Analysis of the main factors influencing the energy consumption of electric vehicles

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***Abstract*—Electric vehicles are currently a field of research with many challenges that raise the interest of many researchers. The major challenge is about the autonomy of electric vehicles, which is limited as compared to that of conventional vehicles, and thus the drivers' anxiety about reaching or not the desired destination is very important. In this paper, we propose an experimental study to understand the energy consumption of electric vehicles, and we investigate some factors that have an important impact on their autonomy, such as the route type, the driving style and the ambient temperature. This study can be very useful in a further step to conceive a driving assistance system that indicates in real time the remaining energy and gives online instructions to reach the next charging station or the final destination. The analysis reported in this paper is based on real-world data collected using a full electric car with different driving conditions.**

***Index Terms*—Ambient temperature, driving style, electric vehicles, energy consumption, route type.**

I. INTRODUCTION

Electric vehicles are currently a field of research with great potential and many challenges. They represent a real alternative to vehicles powered by internal combustion engines, and they are environmentally friendly since they do not produce gas emissions.

The main problem that prevents the popularization of electric vehicles is their autonomy that is much smaller than that of conventional vehicles. From many feedbacks and studies, it has been seen that electric vehicles mileages are almost below 200km due to constraints about the weight and capacity of batteries, while a full tank gasoline vehicle may have a driving range of at least 600km [10]. In addition, the promotion of electric vehicles requires the deployment of charging infrastructures and compensate the lacking of charging facilities by improving battery energy density or decreasing charging time. As a consequence, consumers are still reluctant to invest money to buy an electric car because of the important range anxiety of the drivers about reaching or not the desired destination or the next charging station.

The final goal behind this work for our lab is to develop a driving assistance system in order to reduce electric vehicles drivers anxiety. The aim is to give an accurate real-time estimation of the remaining energy and provide online instructions to the driver in order to adapt his driving style and ensure the best conditions to reach the final stop.

To achieve this goal, we propose in this paper an experimental study to understand the energy consumption of electric vehicles and investigate the factors affecting the most the driving range. Several factors are susceptible to have an effect on the energy consumption, the major ones are listed below [2].

- Ambient temperature: the ambient temperature greatly affects the battery performance, its power output capability, and thus its effectiveness.
- Route type: the energy consumption is very dependent on the driving environment (city, highway, etc.), and the road topography. In city, the consumption may be more important because of the frequent stop and start driving. In addition, going

uphill requires more energy than driving on a flat road, and going downhill requires less energy and may increase the energy regeneration.

- Driving style: an aggressive driving style with raw acceleration and deceleration phases reduces the autonomy of the battery, while economic driving and smooth pedal motions with constant moderate speed decreases the electrical energy consumption.
- Traffic conditions: the consumption may vary depending on traffic conditions and congestion level.
- Vehicle accessory utilization: when using vehicle accessories such as the air conditioner or the defroster system, a significant amount of energy that does not contribute to the propulsion of the vehicle will be consumed permanently.

Some of the above mentioned factors are measurable such as the ambient temperature or the accessories consumed energy, and other ones cannot be directly measured such as the driving style or the route type, which are categorical variables. In this paper, we will investigate in more details the energy consumption of electric vehicles, and we will present different parameters that allow us to estimate the non-measurable factors.

Section II introduces different parameters that can be used to characterize a driving cycle. Section III reports an experimental study of the energy consumption. At first, the influence of different factors on the autonomy of electric vehicles are presented. The identification task of the route type and the driving style is then considered. Finally, in Section IV, the experimental results are discussed and concluding remarks are made.

II. Driving cycle characterization

The analysis reported in this paper is based on real-world data collected from AX Citroen full electric car where the motor switches to generator mode when the acceleration pedal is released or when braking. Different sensors have been installed on the vehicle for data collection at 10Hz frequency. The main measures are:

- Time in seconds (t[s]), distance traveled in meters (D[m]), and GPS position (longitude, latitude and altitude);
- Speed in kilometers per hour (v[km/h]), and acceleration in meter per second squared (a[m/s^2]);
- Battery current in ampere (I[A]), battery voltage in volt (U[V]), and battery state of charge (SOC[%]);
- Ambient temperature (T[$^\circ$C]), and battery cells temperature (T_cell[$^\circ$C]) in Celsius degree.

Figure 1 shows some measures collected for a given driving cycle. The corresponding instantaneous speed, altitude, battery state of charge and battery current are represented as a function of time. From the altitude signal, we deduce that the driving cycle corresponds to a mountain route type. When going uphill the SOC decreases, and when going downhill as in the interval time [1500,1800], the motor is in regeneration mode because the driver released the acceleration pedal, the current is almost negative, the battery is charged, and so the SOC increases.

112 driving cycles with 3 types of route (city, ring road and mountain), and 3 driving styles (calm, normal and aggressive) are recorded. A calm driving style is characterized by smooth accelerations and decelerations, normal style is characterized by moderate speed variation, while for the aggressive one, higher speed with rough acceleration and braking are adopted. Note that no accessory has been used during the data collection except the radio and the windscreen wipers when it was necessary.

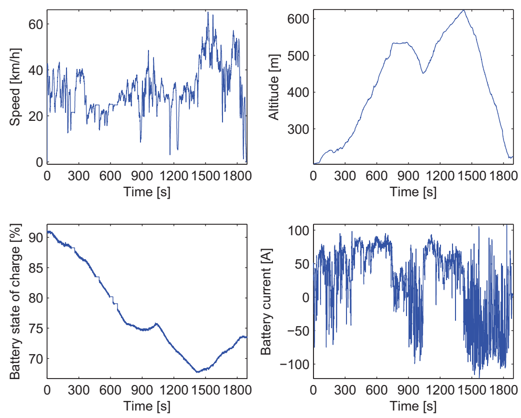

Fig. 1. Some measures representing a driving cycle: speed, altitude, battery state of charge and battery current as a function of time.

In order to recognize and characterize a driving cycle, different parameters can be used [3]. Some of these parameters are specific to electric vehicles while others are common for all kind of vehicles [9]. Among the common parameters, we can cite:

- Average, maximum and standard deviation of speed;

Average values	Route type			Driving style		
	City	Ring road	Mountain	Calm	Normal	Aggressive
v_{max}	66	91	87	84	83	87
v_{mean}	**17.5**	**62.9**	**32.4**	48.9	42.2	45.5
v_{std}	18.6	28.31	22.1	24.25	24.6	25.6
a^{+}_{mean}	0.96	0.55	0.77	0.57	0.67	0.79
a^{+}_{std}	1.88	0.71	0.86	1.02	1.12	1.11
a^{-}_{mean}	-0.98	-0.61	-0.82	-0.64	-0.75	-0.83
a^{-}_{std}	0.96	0.59	0.68	0.61	0.76	0.79
PKE	0.68	0.44	0.61	**0.42**	**0.5**	**0.63**
RPA	3.55	2.23	3.1	**2.13**	**2.58**	**3.18**
RMS(PF)	20.76	26.9	19.9	22	24.1	26.29
Jerk$_{std}$	0.15	0.11	0.10	0.11	0.13	0.14
Regeneration rate	**27.42**	**9.8**	**31.8**	12.85	19.28	21.8
Driving efficiency	1.54	1.73	2	1.75	1.88	1.76
% of time in idle mode ($v \leq 2km/h$)	**37.1**	**3.9**	**7.9**	10.8	14.51	12.6
% of time in engine braking mode ($v > 2$ & $a \approx 0$)	16.46	17.9	16.8	21.8	17.75	14.53
Energy consumption [kwh/km]	0.14	0.1	0.12	0.1	0.11	0.12

TABLE I
COMPARISON OVER SEVERAL PARAMETERS BETWEEN DIFFERENT ROUTE TYPES AND DIFFERENT DRIVING STYLES

- Average, maximum and standard deviation of acceleration/deceleration;
- Positive kinetic energy (PKE) that is defined as the sum of the differences between the squares of the final and initial speeds in successive acceleration manoeuvers, divided by total trip distance, where the speed is expressed in meters per second:

$$PKE = \frac{\sum_i (v_{i+1}^2 - v_i^2)}{D}, v_{i+1} > v_i$$

- Relative positive acceleration (RPA) that is defined as the product of the instantaneous speed and the instantaneous positive acceleration divided by total trip distance:

$$RPA = \frac{\sum_i (v_i * a_i^+)}{D}$$

- Power factor (PF) that is defined as: $PF = 2 * v * a$. As in [7], the root mean square of the power factor over the different time steps can be considered:

$$RMS(PF) = \sqrt{\frac{1}{n}\sum_{i=1}^{n} PF_i^2}$$

- Jerk profile that represents the variation of acceleration. The standard deviation of the jerk profile and the mean absolute values can be considered [6]:

$$Jerk = \frac{da}{dt} = \frac{d^2v}{dt^2}$$

- The percentage of time spent driving at speed and acceleration in certain intervals.

Other parameters are specific to the electric vehicles, among them we can cite [1]:

- Regeneration rate that represents the ratio of the energy recovered by the battery and the energy supplied by this one;
- Driving efficiency that is the distance traveled per unit of SOC [km/SOC];
- Average and standard deviation of electric power $P = U * I$.

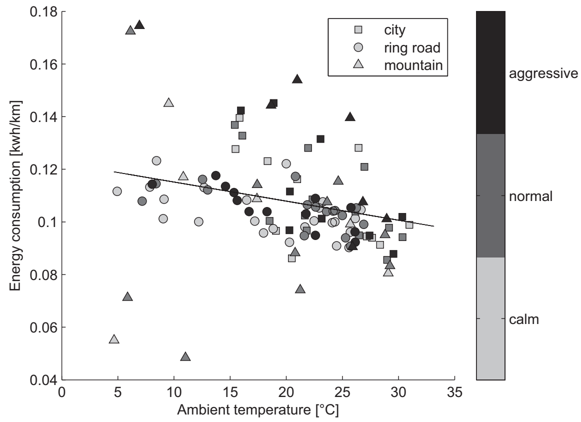

Fig. 2. Influence of the ambient temperature on energy consumption. Each point represents a driving cycle. The form indicates the route type (city, ring road or mountain), and the color indicates the corresponding driving style (calm, normal or aggressive). The solid line represents the linear regression between the two factors.

Table I shows a comparison over many parameters between different route types and different driving styles. For each parameter, the average value over the 112 driving cycles is shown. Parameters

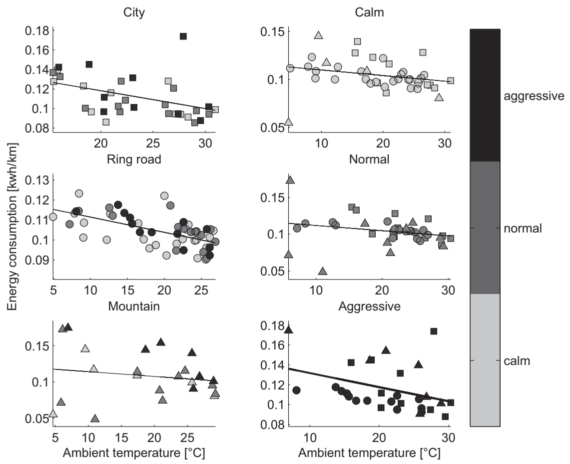

Fig. 3. Influence of the ambient temperature on energy consumption by route type on the left (city, ring road and mountain), and by driving style on the right (calm, normal and aggressive). The solid lines represent the linear regression between the two factors in each case.

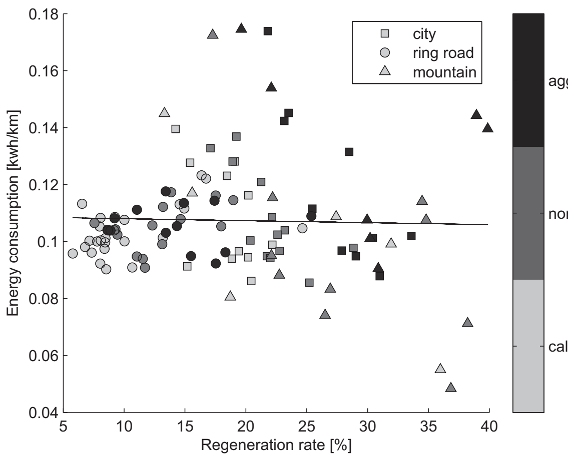

Fig. 4. Energy consumption as a function of battery regeneration rate. Each point represents a driving cycle. The form indicates the route type (city, ring road or mountain), and the color indicates the corresponding driving style (calm, normal or aggressive). The solid line represents the linear regression between the two factors.

like the maximum and the average speed, the average and standard deviation of acceleration (a^+) and deceleration (a^-), and the percentage of time in idle mode depend significantly on the route type. PKE, RPA, RMS(PF) and Jerk$_{std}$ are more or less correlated with the driving style. The higher the value, the more driving aggressiveness. Regeneration rate is maximal in mountain because of the downhill. In addition, this rate is very high in city due to frequent braking manoeuvers. We can notice that, even if the regeneration rate is high in city (27.42%), the corresponding driving efficiency is the worst (1.54 km/SOC). For ring road, the regeneration rate is low (9.8%), however, the driving efficiency is better than that in city

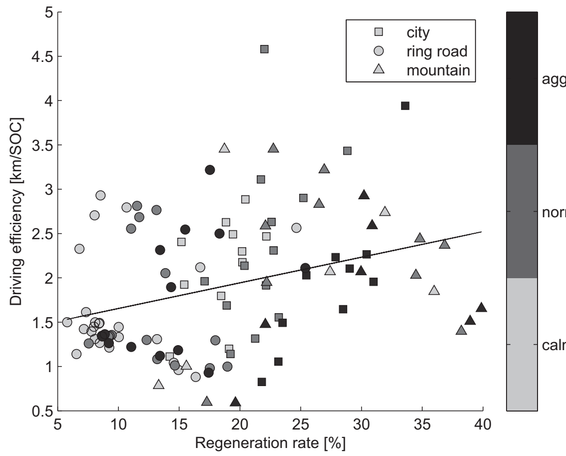

Fig. 5. Driving efficiency as a function of battery regeneration rate. Each point represents a driving cycle. The form indicates the route type (city, ring road or mountain), and the color indicates the corresponding driving style (calm, normal or aggressive). The solid line represents the linear regression between the two factors.

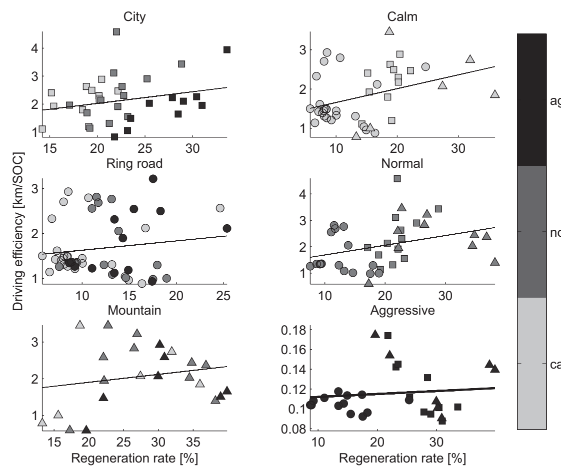

Fig. 6. Driving efficiency as a function of battery regeneration rate for each type of route on the left (city, ring road and mountain), and for each driving style on the right (calm, normal and aggressive). The solid lines represent the linear regression between the two factors in each case.

(1.73 km/SOC). In this case, it can be explained by the fact that the regeneration process is not really efficient because of a lot of losses during the electric power transmission. In addition, we can remark, as expected, that the energy consumption in city is more important than that on ring road, and by adopting a calm driving style, we consume less energy.

III. Study of the Energy Consumption

In this section, experimental results about the influence of some factors on energy consumption, and parameters suitable to identify the route type as well as the driving style are reported.

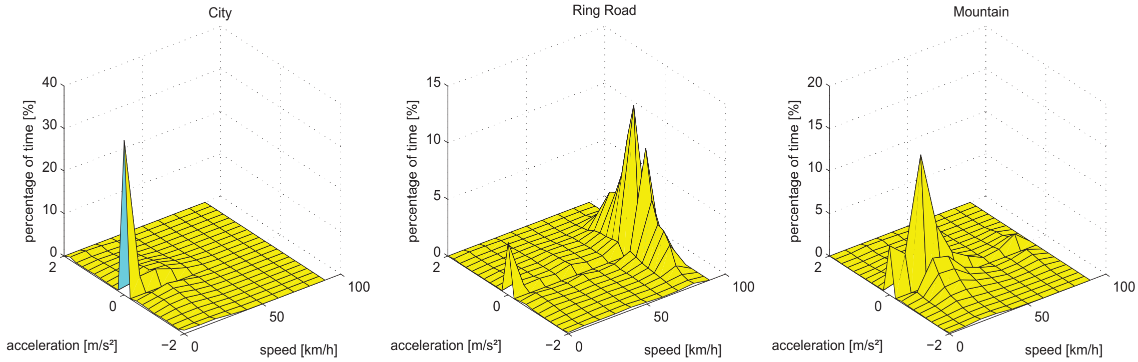

Fig. 7. Speed-acceleration distribution for three types of route: city (left), ring road (middle), and mountain (right).

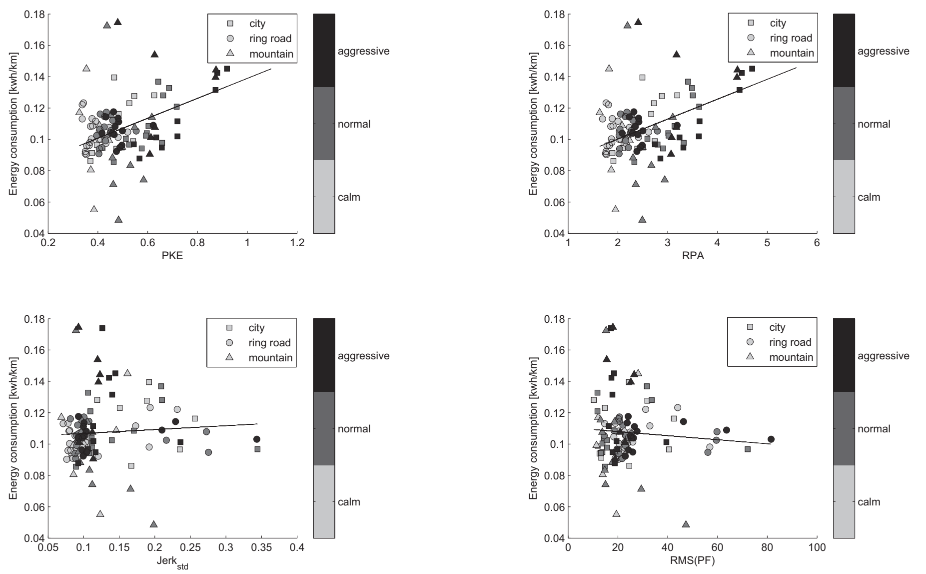

Fig. 8. The energy consumption as a function of PKE (left-up), RPA (right-up), the standard deviation of the jerk profile (left-down), and the root mean square of the power factor (right-down). Each point represents a driving cycle. The form indicates the route type (city, ring road or mountain), and the color indicates the corresponding driving style (calm, normal or aggressive). The solid lines represent the linear regression between the energy consumption and each of the four parameters.

A. Ambient temperature

The ambient temperature may greatly affect the energy consumption as said in the introduction. To demonstrate this fact, Figure 2 shows the influence of the ambient temperature on the energy consumption. For more clarity, Figure 3 shows this influence depending on the type of route and the driving style. Linear regression was used in order to show the relation between these two factors (solid line). We can remark that generally when the temperature decreases, the energy consumption increases as expected. It is known that as the ambient temperature decreases, the battery ability to deliver and receive current is reduced, and this ability goes up as the temperature rises. In addition, it is demonstrated that even though battery capacity at high temperatures is higher, battery life is shortened [8]. Apart the the influence of ambient temperature on battery performance, when it's cold, we generally tend to use air heating system, which requires additional energy demand. On the other hand, when it is hot and that vehicle windows are opened, the vehicle requires more energy when driving at a high speed to compensate the air resistance.

B. Battery regeneration rate

As said before, the vehicle used to collect data is an AX Citroen full electric car where the motor switches to generator mode when the acceleration pedal is released or when braking. From Figure 4 and

Figure 5, we deduce that the regeneration rate is not really correlated to the energy consumption, but it is more or less correlated to the driving efficiency. Figure 6 show that the correlation between the driving efficiency and the battery regeneration rate remains valid for each type of route and for each driving style. Generally, the more the regeneration rate, the more the driving efficiency. We have to mention that in general, depending on the energy regeneration system of the electric vehicle, maximizing the regeneration rate does not necessarily means that the driving efficiency is maximal, because of the losses in power electronics and during energy conversion.

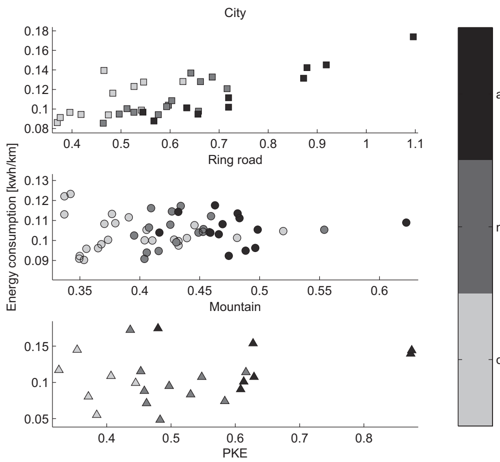

Fig. 9. Energy consumption as a function of the PKE parameter for each type of route: city (top), ring road (middle), and mountain (down). Each point corrsponds to the pke value over a driving cycle. The color indicates the driving style (calm, normal, or aggressive).

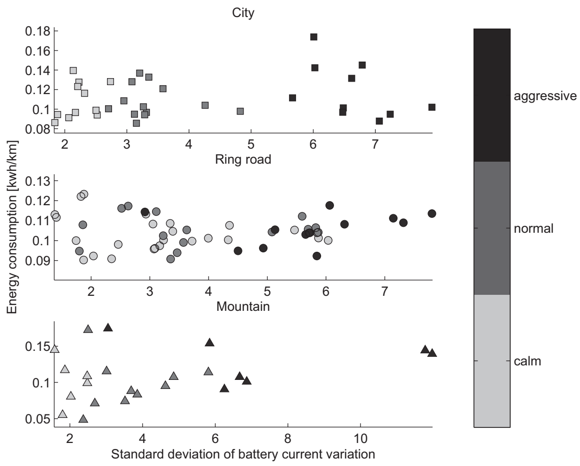

Fig. 10. Standard deviation of battery current variation for each route type: city (top), ring road (middle), and mountain (down). Each point corrsponds to the pke value over a driving cycle. The color indicates the driving style (calm, normal, or aggressive).

C. Parameters correlated to the route type and the driving style

As shown in Table I, parameters like the maximum and the average value of the speed profile, the average value of acceleration, the percentage of time in idle mode are very dependent on the route type. A simple way to take into consideration these parameters at once is to use the speed-acceleration distribution [4]. For a given driving cycle, this distribution represents the percentage of time spent driving at certain speed and acceleration. Figure 7 shows the speed-acceleration distribution after taking into account the whole recorded driving cycles corresponding to each of the three route type considered here: city, ring road and mountain. We can note that by just using this distribution, we can easily distinguish the type of road. In city, most of the time the speed is less than $50\ km/h$ with limited acceleration and deceleration, while on a ring road, the driving speed is generally greater than $50\ km/h$ with a lot of speed variation. For mountain, a simple way to differentiate it from the other route types is to use the difference of altitude.

As regards the driving style, the differentiation between the three styles, calm, normal and aggressive is a more difficult task. Let us consider the following parameters: PKE, RPA, the standard deviation of the jerk profile, and the root mean square of the power factor. Figure 8 shows that the energy consumption is generally correlated to PKE and RPA, while it is not the case for the two other parameters. In addition, PKE and RPA seem to be suitable to differentiate between the three driving styles once the type of route is identified. To illustrate this point, let take a view on Figure 9 that shows the energy consumption as a function of PKE for each type of route: city, ring road and mountain. In general, as the driving is more aggressive with a lot of raw speed variation, the PKE value is higher. For example, in city and mountain, if PKE value is over 0.65, the driving style is aggressive, and if the value is less than 0.45, the driving style is calm. The same results are observed for the RPA parameter.

Another parameter that can be used to identify the driving style is the standard deviation of the variation of electric current delivered by battery. This factor represents the driver activity on the acceleration pedal, and depending on the route type, it is closely correlated to the driving style as shown in Figure 10. For example, in city, if the value of this factor is more than 5, the driving style is aggressive, and if it is less than 2.5, the driving style is calm.

IV. Discussion and conclusion

In this paper, the energy consumption of electric vehicles was investigated based on real-world data collected using a full electric car with various driving conditions (different ambient temperature ranges, different route types, and different driving styles). To characterize each of the recorded driving cycles, different parameters has been presented such as the speed-acceleration distribution, the regeneration rate, the driving efficiency, the positive kinetic energy parameter, the relative positive acceleration parameter, the standard deviation of the jerk profile, and the root mean square of the power factor.

The ambient temperature has an important impact on the energy consumption. As the temperature decreases, the energy consumption increases. This fact has been observed by considering different types of route and different driving styles. In addition, it has been shown that in city, the energy consumption is more important than that on ring road because of the frequent stop and start driving. On the other hand, the energy consumption is reduced when privileging a calm driving style with smooth pedal motions and constant moderate speed.

The ambient temperature can be directly measured, which is not the case for the route type and the driving style. Therefore, we have shown that by considering some of the parameters used to characterize a driving cycle, it is possible to differentiate between the different types of route (city, ring road, and mountain), and the three driving styles (calm, normal, and aggressive). The experimental results demonstrate that there is no one parameter that allows us to distinguish both the driving style and the route type at once, and to recognize the driving style, it is necessary to identify the type of route in a first time. The identification of the route type can be made by simply using the speed-acceleration distribution and the difference of altitude. While for the identification of the driving style, the results show that parameters like PKE, RPA and the standard deviation of the variation of battery current are suitable to differentiate between the three styles, calm, normal and aggressive, depending on the type of route.

Finally, note that in the experiments presented in this paper, the values of the different parameters reported here are computed by considering the whole recorded driving cycles. However, this study is suitable for online application: in order to determine the energy consumption in real time as well as the driving style and the route type, the relevant parameters may be computed on segments of the buffered signal data during a driving cycle. This problem will be investigated in a future paper.

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