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# Behavioral adaptation to electric vehicles – An experimental study

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# 1 INTRODUCTION

## 1.1 BACKGROUND

In the last decades, there has been a growing concern regarding the global impact of pollution and greenhouse gas emissions on the environment. The transportation sector plays a major role in contributing to this concern as the number of vehicles increases from year to year. In recent years, electric vehicles have become a promising technology for reducing the environmental consequences of road transport (Kloess 2011).

The novelty of electric cars draws attention, but drawbacks such as range, lack of charging infrastructure and sale price are serious factors that impede the driver to purchase this technology. Taking into account the impact that electric vehicles can have towards to a more environmentally friendly mobility and their future extent in the automotive industry, it is essential to understand that user acceptance is paramount. Presuming that people will respond positively to electric cars, it is mandatory to understand as accurately as possible how and what will change in people's mobility and driving patterns. The education of drivers is crucial in order for them to learn not only on how to take advantage of this technology, but also to determine the best way to use it (Rolim et al. 2012).

There has been considerable research done in the field of driver behaviour changes due to electric vehicles. From European and global surveys (Deloitte Touche Tohmatsu Limited 2011; Kleber 2011; Thiel et al. 2012) to field trials performed in various locations (Everett et al. 2011; Pilgerstorfer et al. 2012; Turrentino et al. 2011) – all attempted to evaluate the perception of drivers to this new technology. While these studies give valuable insight into users' experiences and attitudes, their conclusions were mostly based on solely subjective data collected by means of questionnaires, online surveys and trip diaries, without any objective vehicle data. Therefore, the questions arise: Can drivers simply switch from combustion engine cars to electric ones? What is the time interval needed for a driver to accommodate himself/herself to an electric car? What are the differences in driver performance and behaviour between electric and combustion engine vehicles?

## 1.2 AIM OF THE PAPER

This paper investigates the user's adaptation to electric vehicles in terms of driver behavior, mobility, performance and comfort. To accomplish this task, a small scale experimental trial was carried out in the area of Vienna, Austria. The trial lasted 6 weeks, during which 4

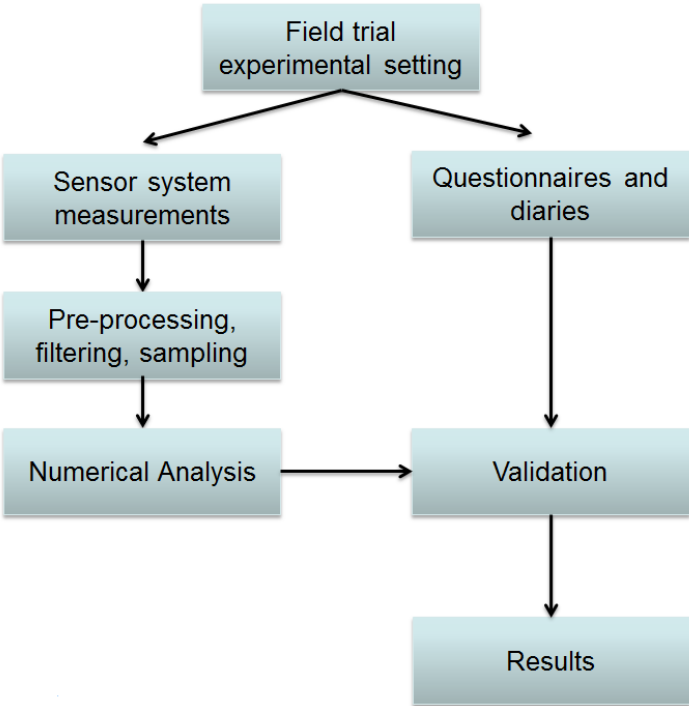
subjects drove an electric vehicle and a combustion-based vehicle. In total, over 60 trips were conducted, amounting to over 1500 kilometers and 30 hours of drive time.

The paper is organized as follows: Chapter 2 describes the methodology developed in the project and reports the study design, vehicles used and the data collection. In Chapter 3 the data analyses results are presented for the quantitative and qualitative data. The conclusions are derived in Chapter 4 along with a complementary discussion, while references are given in Chapter 5.

# 2 METHODOLOGY

## 2.1 OVERVIEW

The focus of the trial was to evaluate the adaptation of drivers to electric vehicles and to perform a comparison in performance and behaviour between combustion and electric cars. Figure 1 presents an overview of the study methodology.



*Figure 1 Overview of methodology*

The trial lasted six weeks, during which the participants drove an electric vehicle and a combustion engine car, each for the duration of one week. The drivers did not have a predefined route and were allowed and encouraged to drive the electric car as they preferred. Technical data such as GPS position, velocity and three-axes acceleration was collected by means of a sensor system installed in the vehicles. Subjective data was acquired through pre and post-questionnaires and also with travel diaries, which drivers kept daily. Each driver participated in two trials, each lasting up to five days. The first one was performed with the electric vehicle, during which sensor data was acquired in order to evaluate the driver’s adaptation and behaviour. The second trial was performed with a

combustion engine vehicle, which in every case, was the private car of each of the participants. This set of data was required in order to have a baseline for comparison.

In total, over 60 trips were conducted in Vienna and the surrounding areas, amounting to over 1500 kilometres and 30 hours of test trials, from which over 750 kilometres and 17 hours with the electric vehicle. After the completion of the test trials, all collected data was analysed with a dedicated software tool, which allowed performing specific operations in order to evaluate the adaptation of drivers and potential behavioural changes.

## 2.2 SELECTION OF DRIVERS

Due to the short period available for carrying out the trial and due to its experimental design, the test subjects were selected from AIT's database. Methods typical for such exercises, i.e. word of mouth, group emailing, etc. were employed. In terms of driving experience and style, it was decided to focus on various driver types. Another criteria used was to choose drivers, which owned a personal internal combustion engine car and used it every day for their commute, i.e. work – home, as well as other personal/business travels. Due to the limited time available to conduct this study, only three male and one female driver were selected. A balance between genders was not reached, as the majority of the subjects interested in participating were male and social representativeness was not a goal of this study. Before the trial, a pre-questionnaire was completed by each participant. The aim was to find out their level of experience with an electric car and their expectations, as well as general data regarding self-assessing driving style (careful to aggressive) (Stanton et al. 2014) and experience (number of kilometres driven per year). Table 1 presents the drivers along with their age and driving experience.

Table 1 Description of drivers

Driver	Gender	Age	Driving experience (km/year)	Driving style	Driving experience with an electric car
#1	Male	39	10.000	Careful	Once
#2	Male	34	25.000	Moderate	Once
#3	Female	24	15.000	Sporty	Never
#4	Male	40	30.000	Careful	A few times

## 2.3 VEHICLES

The electric vehicle used in this study was the Renault Fluence Z.E. (i.e. Zero Emission). This vehicle (see Figure 2) is the electric version of the common internal combustion-engine car,

the two being relatively similar in length, width, interior layout, design, etc. The vehicle has a synchronous electric motor with rotor coil, with peak power of 70 kW at 11.000 rpm. The battery is Lithium-Ion technology with a capacity of 22 kW, capable of a range of 160 km. An energy recovery system is also present, allowing the battery to be recharged when the car decelerates. Top speed is capped electronically at 135 km/h. ABS (Anti-Lock Braking System) and ESC (Electronic Stability Control) driving aids are also present (Renault 2010).



Figure 2 Electric test vehicle – Renault Fluence Z.E. (own source)

The combustion engine vehicles, used for the collection of comparative data, were in each case – the private vehicles of each of the trial participants. Table 2, Figure 3 and Figure 4 illustrate the vehicles:

Table 2 Description of combustion engine vehicles

Driver	Combustion engine vehicle	Maximum power (kW)	ABS	ESC/ESP
#1	Mercedes Benz A180, 2010	80	yes	yes
#2	Ford Galaxy, 2007	66	yes	yes
#3	Seat Ibiza, 2008	51	yes	yes
#4	Ford C-Max, 2011	70	yes	yes



Figure 3 Combustion-engine test vehicles –Mercedes A180 and Ford Galaxy (own source)



*Figure 4 Combustion-engine test vehicles – Seat Ibiza and Ford C-Max (own source)*

## **2.4 DATA ACQUISITION SYSTEM**

All the vehicles were equipped with a data acquisition system that needed to include a GPS receiver, an accelerometer, data processor and means to store the data. The system needed to be integrated, so that a common time stamp could be used to synchronize all collected data. Another goal was to have a sensor system which was compact, lightweight and easy to handle and to be unobtrusive to the drivers during the test trial. The participants needed to easily forget that the equipment was in the vehicle, in order for their behaviour to be as natural as possible.

The quantitative data, which was decided to be collected, were:

- GPS position;
- GPS velocity;
- Position angle;
- Lateral acceleration  $a_y$ ;
- Longitudinal acceleration  $a_x$ ;
- Vertical acceleration  $a_z$ ;
- Date and time.

All of these data sources can be collected with modern smartphones. Therefore, a state of the art smartphone was used, with integrated GPS receiver, and motion sensing technology (accelerometer, gyroscope and magnetometer) in combination with solid mounts.

The device was solely used for collecting measurement data, i.e. longitudinal, lateral and vertical acceleration/deceleration, roll, pitch and yaw rate. In order to get proper accuracy, the phone was fixed near the centre console, on the adjustment rail of the front passenger seat (see Figure 5). This ensured a stable recording of the acceleration values near the centre of gravity, along the central longitudinal axis of the vehicle, while avoiding vibrations and potential displacements. The position was also chosen so that drivers were not distracted by visible devices, reminding them that their driving behaviour was being recorded.



*Figure 5 Data acquisition system (own source)*

## **2.5 DATA COLLECTION**

### *2.5.1 Quantitative data*

The quantitative data (GPS velocity, 3-axes acceleration, etc.) was collected by means of a smartphone. One device was installed in the Renault Fluence Z.E., by means of special mountings and calibrated for accurate precision. The second smartphone was installed in each private combustion engine vehicle during the trial duration. The mounting and calibration of the equipment was performed by expert personnel at AIT. At the beginning of each test, the drivers were given the smartphone along with its charger and the trip diary. All drivers were instructed on how to use the device for recording the data.

The acquisition of data from the smartphone sensors was possible through a dedicated mobile application developed at AIT. The drivers were shown how to use the application to start the recordings. All they had to do is enter the application and click on a button. At the end of the trip, they had to click on another button. After the application was stopped, a file was automatically created and stored on the smartphone's memory card. All files were stamped with the time and date of the recording.

All collected data went through several processes of filtering and down sampling and was afterwards examined by means of numerical analyses in Python (Kuhlman 2012).

### *2.5.2 Qualitative data*

During the test trial, each driver was asked to fill in a travel diary which would provide information of every trip performed. This information was needed in order to correlate the technical data to the participants' information. The diary was given to each subject at the beginning of the trial and contained questions regarding: trip purpose, times of start and end

of a trip, point of departure and arrival, battery status and expected range distance (shown on the board display of the electric vehicle) at the beginning and end of the trip, traffic conditions (e.g. free flow, congestion), weather conditions, features turned on during the trip (e.g. radio, heating, air conditioning, etc.), potential conflicts with the vehicle or with other traffic participants.

The goal of the trip diary was not only to gather information regarding the travel behaviour and kilometres travelled, but more to find out how various factors, such as range anxiety, may influence driving behaviour.

Drivers received post-questionnaires at the end of the trial, in order to assess their experience with the electric vehicle and to gather subjective data on: overall driving experience with the electric vehicle; meeting of expectations in terms of ease of use, performance and satisfying daily needs; safety of the electric car, in comparison to their own car; period of adaptation with the electric vehicle; differences between the electric and internal combustion vehicle in terms of noise, acceleration and braking; influence of driving behaviour due to the range of the electric vehicle.

The post-questionnaires were useful in acquiring information on how drivers perceived the electric vehicle, if they adapted quickly to it and if they were satisfied with its performance.

# 3 DATA ANALYSIS AND RESULTS

## 3.1 QUANTITATIVE DATA

An evaluation of adaptation and overall performance was carried out for each driver:

- Performance – A comparison between all trips with the electric vehicle and all trips with the combustion car, in terms of longitudinal acceleration and velocity.
- Adaptation – A comparison between the first and last trip with the electric vehicle, in terms of longitudinal acceleration and velocity.

For analysing the performance of each driver, data collected from his trips with the electric car and his trips with the combustion-engine car respectively were grouped separately. The comparison was then performed between the two sets of data. For analysing adaptation, data from only the first and last trip with the electric vehicle was taken into consideration. This method was adopted in order to have similar traffic conditions, in terms of time of day, day of the week, etc.

The results of the numerical analyses are shown in density plots, in the form of violin plots. Violin plots are a combination between common box plots and a kernel density plot, with the shape and the size of the violin denoting where the data points fall. In simple terms, the larger the width of a violin's section, the greater the number of points that fall at that specific value. Through this operation, the resulting graph shows the probability density of the data at different values (Coelho 2009).

### 3.1.1 Vehicle performance

During the trial, the drivers performed daily trips (e.g. commute work place – home, shopping, picking children from school, etc.). The shortest trip was three kilometres, while the longest one was 53 kilometres. The number of trips per driver, with each vehicle, varied from six to eight. Table 3 shows more details regarding the trial.

Table 3 Trial details

Driver	Nr of trips with electric car	Nr of trips with combustion-engine car	Mean trip length (km)
#1	6	7	11
#2	8	8	14
#3	8	6	24
#4	8	8	53

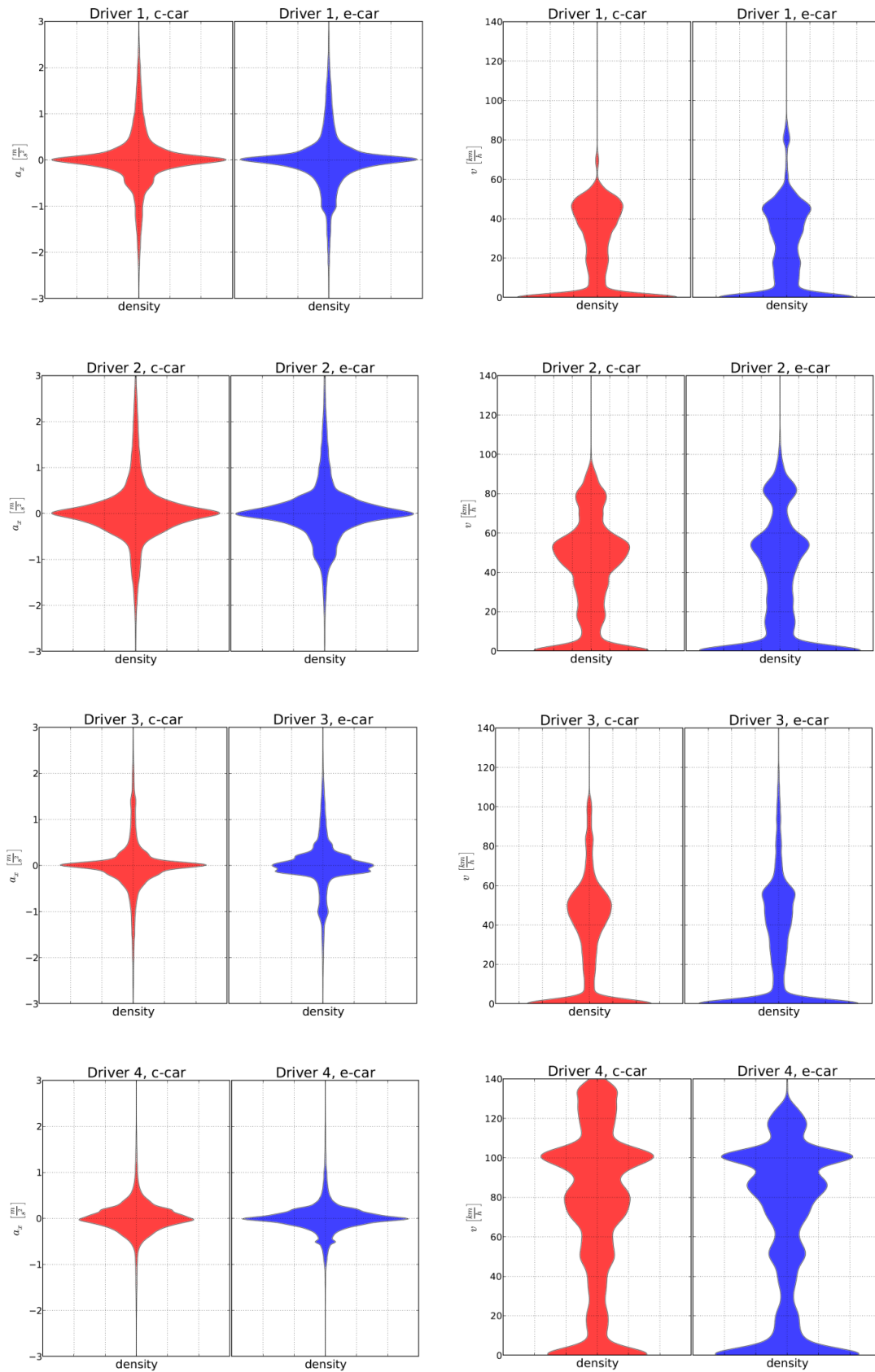


Figure 6 Analyses of vehicle performance for all vehicle pairs – **longitudinal acceleration** (left) and **velocity** (right)

The violin plots in Figure 6 show the analysis performed for all drivers on the longitudinal accelerations  $a_x$  (plots left) and velocities  $v$  (plots right) of all trips for each pair of combustion – electric cars.

The positive acceleration values in the density estimations shows little differences between the electric and combustion vehicles performance (with the exception of Driver #3), indicating that the drivers enjoyed the electric car and its performance as much as their personal vehicles. The data is also supported by the feedback of the post-questionnaire, where drivers indicated that the acceleration of the electric car is strong but smooth. The analysis of the acceleration values for the third driver, female, shows differences between the two vehicles. While the acceleration of the combustion vehicle is quite smooth, the profile of the electric car shows multiple density values. This result could be explained by the driver wanting to experiment with the electric vehicle. The data is supported by the feedback from the questionnaires, in which the driver stated that the electric car was faster than her own vehicle and the acceleration was stronger.

When looking at the negative acceleration values for all drivers, differences can be observed, when decelerating. Small peaks of the electric car in the range of  $a_x \in (-0.5, -1) \text{ m/s}^2$  suggest that the regenerative braking occurred in this range.

In terms of velocities, it can be observed that drivers had no reservations towards the electric car, engaging in similar speeds with both vehicles. The higher density values in the lower speeds range  $v \in (40, 60) \text{ km/h}$  for the first three drivers can be explained by the traffic speed limitations of the city, as their routes were mainly in the city of Vienna, while for the fourth driver – the higher speed range  $v \in (80, 100) \text{ km/h}$  can be explained by the fact that his trips were predominantly on the motorway.

### 3.1.2 Driver adaptation

In order to show a more accurate evaluation of the adaptation, the first and last trips of each driver with the electric vehicle were compared in terms of longitudinal acceleration  $a_x$  (left plots) and velocity  $v$  (plots right) profiles for all drivers. The first and last trips of each driver are comparable in terms of route (e.g. first trip – work to home, last trip – home to work) and also comparable in terms of length and speed limits. Table 4 shows more details regarding the trips with the electric car. The violin plots in Figure 7 show the analyses performed.

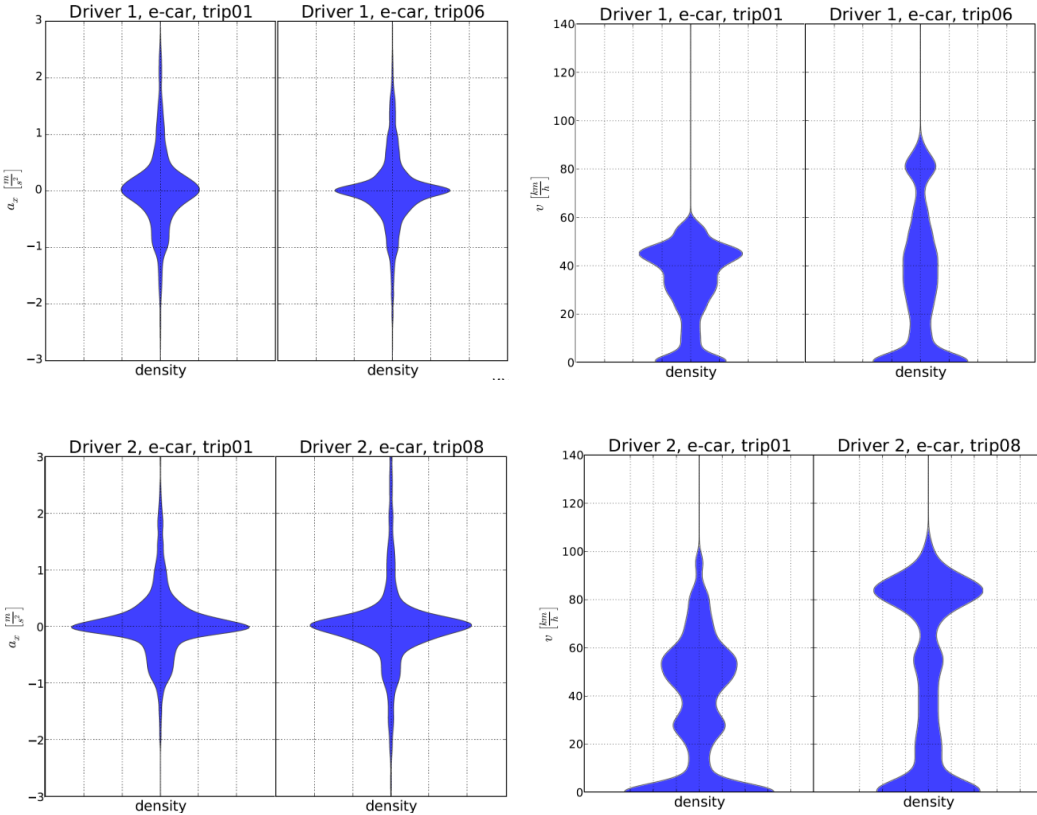
Table 4 Trial details

Driver	Length of first trip (km)	Length of last trip (km)	Maximum speed limit first trip (km/h)	Maximum speed limit last trip (km/h)
#1	10	10	100	100
#2	14	21	130	130
#3	27	24	100	100
#4	51	54	130	130

The left plots show the comparison of longitudinal accelerations. A slight difference can be observed for all drivers, in the time spent at a constant speed, with an acceleration of  $a_x = 0 \text{ m/s}^2$ . In the first trip, the drivers spent more time accelerating and decelerating, indicating the customization to the electric vehicle, while in the last trip, this constant speed time interval was enlarged, suggesting that the drivers adapted to the car and were more at ease with it. This data is also supported by the subjective feedback provided in the questionnaires.

The positive acceleration profiles are similar, while the braking patterns show again the use of regenerative braking. The latter was used more in the first trip than in the last, which could indicate that the novelty of the car wore off as the driver got accustomed to it. This distinction can be most clearly observed in the analysis of the data from the fourth driver.

The velocity profiles (right plots) indicate a larger density of smaller speed values in the first trip, compared to the last for all drivers. While this pattern may show that the drivers adapted to the vehicle and were more confident to accelerate and drive at higher speeds, it may also be due to the traffic conditions encountered in their route, as factors like day of the week or time of day could influence traffic volume and hence travel speed. Even so, noticeable differences can be observed in the maximum speed values, which are higher for all drivers, in their final trip with the electric car. This may indicate an adaptation to the electric vehicle, the drivers feeling more at ease with the car to attempt higher speeds.



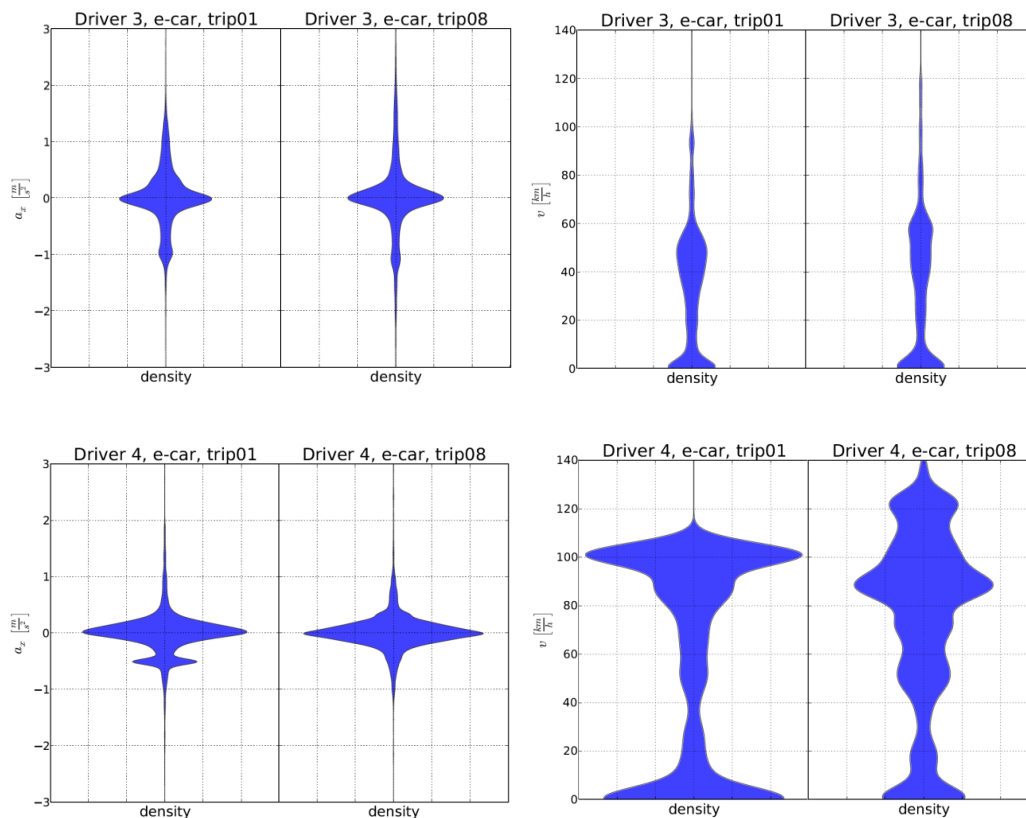


Figure 7 Analyses of drivers' adaptation – *longitudinal acceleration* (left) and *velocity* (right)

## 3.2 QUALITATIVE DATA

This section examines the data that resulted from the post-questionnaires given to the trial participants. The drivers were asked to evaluate several aspects of their driving experience with the electric vehicle.

### 3.2.1 Expectations

The drivers were asked both in the pre- and post- questionnaire, what their expectations were regarding the electric car, in terms of ease of use, performance (e.g. acceleration, handling, comfort, etc.) and satisfying daily travel needs.

All drivers, except one, expected that the electric car will be as easy to use as any other vehicle. After the trial, all participants responded that the electric car was as easy to use as other vehicles.

Opposite to the ease of use, three out of four drivers expected the electric car to have a poorer performance than a combustion engine vehicle. After the trial, all participants found the car's performance the same and even better in comparison to a conventional vehicle.

In terms of satisfying daily needs, two drivers expected that the electric car will suffice for their daily trips, while the other two did not think so. The fact that one of the drivers, which had the longest daily trips expected the car to satisfy its needs, while another participant which drove less than half that amount per day did not think so, proves the premise that drivers were not sure what to expect from electric vehicles. After the end of the trials, three of the participants stated that the car satisfied their travel needs.

### *3.2.2 Vehicle dynamics and acoustics*

In terms of acceleration, two drivers stated that they noticed no significant differences between their personal vehicles and the electric car. The other two, evaluated the acceleration as better, stating for example, that full torque was available from idle speed. Regarding the braking characteristics, all drivers were pleasantly surprised and enjoyed the engine brake of the electric vehicle and used it frequently. One of the drivers was also pleased that by using the brake less, energy as well as brake pads and other mechanical components were saved. The same driver drew attention to a noteworthy fact: by using the engine brake, other traffic participants were surprised when the electric car slowed down. This behaviour appeared due to the fact that when using the engine brake, the brake lights did not turn on unless a specific threshold of deceleration was reached.

As expected, all drivers stated that the noise level of the electric car is very low. However, one of the drivers pointed out that in some cases other traffic participants like pedestrians or even other vehicles did not notice the vehicle approaching. Another aspect mentioned was that because the engine was so silent, he could not evaluate properly the vehicle's speed and often found himself driving faster than expected.

In terms of vehicle performance at curves, roundabouts and intersections, none of the drivers found any major differences, suggesting that they had no problems manoeuvring the electric vehicle and its behaviour was comparable to that of the combustion engine vehicles.

### *3.2.3 Adaptation*

In terms of adaptation with regard to the electric vehicle, the questionnaire asked the participants to state the time in which they considered themselves adapted to the car. The choices for the adaptation period were – “less than 1 hour”, “less than 1 day”, “less than 4 days” and “need more time”.

The first two drivers with one previous driving experience with the electric car, answered differently, one stating that it took him less than a day, while the other – in less than one hour. The driver with no experience reported an adaptation period of less than one hour. The driver with the most experience stated that it took him less than a day to adapt. It can be observed that the periods of adaptation varied and previous experience was not a factor.

### *3.2.4 Safety*

Safety is an important factor when evaluating overall performance and comfort in a new vehicle. The electric vehicle was evaluated to be as safe as any other combustion engine vehicle, although one of the drivers stated that due to low level noise, he was not able to properly evaluate the value of its speed, driving faster than expected. Because of this concern, he rated the electric car as less safe than his combustion engine vehicle.

### *3.2.5 Vehicle range*

All drivers responded that in general, the range did not affect them. Even the driver which had to recharge at home and at work every day, did not consider it to be a problem. Another driver was even pleasantly surprised by the range, as he pointed out that the battery discharged slower than expected. Even so, he stated that he had to use his second vehicle for other trips that could not be performed due to the range limitations.

Although three of the participants had daily trips of less than 40km, they still preferred to recharge the vehicle as often as they had the opportunity. This suggests that the drivers were aware of the limited range and preferred to have a full battery, even though in some situations it was not necessary.

## 4 CONCLUSIONS AND DISCUSSION

A user's adaptation to electric vehicles was investigated by conducting a small experimental test trial, with four participants, with data collection on two levels: pre- and post-questionnaires and diaries and vehicle data. The subjective data enabled to evaluate drivers' personal opinions regarding adaptation to the vehicle, performance, safety, expectations and preferences while, a detailed analysis of the vehicle data made it possible to objectively evaluate the adaptation of drivers to the electric vehicle.

Results from both qualitative and quantitative data analyses indicate an overall driver adaptation period to electric vehicles of less than one day. Comparisons of first and last trips performed with the electric vehicle show slightly higher velocity levels in the latter, as well as smoother acceleration profiles. The results suggest that drivers are able to easily adapt to electric cars. Moreover, with the increase of kilometres driven, drivers become more and more comfortable with the electric car and develop more trust in its capabilities. The indication is that a greater exposure of drivers to electric vehicles would increase the acceptance of this technology.

In terms of overall performance, although small differences could be observed between the electric and combustion cars, it can be stated that no significant dissimilarities in velocity and acceleration/braking behaviour were found. All drivers were satisfied with the performance and ease of use of the electric car. However, as observed in the data, the level of deceleration achieved by energy recuperation with the electric car was significantly higher than the engine brake of the combustion cars. Since the (electric) engine brake does not activate the brake lights unless a specific threshold is reached, this deceleration may go unnoticed by other traffic participants and lead to potential safety risks.

Moreover, the low acoustic feedback of the electric vehicle was found to be of relevance. Pedestrians, as well as other traffic participants may not hear the approach of an electric vehicle, due to their customization with the sound of combustion engines, which could lead to potential safety problems. In addition, the issue of underestimating the electric vehicle's velocity could lead to potential road safety risks.

As this study's predecessor, the E-FFEKT project (Nitsche et al. 2014), performed by AIT, aimed to identify the potential risks of electric vehicles in traffic, by conducting a trial in which 90 drivers drove an electric car for 50 minutes each. Due to the short drive interval for each driver (i.e. 50 minutes), the adaptation process to electric vehicles was not identified. Hence, this study aimed to fill the gap and evaluate a driver's adaptation to electric vehicles in terms of driver behaviour, safety, mobility and comfort. As it was conducted in an experimental setting, due to time constraints, the study limitations are to be taken into account.

However, the developed methodologies and results hinted at relevant research topics, which are currently being researched in other European projects. One example is E-ENDORSE (Fondation MAIF 2015), a project conducted also by AIT, where among others, the low acoustic feedback and underestimation of speed of electric vehicles are currently being investigated.

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