smart phone’s sensors at a frequency of 25 Hz. GPS position, direction vector and speed relative to the track segments was provided by the GPS sensor included in the mobile phone. Gathered data packets were sent to a web server by an application especially designed for this purpose. This flexible logging method made it possible to collect driving dynamics data that were comparable both in electric and in combustion vehicles.

The collected data allowed us to perform a specific analysis of driving behavior depending on the different road types and the dependent variables being the average velocity and the percentage of acceleration in five categories: strong deceleration (-10.0 m/s² ... -2.3 m/s²), regenerative deceleration (-2.3 m/s² ... -0.6 m/s²), drag torque deceleration (-0.6 m/s² ... -0.4 m/s²), constant driving (-0.4 m/s² ... 0.4 m/s²) and acceleration (0.4 m/s² ... 4 m/s²). These categories of acceleration were predefined by the characteristics of the EV’s and ICE’s power trains with the limits of:

- -10.0 m/s² maximum possible deceleration,
- -2.3 m/s² maximum of EV regenerative braking,
- -0.6 m/s² and -0.4 m/s² range of deceleration caused by the ICE engine’s drag torque, and
- 4 m/s² maximum possible acceleration with the EV.

The percentage of acceleration in the different categories was investigated by dividing the results of a histogram of measured acceleration in the categories mentioned above and referring the respective sum of data points to the total amount of acceleration data points.

The respective values were calculated for each road section and whole test circuit for each participant in each lap. A paired t-test was used to investigate the differences in driving behavior with EVs and ICEs. The standard alpha level for significance of .05 was chosen.

Due to uncontrollable real traffic conditions (e.g. traffic jams) which are typical disadvantages of field trials, some data sets had to be filtered in the analysis. Thereby the final datapool for the first experiment contained 23 participants (70% males, 30% females, mean age = 42.2 (SD = 10.8)), the one for the second experiment 30 participants (77% males, 23% females, mean age = 42.6 (SD = 10.3)).

V. RESULTS

We present in this section the results obtained from our experiment beginning with the speed metrics, following with the deceleration metrics and closing with the acceleration metrics.

A. Speed Metric Evaluation

Regarding the speed metric evaluation results, neither the first experiment prior to proper adaptation nor the second experiment after 5 months of driving an EV indicated significant differences in the average speed in any of the sections of the entire test route. However in the first contact, a tendency to a slower driving behavior with the EV in the fast driven sections became apparent.

As shown in Figure 5, in the first experiment the average speed with the EV (M = 74.47 km/h; (SD = 20.27 km/h)) in the Motorway scenario was slightly lower than with the ICE (M = 76.01 km/h; (SD = 23.55 km/h)), but this difference was not significant t(22) = -0.621; p = 0.541.

In the Country Road (1-lane) scenario the results were similar, being that the EV average speed (M = 58.16 km/h; (SD = 5.00 km/h)) was lower than the ICE (M = 61.22 km/h; (SD = 5.73 km/h)). These differences were not significant t(22) = -1.663; p = 0.110.

In the second experiment five months later, there was not a tendency of differences in average speed with EVs and ICEs.

B. Strong Deceleration Metric Evaluation

Additionally, the evaluation for the category of strong deceleration did not reveal significant differences between EV and ICE driving behavior for most of the sections in neither the first nor the second experiment. The only peculiarity to be mentioned in this context is the section Motorway. After
five months of EV driving, participants used the mechanical brake of the EV ($M = 0.04\%$); ($SD = 0.11\%$) significantly less frequently than the brake of the ICE for this category of deceleration ($M = 0.22\%$); ($SD = 0.33\%$), $t(25) = -2.488$; $p = 0.020$, while in the initial contact experiment there was no significant difference between EV ($M = 0.11\%$); ($SD = 0.23\%$) and ICE ($M = 0.12\%$); ($SD = 0.23\%$) deceleration behavior, $t(22) = -0.097$; $p = 0.923$.

Furthermore, the section *Arterial Road* is worth to be highlighted here. Although the percentage of strong braking maneuvers for EV driving ($M = 0.28\%$); ($SD = 0.57\%$) did not significantly differ from that for ICE driving ($M = 0.78\%$); ($SD = 1.10\%$) in the final experiment, $t(27) = -2.000$; $p = 0.056$, the tendency of less frequently mechanical braking with the EV is also visible for this road type.

### C. Regenerative Deceleration Metric Evaluation

While driving behavior with electric and conventional vehicles did not differ largely in average speed and in the percentage of strong deceleration, a significant contrast became obvious in regenerative deceleration performance. Figure 6 shows the results for the initial experiment and the experiment performed five months later, after having acquired the habit of driving an electric vehicle.

Regarding the category of regenerative braking, during the initial contact experiment participants decelerated significantly more frequently with the EV ($M = 10.52\%$); ($SD = 2.08\%$) than with the ICE ($M = 8.37\%$); ($SD = 2.19\%$) on the whole test circuit, $t(22) = 4.393$; $p = 0.000$.

Particularly we observed significant differences within the context of varying road types showed on Table I. Therefore, we can appreciate deceleration patterns that are directly related to the use of the regenerative braking system and seem to be independent from the driven speed and road type. Only in the following sections was the percentage of regenerative braking for EVs not significantly higher than the respective intensity of ICE deceleration.

- **Country Road (1-lane)** (EV: $M = 8.06\%$; ($SD = 2.17\%$), ICE: $M = 6.93\%$; ($SD = 4.50\%$), $t(22) = 1.223$; $p = 0.234$)
- **Inner-city 60** (EV: $M = 10.94\%$; ($SD = 2.33\%$), ICE: $M = 9.96\%$; ($SD = 3.29\%$), $t(22) = 1.253$; $p = 0.223$)

Regarding the regenerative deceleration values measured with EVs, in contrast to the results from the initial experiment a general tendency towards a smoother deceleration could be observed after five months of regularly driving an EV. Although the differences between EV and ICE driving were smaller, except for *Country Road (1-lane)*, in the following sections and on the whole test circuit they were still significant.

- **Country Road (1-lane)** (EV: $M = 7.27\%$; ($SD = 2.18\%$), ICE: $M = 5.70\%$; ($SD = 1.82\%$), $t(23) = 3.062$; $p = 0.006$)
- **Inner-city 30** (EV: $M = 13.51\%$; ($SD = 2.77\%$), ICE: $M = 11.33\%$; ($SD = 3.21\%$), $t(27) = 4.456$; $p = 0.000$)
- **Whole Test Track** (EV: $M = 9.69\%$; ($SD = 1.73\%$), ICE: $M = 8.51\%$; ($SD = 1.66\%$), $t(22) = 3.718$; $p = 0.001$)

Contrary to the initial contact experiment, in the sections *Motorway* and *Arterial Road* participants did not show significant differences in deceleration behavior with the EVs regenerative brake and the ICE.

- **Motorway** (EV: $M = 7.12\%$; ($SD = 2.17\%$), ICE: $M = 6.81\%$; ($SD = 3.34\%$), $t(25) = 0.564$; $p = 0.578$)
- **Arterial Road** (EV: $M = 13.95\%$; ($SD = 3.48\%$), ICE: $M = 12.96\%$; ($SD = 3.79\%$), $t(27) = 1.042$; $p = 0.307$)

Also for the section *Inner-city 60* results did not show significantly higher percentages of regenerative deceleration for EV ($M = 10.54\%$); ($SD = 3.04\%$) than for ICE ($M = 10.76\%$); ($SD = 3.95\%$), $t(29) = 0.244$; $p = 0.809$. This could be due to the high number of traffic lights that inevitably lead to a high percentage of deceleration for the ICE in this category.
Regarding the implementation of the EV’s regenerative braking system, the evaluation of subjective questionnaire data showed that already after the first trip 95% of the participants liked the one-pedal interaction concept of the MINI E.

D. Drag Torque Deceleration Metric Evaluation

The evaluation for deceleration in the category of the ICE engine’s drag torque showed no relevant variation with the EV driving experience. In both the initial contact and the final experiment, participants showed a significantly or at least marginally higher percentage of drag torque decelerations with the ICE than with the EV on the whole test route and three of the five sections depicted in Table II. Only in the sections where the traffic was controlled by traffic lights was the percentage of drag torque decelerations measured for ICE not significantly different from the respective EV deceleration. This is the same for the initial contact experiment and for the final experiment as shown in Table III. Figure 7 shows the results for the initial experiment and the experiment performed five months later after having acquired the habit of driving an electric vehicle.

E. Constant Driving Evaluation

Regarding constant driving there are no significant differences in any of the sections for the initial contact experiment as shown in Figure 8 and Table IV. Also spanning the whole test track the difference between the percentage of constant driving with EVs ($M = 57.12\%$); ($SD = 5.12\%$) and those of driving with ICES ($M = 56.82\%$); ($SD = 6.88\%$) was not significant, $t(22) = 0.260; p = 0.797$.

In the final experiment, only the motorway section caused a significantly higher percentage of constant driving with EV ($M$
In this paper we studied driving behavior with EVs and ICEs in two conditions: without having the drivers previously driven part of the test route with the exception of the slowest subjects in our study tended to accelerate smoother with the EV than with the ICE in the final experiment.

### Table II: Significant differences on the drag torque deceleration metric results for the initial and the final experiment depending on road type

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Initial Experiment</th>
<th>Final Experiment</th>
<th>T-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial Road</td>
<td>EV</td>
<td>ICE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>M</td>
<td>t</td>
</tr>
<tr>
<td>Motorway</td>
<td>13.77%</td>
<td>15.78%</td>
<td>-1.984</td>
</tr>
<tr>
<td>Country Road</td>
<td>10.94%</td>
<td>14.69%</td>
<td>-2.461</td>
</tr>
<tr>
<td>(1-lane)</td>
<td>10.91%</td>
<td>13.38%</td>
<td>-2.575</td>
</tr>
<tr>
<td>Inner-city 30</td>
<td>11.30%</td>
<td>13.75%</td>
<td>-3.677</td>
</tr>
<tr>
<td>Whole Test Track</td>
<td>11.03%</td>
<td>13.96%</td>
<td>-3.09</td>
</tr>
</tbody>
</table>

### Table III: Non-significant differences on the drag torque deceleration metric results for the initial and final experiment depending on road type

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Initial Experiment</th>
<th>Final Experiment</th>
<th>T-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial Road</td>
<td>EV</td>
<td>ICE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>M</td>
<td>t</td>
</tr>
<tr>
<td>Motorway</td>
<td>11.70%</td>
<td>15.93%</td>
<td>-3.897</td>
</tr>
<tr>
<td>Country Road</td>
<td>9.98%</td>
<td>13.64%</td>
<td>-2.855</td>
</tr>
<tr>
<td>(1-lane)</td>
<td>10.06%</td>
<td>13.49%</td>
<td>-6.518</td>
</tr>
<tr>
<td>Inner-city 60</td>
<td>11.03%</td>
<td>13.96%</td>
<td>-4.312</td>
</tr>
</tbody>
</table>

### Table IV: Non-significant differences on the constant driving deceleration metric results for the initial experiment depending on road type

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Initial Experiment</th>
<th>Final Experiment</th>
<th>T-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial Road</td>
<td>EV</td>
<td>ICE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>M</td>
<td>t</td>
</tr>
<tr>
<td>Motorway</td>
<td>11.80%</td>
<td>12.19%</td>
<td>-0.371</td>
</tr>
<tr>
<td>Country Road</td>
<td>10.48%</td>
<td>11.60%</td>
<td>-0.668</td>
</tr>
</tbody>
</table>

The acceleration performance analysis showed a similar trend as investigated for the category of regenerative deceleration. Figure 9 illustrates the results.

### Table V: Acceleration metric evaluation

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Initial Experiment</th>
<th>Final Experiment</th>
<th>T-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorway</td>
<td>13.77%</td>
<td>15.78%</td>
<td>-1.984</td>
</tr>
<tr>
<td>Country Road</td>
<td>10.94%</td>
<td>14.69%</td>
<td>-2.461</td>
</tr>
<tr>
<td>(1-lane)</td>
<td>10.91%</td>
<td>13.38%</td>
<td>-2.575</td>
</tr>
<tr>
<td>Inner-city 30</td>
<td>11.30%</td>
<td>13.75%</td>
<td>-3.677</td>
</tr>
</tbody>
</table>

In the initial experiment the participants showed a tendency to accelerate more powerfully with EVs than with ICEs on Country Road (1-lane), Arterial Road and Inner-city 60. None of the differences were significant. After five months of driving with electric vehicles the test subjects in our study tended to accelerate smoother with the EVs (M = 19.96%); (SD = 2.25%) than with their ICEs (M = 21.08%); (SD = 3.01%) over the whole test circuit, t(22) = -1.875; p = 0.074. This trend of a smaller percentage of acceleration with EV than with ICE was recognizable on every section of the test route with the exception of the slowest driven part Inner-city 30.

### VI. Conclusion and Future Work

In this paper we studied driving behavior with EVs and ICEs in two conditions: without having the drivers previously
familiarized with electric vehicles and after several months of electric driving experience. We showed that driving an EV does not affect the average speed which is driven, indicating that in general the drivers keep up their driving style on these dimensions. However, on motorways and country roads drivers driving for the first time EVs might drive slightly slower than when they drive ICE vehicles. It is likely that drivers simply did not want to reduce range of the EVs by driving higher velocity, but as this pattern only was visible in the first experiment it can also simply reflect unfamiliarity with the vehicle.

Regarding acceleration and braking maneuvers a development from stronger accelerating and decelerating within the first experiences with EVs to a more calm driving after 5 months of experience was noticeable. In the case of decelerations, results indicated that the participants of this study improved their regenerative braking patterns towards more anticipatory and efficient driving through a more thorough application of driving skills. Therefore, regenerative braking implemented in the accelerator pedal proved to be a successful means of supporting efficient driving, which is well accepted by customers.

Another aspect is the improved driving skill with constant velocity after 5 months of accustomization to EV. The generally higher percentage of constant driving with EV than with ICE indicates that the accustomization to the EV leads to an improved speed keeping with EVs and proves that interaction with EV’s one-pedal driving capability is not a barrier for efficient driving with constant velocity. Combined with the data on usage of regenerative braking and the high attractiveness of the features to the customers which was indentified also in several comparable field studies [30], implementing regenerative braking in the accelerator pedal should be strongly promoted for EVs.

One very important conclusion is that the results of this study, especially those of the second experiment after 5 months of electric driving, can be only regarded as a snapshot of daily driving behavior. Driving behavior varies with many uncontrollable variables from personal condition to situation specific parameters which might not have be captured in this data set. Therefore smaller differences in driving behavior patterns might not have become significant in this case as they could have been annihilated by a variety of confounding variables.

The fact, that all participants had been driving through the test circuit for several times before the post acclimation experiment was conducted, seems to suggest an adaptation of circuit specific driving. This effect might be one reason for the generally faster driving in the second experiment - with both electric and conventional vehicles. Therefore, a direct value-by-value comparison of these two experiments has to be taken with care.

We showed in this paper that there is a significant difference in the driving habits of an internal combustion vehicle and that of an electric vehicle. Particularly a development from stronger accelerating and decelerating within the first experiences with electric vehicles to a more calm driving after 5 months of experience was noticeable in acceleration and braking maneuvers. A detailed analysis of this driving behavior adaptation is the objective of further experiments in future work. Also individual effects which might be a reason for the high standard deviations in measured variables should be considered in further studies.

ACKNOWLEDGMENT

The authors would like to acknowledge the Bavarian Ministry of Economic Affairs, Infrastructure, Transport and Technology and the BMW Group for making this research possible. We also want to give special thanks to the team members of the project at the BMW Group and eMUC at TUM for their valuable contributions. Finally, in behalf of everybody involved in this project, we would like to thank our MINI E customers for their very helpful feedback and their strong commitment to our research project.
REFERENCES


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Cristina Olaverri Monreal graduated with a Masters degree in Computational Linguistics, Computer Science and Phonetics from the Ludwig-Maximilians University (LMU) of Munich 2002 and received her PhD 2006 in cooperation with BMW. After working at the Seed Biotechnology Center at the University of California in Davis, SDL International and Lionbridge Technologies at Boulder, Colorado, USA and as a Postdoc at the Instituto de Telecomunicacões, University of Porto, she is currently a research scientist at the Technische Universität München (TUM). Her research aims to minimize the barrier between the user and the system in complex, dynamic scenarios that are critical to decision-making processes, such as driving a vehicle. Her research interests include the study of vehicular multi-functional systems as well as driver behavior, driving simulation tools and research concerning Intelligent Transportation Systems (ITS).
Klaus Bengler graduated with a degree in psychology at the University of Regensburg in 1991 and received his Doctorate in 1994 in cooperation with BMW. After his diploma, he worked extensively on topics of software ergonomics and evaluation of human-machine interfaces. Additionally, he investigated the influence of multitasking on driving performance in several studies within EMMIS EU project and in contract with BMW. In 1997 he joined BMW where he was responsible for projects on HMI research (MOTIV program, EU project Speechdat Car, etc). During his career, Prof. Bengler has trained at an advanced level over 40 researchers with a PhD within the field of HMI and Human Factors. Since May 2009 he has been a leader of the Institute of Ergonomics at the Technische Universität München and active in research areas like digital human modeling, human robot cooperation, driver assistance HMI and human reliability.

Roman Vilimek works in the Concept Quality and Usability department of the BMW Group where he is responsible for user research in the worldwide EV pilot projects. He graduated with a degree in psychology at the University of Regensburg in 2003 and received his Doctorate with highest distinctions in cooperation with Siemens Corporate Technology in 2007. While with Siemens he extensively investigated a large variety of HMI topics like user centered design of advanced interaction technologies, multimodal systems, health care systems and intranet applications. Since 2010 he focuses on in-vehicle HMI concepts and user experience, driver distraction research and electromobility.

Andreas Keinath graduated with a degree in psychology from University of Regensburg in 1997. He received his doctorate from University of Technology in Chemnitz in 2003. After his PhD he started working at BMW Group Research and Technology and worked intensively on driver distraction and HMI design and evaluation. Since 2009 he is Head of Concept Quality and Usability of the BMW Group. In this position he was responsible for the coordination of the scientific research of the international MINI E and BMW Active E projects as well as the BMW i3 and i8 usability engineering process. His research interests include field trials of innovative systems, distraction research and HMI evaluation.