Development of driving cycles for electric vehicles in the context of the city of Florence

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Abstract: Use cycles represent one of the main input in any design activity; within automotive engineering strong efforts are spent for the creation of so called driving cycles. Vehicle driving cycle development has been a topic under research over the last thirty years, since it is a key activity both from an Authority and from an industrial research point of view. Considering the innovative characteristics of EVs and their diffusion on certain contexts (e.g. city centers), the demand for tailored cycles arises. A framework for driving data analysis has been developed through the review and the selection of known literature experiences, having as a goal the application on a case study. A measurements campaign in the city of Florence has been conducted; three different EVs categories have been monitored through a non-invasive data logging system. After data acquisition, time series have been processed for filtering and grouping. A method used for cycle synthesis based on general statistical competencies has been proposed and used for the generation of new cycles. The main product of the activity consists of a set of representative driving cycles for which only data coming from EVs are used. A comparison between existing cycles shows that typical driving pattern indicators are coherent with new cycle ones; a few differences are noticed. Another product of the activity is a software package which can be used to generate cycles within simulation environment, thus making accessible not only the synthetized cycles but, under certain boundary conditions, the whole measured data.

Highlights

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- The study deals with Driving Cycle development for Electric Vehicles
- A review of the driving cycle analysis, synthesis and use methods is presented
- The results from driving data acquisition under naturalistic conditions are presented
- A personalized method is developed and used to process the data
- A set of Electric Vehicle cycles is presented as final product
- A tool for “batch” cycle synthesis under tailored conditions is also presented.

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Abstract

Use cycles represent one of the main input in any design activity; within automotive engineering strong efforts are spent for the creation of so called driving cycles. Vehicle driving cycle development has been a topic under research over the last thirty years, since it is a key activity both from an Authority and from an industrial research point of view. Considering the innovative characteristics of EVs and their diffusion on certain contexts (e.g. city centers), the demand for tailored cycles arises. A framework for driving data analysis has been developed through the review and the selection of known literature experiences, having as a goal the application on a case study. A measurements campaign in the city of Florence has been conducted; three different EVs categories have been monitored through a non-invasive data logging system. After data acquisition, time series have been processed for filtering and grouping. A method used for cycle synthesis based on general statistical competencies has been proposed and used for the generation of new cycles. The main product of the activity consists of a set of representative driving cycles for which only data coming from EVs are used. A comparison between existing cycles shows that typical driving pattern indicators are coherent with new cycle ones; a few differences are noticed. Another product of the activity is a software package which can be used to generate cycles within simulation environment, thus making accessible not only the synthetized cycles but, under certain boundary conditions, the whole measured data.

Keywords: Driving cycle, grouping, speed, electric vehicles, regeneration, random walk

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Glossary

BEV: Battery Electric Vehicle

EV: Electric Vehicle

FEV: Fully Electric Vehicle

GHG: Greenhouse Gases

HEV: Hybrid Electric Vehicle

ICE: Internal Combustion Engine

LDV: Light Delivery Vehicle

NEDC: New European Driving Cycle

SAPD: Speed Acceleration Probability Distribution

WLTC: Worldwide harmonized Light vehicles Test Cycles

1 - Introduction

A driving cycle can be considered as a part of a standardized procedure aimed to evaluate vehicle performance in a reproducible way under controlled or laboratory conditions, such as simulation environment, power–adsorbing chassis dynamometer, testbed and sometimes road track. It has to include a time–vehicle speed signal as main input data, but a large set of boundary conditions can be also defined: dynamometer settings, gear shifting points, reference atmospherics conditions, vehicle conditions (tyre pressure, lighting, oil viscosity, transported mass..), “cold start” conditions (critical, for different reasons, both for ICE and EV vehicles) and any other parameter influencing the performances of the product under test.

According to the large differences in terms of driving habitudes, user needs, road characteristics and others it is known that the exact duty cycle to be satisfied during the life of a certain vehicle is not fully predictable. It is therefore probable that a single “driving cycle” cannot represent all the possible conditions on which the vehicle could be used during its life, but that some kind of compromises are needed. Despite of the fact that the research and the standardization process started in the early ‘70s, the definition of driving cycles is still a topic under development in scientific and technical literature.

The aim of the activity presented in this paper is to propose a group of driving cycles which are suitable for EVs; the study includes the definition of a procedure for driving cycle definition and the description of its application on a case-study. The document is structured as follows: section 1 introduces the topic, proposes a brief review of literature information and recalls state-of-the-art experiences; section 2 deals with the definition of a procedure for data analysis and cycle synthesis; section 3 describes the tailored approach developed and its application to a real case study, including data acquisition on the city of Florence (Italy); results and conclusions are then presented.

1.1 - Driving cycles

In the legislative context, type approval procedures include scheduled tests over standardized driving cycles. The assessed parameters are mainly related to the evaluation of the environmental impact of the vehicle; in case of ICE ones, in fact, since the early 1970 years the attention has been focused on air pollutants and, recently, on GHG emissions, according to Regulation EC No 443/2009. Currently a very large number of driving cycles are used worldwide for homologation: e.g. EU cycles, US cycles, Japanese cycles and many others (Barlow et al., 2009). Legislative ones also differ on the basis of the class of the vehicle to be tested; main procedures have been defined for M-class passenger cars, light or heavy duty N-class vans or trucks, L-class vehicles such as quadricycles (distinguishing between low and full power ones) and motorcycles. These cycles often include more subphases which are aimed to represent low and high speed sequences, or, from another point of view, different driving areas such as urban, rural or motorway roads.

As explained since the presentation of early research articles on the topic, Driving Cycles are built on the basis of the processing of real-world measurements (Kenworthy et al., 1992; Lyons et al., 1986; Newman et al., 1992). Depending on the resolution used to describe the synthetic cycle, the driving sequences can include or not the irregularities in speed which are typical of real-world driving by the users; as an extreme, smoothing and decimation of the curves can result in driving sequences composed by straight lines on the time-speed charts, thus corresponding to constant or zero acceleration phases. The widely used NEDC cycle is one example of such approach, even if, according to recent trends, the newly defined WLTC cycle (UNECE, 2015) is going to be used for type approval on next years, improving the representativeness of tailpipe emissions and fuel consumption assessments. Recent literature papers on the topic agree on the opportunity of such introduction (Demuynck et al., 2012; Sileghem et al., 2014; Weiss et al., 2012).

In general, a large number of factors are acting on vehicle energy consumption and on the related emissions, including driver capabilities, driving context, traffic conditions, ambient temperature etc.: such variability is the reason determining the need for extensive testing on the road of any kind of vehicle during its final development phase. Using appropriate parameters to evaluate the characteristics of driving cycles, the evidence explained in literature is that local or regional conditions can differentiate driving patterns depending on the area under examination (Lin and Niemeier, 2003; Wang et al., 2008).

Therefore, in addition to the standardized cycles used for type approval, experiences in applied research show a wide variety of data which are aimed to improve the representativeness of emissions assessments and, in some cases, are directly used during product development. In order to reduce the cost of such critical phase, virtual and testbed testing procedures are performed, and in this controlled contexts a representative driving cycle is needed as input. The cycles can be defined depending on:

- load patterns (including continuous or transient speed phases)
- context of applicability (urban, extra urban, motorway)

- expected vehicle mission profile (e.g. private passenger use, freight delivery, bus service, etc.).

Car manufacturers usually perform activities on driver and cycle characterization in order to improve their own knowledge on representative test sequences, both using methods for driving cycle synthesis after acquisition on real-world use (Borgarello et al., 2010; Ma and Andreasson, 2007) and experimental test using professional drivers on controlled track conditions (Capitani et al., 2003). Tailored driving cycles have also been prepared to consider special applications for which general cycles are not suitable (Han et al., 2012) or to assess the behavior of a particular vehicle category on a known path, e.g. motorcycles on typical home-work routes (Saleh et al., 2009).

1.2 - Use patterns and cycles for Electric Vehicles

In most recent formulation of homologation procedure (see UNECE Regulation 101), the procedures to evaluate the performances of FEVs have been introduced, e.g. through the use of weighting formulae for the assessment of electric energy and combined fuel consumption in case of HEVs. However, FEVs introduce new parameters for the evaluation of their performances and are affected by specific criticalities in comparison to conventional vehicles. A brief list of such new factors includes:

- the possibility of energy recovery during braking, which could induce the drivers to modify their style in order to optimize the energy consumption according to this feature, e.g. reducing as much as possible the use of mechanical brakes on “smooth” deceleration; regenerative braking, in particular, has been identified as a key element for the overall EV efficiency, especially in certain driving contexts (Travesset-Baro et al., 2015)
- the range is usually below a value of about 150km on optimal conditions for most EVs currently on the market; the limitation could induce drivers to particularly smooth, benign driving style under specific conditions as occasionally high daily distance driven or unavailability of charging points; such boundaries can also determine the so–called “range anxiety” phenomena (Neubauer and Wood, 2014)
- a different perception of vehicle performances, due to different acoustic sensations, throttle feeling, and torque availability from the powertrain in comparison with conventional ICE vehicles
- a different sensitiveness of the vehicle to the use of auxiliary systems, which could reduce the range up to 50% (Geringer and Tober, 2012) .

A particular cycle developed for Electric Vehicles is available in literature (Alessandrini and Orecchini, 2003); the same study also highlighted that the characteristics of electric vehicles can induce a driving pattern somehow different from those adopted on conventional vehicles by the same users, such as:

- the frequent occurrence of moderately strong accelerations, especially at low speed, even for non–aggressive drivers; this can happen due to human perceptions in terms of reduced noise, that is typical of electric traction systems
- the low peak power reduces aggressiveness on moderate or high speed; this occurrence could be related to the vehicle used in the cited study. For latest N1 or M1 class EVs maximum power

is usually comparable with similar conventional vehicle; this observation, however, can still be appropriate for low powered vehicle such as electric quadricycles.

The cycle has been reported to be almost unique at least until 2011 (Chaudhari and Thring, 2011), while even recent works, which are aimed to assess the applicability of real world cycles on EVs, have been using time-series data acquired from conventional ones (Ozdemir et al., 2014).

Recent works on EVs are also aimed to characterize the users on the basis of their needs and habitudes in order to verify the suitability of EVs for general purpose use; in particular, the characterization of so-called “trip chains” (Primerano et al., 2008) has been studied both in Europe (Pasaoglu et al., 2014) and USA (Krumm, 2012; Van Haaren, 2011); trip-chaining is fundamental in, fact, in order to identify charging opportunities for EV users (Smith et al., 2011). Results on the use of electric vehicles by a panel of drivers have been published, and the data reported are useful to complete the duty cycle definition together with general use information such as charging habitudes (Adornato et al., 2009; Smart et al., 2013); field operational tests also offer the opportunity to rank powertrain use patterns on the basis of intensity and context identification (Liaw and Dubarry, 2007; Shankar et al., 2012).

2 - Development of driving cycles

A number of different methodologies can be used for data acquisition and for their synthesis in a representative cycle; main approaches are well described in literature, as highlighted in a recent review (Tong and Hung, 2010).

2.1 - Driving sequences analysis

Numerical parameters are needed for the comparison of signals coming from different measurements. Since driving cycle are coming from some kind of synthesis algorithm, the identification of numerical characteristics of input data permits the possibility to validate the representativeness of the compressed cycles. One important limitation that is often taken into account is that the duration and/or the total length (in terms of run distance) of some driving cycles is limited by practical needs (e.g. for test–bed execution); typical durations are in the range of 500–1500s.

In this paragraph, numerical parameters will be reported using a few reference articles. It is possible to distinguish at least six main categories of driving segment/cycles parameters depending on their physical dimension: distance, time, speed, acceleration, stop data (e.g. % of time or event count), indicators of dynamics. Considering relevant experiences such as the ARTEMIS project , the full list of the parameters used includes 40 elements (André, 2004; Barlow et al., 2009); their list is provided on Table 1. In most research activities only a subset of such parameters has been considered; looking at literature works, the evaluation can be based on a reduced set of indicators, such as 22 parameters (Hung et al., 2007), 13 or 12 parameters (Kumar et al., 2012; Saleh et al., 2009).

Group	Parameter	Units
Distance related	Total distance	m
	Total time	s
	Driving time	s
	Cruising time	s
	Drive time spent accelerating	s
	Drive time spent decelerating	s
	Time spent braking	s
Time related	Standing time	s
	% of time driving	%
	% of cruising	%
	% of time accelerating	%
	% of time decelerating	%
	% of time braking	%
	% of time standing	%
	Average trip speed	km/h
	Average driving speed	km/h
Speed related	Standard deviation of speed	km/h
	Speed: 75th – 25th percentile	km/h
	Maximum speed	km/h
	Average acceleration	m/s^2
	Average positive acceleration	m/s^2
	Average negative acceleration	m/s^2
Acceleration related	Standard deviation of acceleration	m/s^2
	Standard deviation of positive acceleration	m/s^2
	Acceleration: 75th – 25th percentile	m/s^2
	Number of acceleration per km	[null]/km
	Number of stops	[null]
Stop related	Number of stops per km	[null]/km
	Average stop duration	s
	Average distance between stops	m
	Relative positive acceleration (RPA)	m/s^3
	Positiv kinetic energy (PKE)	m/s^2
	Relative positive speed (RPS)	[null]
	Relative real speed (RRS)	[null]
Dynamics related	Relative square speed (RSS)	m/s
	Relative positive square speed (RRSS)	m/s
	Relative cubic speed (RCS)	m/s
	Relative positive cubic speed (RPCS)	m^2/s^2
	Relative real cubic speed (RRCS)	m^2/s^2
	Root mean square of acceleration (RMSA)	m^2/s^2

Table 1 – Full list of indicators to describe driving cycles (Barlow et al., 2009; Tong and Hung, 2010).

During the analysis of the data, trip events (i.e. a driving sequence between key–on and key–off events) and microtrip ones (i.e. a sequence measured between two stops events) are identified. The numerical parameters above described offer an aggregate information of the average results of cycle analysis. In addition to this, the analysis of cycles on the basis of quantitative information can take into account a large set of data represented in the form of statistical distribution. Typical data can be calculated in terms of absolute indicators (e.g. distance driven or time spent over a certain condition) or in terms of relative frequencies (e.g. percentage of occurrence of a certain class of events). Regarding 2–variables distribution, a largely used method for cycle clustering and cycle build–up is based on the analysis of the distribution of events falling in a determined class of speed–acceleration couple, expressed as relative frequency of occurrence or as total time (De Haan and Keller, 2004). In case of the use of such information for the extrapolation of a new cycle, the relative frequency assumes the meaning of "probability" of a determined class; the definition used by some authors is therefore SAPD (Hung et al., 2007). The scope of distribution analysis is both related to data visual interpretation and to extended data processing; in particular, in case of creation of a new cycle using randomization methods, data distribution can used for the selection of sequences through random walk approaches, as described in next chapter (Lee et al., 2011).

The ability to group into categories the different segments of measured driving sequences is fundamental for cycle synthesis; clustering activities can be based on a vector of indicators such as those in Table 1 (Borgarello et al., 2001) or directly on SAPD. In this latter case, it can be needed to introduce a correction criteria on the acceleration values. In fact, considering that the occurrence of certain speed–acceleration couples on the whole range of possible values is very low or even zero, acceleration values can be artificially enhanced to improve the resolution of the SAPD. A suitable option is to multiply it by a factor that increases linearly from 1 at low speed to 2 at typical motorway speed (André, 2004; André et al., 2006). Other classification methods based on fuzzy logic are documented in literature (Liaw, 2004; Tong and Hung, 2010).

2.2 - Signal acquisition and treatment

The acquisition of data from vehicles usually can comprehend a large number of parameters. Tipically, values about dynamics can be obtained by accelerometers (e.g. inertial platforms used for multiaxial accelerations); together with GPS data such analysis can completely describe the kinematic of the vehicle and the context in which it is moving. However, logging of powertrain values can also be needed (e.g. rpm, speed, throttle position, engine parameters if ICE, battery/inverter/powertrain parameters if EV or HEV) especially in the case that the aim is to correlate emissions (directly measured at tailpipe) and driving style (Alessandrini et al., 2009) or to correlate traction power to probability of occurrence (Shankar et al., 2012). The availability of logging capabilities through cheap and wide diffusion devices such as car infotainment system and smartphones highlights new possibilities for the monitoring of driving attitudes (Gerardo and Lee, 2009); such data can be used for driver training through continuous learning (Beusen et al., 2009; Corcoba Magana and M unoz-Organero, 2011; Manzoni et al., 2010), thus promoting safe or fuel-saving driving styles. When preparing a vehicle for data acquisition, the naturalistic behavior of the drivers can be influenced by the use of highly instrumented vehicles; the relation has been clarified in literature considering former research experiences (Valero-Mora et al., 2013).

The minimum data acquisition frequency for vehicle speed should be at least 1Hz, that is also the value used for the time-speed signals defining most existing driving cycle; decimation at 1Hz has been suggested in defining driving cycle construction framework (Bishop et al., 2012). However, it has been demonstrated that vehicle energy consumption and efficiency can be evaluated with acceptable results using low sample rates (0.2 – 1Hz) if a compensation technique is provided, but that higher sampling rate (from 2Hz to 10Hz) provide more accuracy and reliability for vehicle efficiency characterization due to the possibility to better describe vehicle dynamics (Corti et al., 2012). During pre–processing of the data, the first need is to check the continuity of the information: data affected by strong cold–start uncertainties, that is typical of GPS devices, large signal lack or similar should be rejected. Also, if a fleet is monitored on naturalistic conditions, some events should be excluded from driving patterns analysis (e.g. parking phases). After that, the data signal should be appropriately filtered. Regarding GPS data, there are different suitable filtering methodologies, each one presenting advantages and disadvantages (Jun et al., 2006):

- Piecewise polynomial regression model
- Kernel–based smoothing methods
- Discrete Kalman filter
- Modified Kalman filter

In other experiences (Alessandrini et al., 2006) filtering techniques set at fixed cutting frequency are used; 0.5Hz is a typical value.

When studying the characteristics of typical driving patterns of a certain fleet, there are two main alternatives for the selection of drivers panel and of their route: on board measurement of vehicle/fleet monitoring and “chase” car approach. The reliability of the first method is related to the size and the characteristics of the monitored fleet itself. The more varied data are acquired (number of drivers, of vehicles, distance run), the more the acquired data are appropriate to fit the real characteristics of the fleet under study. A large data collection could be therefore necessary. The second method is widely used for the acquisition of data in order to represent the characteristics of the driving style on a specific area, e.g. to identify local driving patterns. Car chasing consists in following a “target” vehicle, initially randomly selected, with another vehicle; as soon as the chased vehicle stops or is loss, another vehicle is selected. A trained driver is therefore needed, while the measurement is performed on the chasing vehicle even if the characterization is related to the “target” vehicle. The main advantage of the method is the possibility to acquire a large amount of data related to a population within its operating area, while the main disadvantage is the risk of data deformation: chased and chasing vehicle transient speed difference could occur, or chasing vehicles could interfere with chased vehicle, thus influencing the driving style.

2.3 - Synthesis of driving cycles

According to an early but still applicable definition (Lyons et al., 1986), during the synthesis of a new cycle a “compression” algorithm has to be defined; in general a time–speed history of “real” driving data is selected and assembled in such a way that it matches the overall characteristics of the data set. Summarizing, the parts selected and processed to build the representative cycles can include sequences or reduced trips along a particular route, or a number of randomly matched microtrips from the data.

From early works, a large number of applications of similar or improved methods has been proposed. A synthesis method, however, is usually composed by four main phases:

- the processing of the data, through calculation of kinematic indicators and distribution data; when applicable, partial data (events) are grouped in different classes, each representative of a certain typical driving sequence such as urban, rural, smooth, aggressive
    - events can include “modal events”, such as i.e. acceleration, deceleration, cruise and idle driving segments, or full microtrips segments, or partial microtrips segments
- using the available database of driving sequences and of the associated kinematic parameters, a number of events is randomly selected according to the desired characteristics of the cycles; for general representativeness, a suitable method is to choose events from each group, maintaining

the same proportion in terms of distance or duration that was identified between group data and total measured data

- the elements are randomly “glued” according to “matching” criteria
    - a criteria to order the transitions from a certain driving sequence to another, as well as for the transition from a recognizable driving pattern to another (e.g. from city to highway and then to city again, as typical), can be used; such random walk can be created on the basis of a transition probability matrix, so that typical methods for Markov chain creation are applied (Bishop et al., 2012)
    - the coherence in terms of final speed of the preceding segment to the speed of its next segment has to be complied; as an example, in case of microtrips linking, speed is zero, so that the juxtaposition of events requires only the proposal of a duration for stop phase and, in some cases, an acceleration value for the next event
- as soon as the target duration or distance has been reached, a verification of the representativeness of the cycle is performed according to appropriate control parameters.

All the phases, depending on the goodness of fit of the compressed cycle in comparison with objective parameters, can be repeated from the beginning in trial-and-error processes. Various randomization methods have been used in literature, as summarized in previous works (Esteves-Booth et al., 2002; Tong and Hung, 2010).

2.3.1 - Control parameters

In general, the synthesis procedure is iterated several times to obtain the satisfaction of basic matching condition. A general indication to be respected is (Hung et al., 2007):

$$\forall \vartheta_t \in \bar{\vartheta}_t, \left[\frac{\vartheta_t - \vartheta_i}{\vartheta_t}\right] < threshold$$

Where $\underline{\vartheta}_t$ is the vector of the indicators (see Table 1) calculated for the main dataset and $\underline{\vartheta}_i$ is the same vector calculated for the synthetic cycle; the choice of the parameters to be included in the vector $\underline{\vartheta}_t$ can vary depending on the author. After that a number of possible candidate cycles are defined, additional confrontation parameters can be calculated, in order to let the user select the one having most favorable ones. Typical quantitative values are:

- Performance Value (PV), that is the scalar product of the difference between $\underline{\vartheta}$ vectors with a weighting vector:

$$PV = \left|\bar{\vartheta}_t - \bar{\vartheta}_i\right| \cdot W^T$$

    - an example of PV definition is (Lin and Niemeier, 2003):

$$PV = |\Delta\bar{v}| + |\Delta\bar{a}| + |\Delta v_{max}| \times 0.1 + |\Delta v_{min}| + |\Delta a_{max}| + |\Delta a_{min}| + |\Delta\%_{idle}| + |\Delta\bar{P}_d| + |\Delta v_{95}| + |\Delta a_{95}| + |\Delta P_{95}|$$

- Sum Square Difference – SSD – of SAPDs, that is the summary of quadratic product of the probability of each class of speed (N_s) and acceleration (N_a) for the source data (p_{ij}) and the candidate cycle (q_{ij}):

$$SSD = \sum_{i=1}^{N_s} \sum_{j=1}^{N_a} \left(p_{ij} - q_{ij}\right)^2$$

As highlighted in literature, the longer the generated cycle, the smaller the distance between it and the original data (Waldowski et al., 2011).

2.3.2 - From driving cycles to sequence generator

According to those literature works related with development of vehicle management strategies (e.g. for HEV or PHEV, or for automatic transmissions on ICE vehicles), the importance of the availability of a large set of real world driving data is undoubted. The last trends in driving cycle definition methods show an evolution from the construction of synthetic cycles – that, after that moment, are somehow “rigid” – to the definition of a set of data which can be manipulated on the basis of probabilistic criteria (e.g. Markov chain approaches). This methods can improve the value of vehicle performance simulation, thus being suitable for the optimization of certain performances over non-repetitive cycles or for the build-up of predictive control techniques (Gong et al., 2012; Montazeri et al., 2012; Moura et al., 2011; Schwarzer and Ghorbani, 2013; Souffran et al., 2012). Data measured can therefore be used as a whole, as an historical dataset of driving situations; in Montecarlo applications, such databases can be used for the execution of a batch of simulations and/or experiments getting randomly extracted data from a suitable space. If a database of driving sequences is available for consultation and processing, each simulation can use a newly extracted driving cycle, exploring a large part of possible driving situations space. The present work also includes a proposal for the extended use of all acquired data.

3 - Case study: the city of Florence

This chapter describes the acquisition of data from EVs circulating in the city of Florence (Italy) and their use for generation of a new group of driving cycles. Florence is located in the central area of Italy, it is a Large city according to Eurobarometers criteria, its population being about 380.000 inhabitants for the municipality and about 1 million of inhabitants for its Metropolitan area (formerly defined as Province). The city applied in the last years a number of limitations for motor vehicles, including parking fares (on the whole city) and restricted access to central historical area, including large pedestrian zones. EVs are not subjected to restricted access and can also be driven on some of the pedestrian areas. A low power charging infrastructure is also available (about 110 points, for a total availability of about 450 plugs).

The first aim of the development of a driving cycle for the Florence case study is to include all the peculiarities of driving in an historical city in a synthetic time–speed cycle (or a number of them) using only data coming from EVs. A second aim is to make the dataset of acquired data available for processing in other applications as a source of driving data, as explained in paragraph 2.3.2.

3.1 - Description

The data acquisition took place on vehicles which were used during their normal service both for private and business use. The speed of the vehicles, together with other powertrain information, have been acquired from on-board diagnostics; GPS data have been used mainly for geo-referencing and identification of suitable driving sequences when manually examining the data in post processing. The acquisition sessions took place for nine months on 2013 in the city of Florence (Pfluegl et al., 2015). The usable acquired data comprehend about 2500 km. It is notably to say that all the users and the owners declared that the one of the main reason for the use of electric vehicles was determined by the necessity to drive within the restricted traffic area of the city.

Large part of the acquisition included data coming from vehicles used by a freight delivery company in city context, a service similar to post delivery. The vehicles include light vans (Renault Kangoo ZE, M1 class vehicle, electric, curb mass about 1400kg) and quadricycles (Renault Twizy, L7e class, curb mass about 470 kg). The company owns a fleet of 15 electric vehicles in total, but, in general, not all the vehicles of the fleet are used every day, since this depends on the workload and on the availability of the drivers. As a consequence, the same vehicle can be used by different drivers. The use of the fleet was quite intense and the required range in some days exceeded the capability of the vehicles, so that they were charged everyday: charging during night was always performed, while partial charge during the day was also done frequently (e.g. at lunch break). It is important to note that due to the availability of a charging infrastructure in Florence – even if suitable only for low power charging solution due to the presence of single phase plugs, comparable with home plugs – some drivers use the vehicles to go home, then park and charge there. Such kind of trips can be longer than usual delivery trips (e.g. some systematic runs of about 10-15km in morning and evening hours have been recognized); it was chosen not to exclude this data from analysis.

Another part of the data are related to passenger transport. Two types of vehicles have been used: the already cited Renault Twizy and the electric passenger vehicle of the PSA group (Peugeot iOn or Citroen C–zero). Three different cars of this type have been monitored, including one used by the members of a family for their daily needs (home – work trips, personal needs, weekend trips – but in this case, only if the expected distance is below about 100 km) and other two owned by a company and used by the workers for their movements within urban and suburban area. For this latter, most trips were systematic, being between two different sites of the Company (from city center -that is a pedestrian area accessible to EVs- to the peripheral area of Florence).

3.2 - Data post processing and synthesis

The first step of the analysis included speed data filtering for the elimination of "spikes" or of any irregular data. Data have been acquired at a rate of 4 Hz, than a kernel filter – as described in section 2.2 – has been applied, considering a time interval of one second. An example of speed signal smoothing through this method is shown on Figure 1.

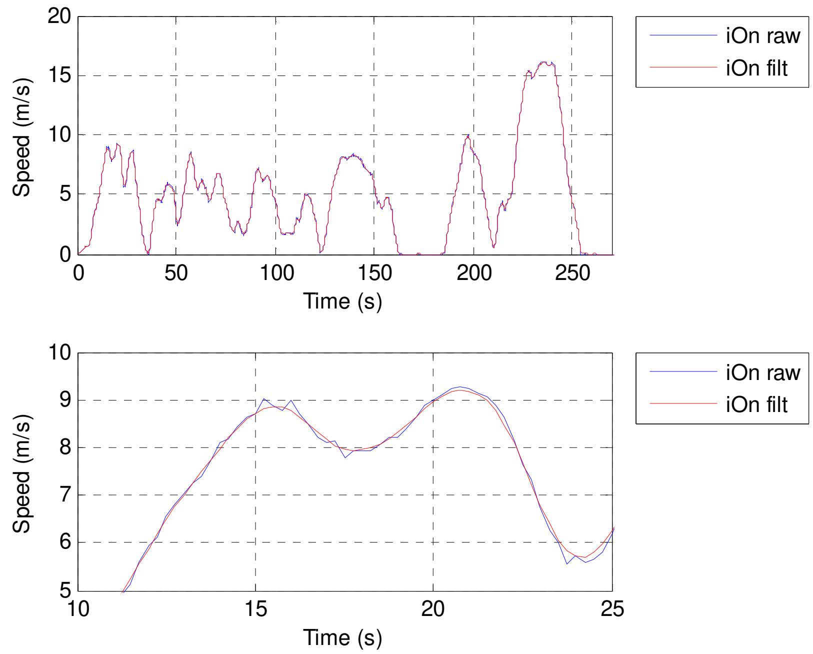

Figure 1 – Upper plot: a portion of speed measurement for iOn passenger vehicle, showing a comparison between raw and filtered data. Lower plot: a detail coming from the same measurement.

The second step of the analysis included the grouping of the data in different categories. The main strategy adopted is to identify in each mission (or trip) the sequences between two events of speed being equal to zero (microtrips); after that, for each microtrip two different sets of parameters were calculated:

- a vector of indicators, that is a selection of those adopted in literature (see Table 2)
- a speed–acceleration density matrix.

Regarding the vectors (edges) used for the calculation of SAPD matrix, the limit values have been selected considering the maximum values measured (about 30 m/s for speed and 2.5 m/s2 for acceleration); the first speed class includes only very low speed (from 0 to 0.1 m/s2) to identify zero speed phases.

Two calculation methods have been adopted for mean positive and negative accelerations:

- the first method calculates these values considering the same threshold used for cruise and acceleration time percentage calculation. In other words, each value of is coherent with the related others (e.g. mean positive acceleration value is calculated for those phases which are considered effective acceleration phases);

- the second method does not consider any threshold for acceleration, thus the mean acceleration value is not perfectly coherent with acceleration time percentage; this criteria is applied only to perform a confrontation with some literature works.

Parameter	Unit	Note	Abbreviation
Duration	s		duration (s)
Distance	m		distance (m)
Percentage of idle time	%	a=0; v=0;	idle %
Percentage of cruise time	%	|a|< 0.05 m/s^2	cruise %
Percentage of positive acceleration time	%	a>0.05 m/s^2	acc %
Percentage of negative acceleration time	%	a<–0.05 m/s^2	dec %
Average speed	m/s		avg speed (m/s)
Average moving speed	m/s	v>0	avg mov speed (m/s)
Mean positive acceleration (a>threshold)	m/s^2	a>0.05	acc+
Mean negative acceleration (a< threshold)	m/s^2	a<–0.05	acc–
Root Mean Square of speed	m/s^2		RMS
Positive Kinetic Energy	m/s^2		PKE
Relative Positive Acceleration	m/s^3		RPA
Stop rate	–		stops/km
Additional parameters			
Mean positive acceleration (without using threshold)	m/s^2	a>0	acc+ noth
Mean negative acceleration (without using threshold)	m/s^2	a<0	acc– noth
SAPD edges			
Acceleration classes (51 classes)	m/s^2	from –2.5 to 2.5	
Speed classes (17 classes)	m/s	from 0 to 0.1 and from 0.1 to 30	

Table 2 – Parameters used for cycle characterization and grouping.

3.2.1 - Analysis and clustering of driving sequences

Before the application of a grouping algorithm on the data, a manual cleanup has been performed. Short distance microtrips have been identified, since they can include data which are not suitable for general driving cycle generation, such as incomplete microtrips (e.g. generated by a delay between vehicle key–on event and logging start), sequences including reverse gear maneuvers, small vehicle displacement (e.g. stop on traffic light without using brake pedal). The examination of total distance run at high speed (exceeding 25 m/s. which has been chosen as threshold) together with the comparison with GPS data (where available) confirms that no continuous motorway driving has been measured for the vehicles under study; however, short trips on interchange roads (similar to motorways) have been found. After preliminary selection, the microtrips have been subjected to grouping process. The selected algorithm is the k–means ones. The conditions used for partitioning are:

- each sample is described by SAPD density elements and by RMS, RPA and PKE element, that are all descriptors of microtrip speed and acceleration

- the k-means “distance” is calculated as correlation between points
- 9 different clusters have been determined.

The results of the grouping algorithms are shown in Table 3, which includes a selection of main parameters describing the microtrips included in the group and some notes describing the most probable driving situation for each cluster, whichis coherent with the scatter plot shown on Figure 2. A priori classification (e.g. on vehicle type, since three different have been used) has not been performed, so that each cluster can contain microtrips coming from different vehicles and drivers.

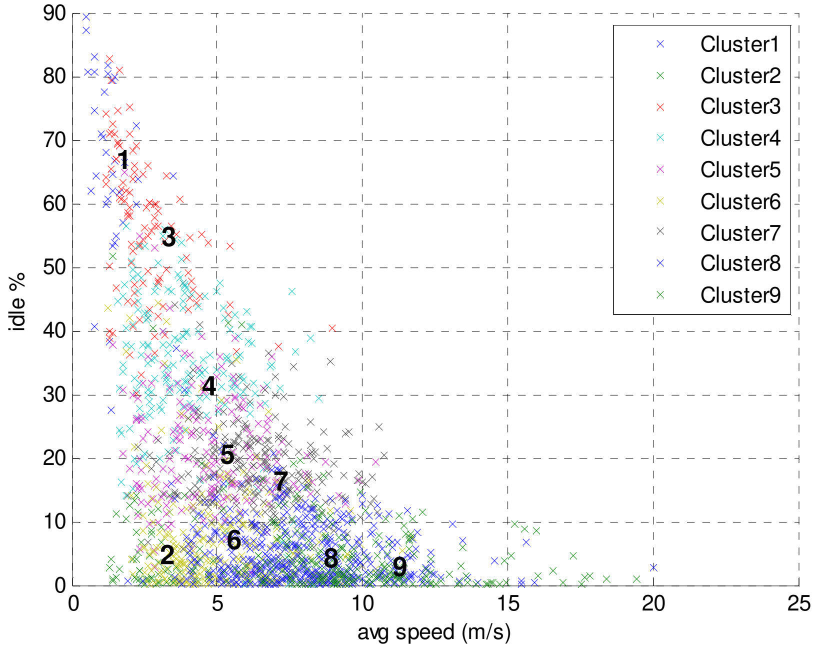

Figure 2 – Scatter plot representing average positive and negative accelerations for all cluster elements; centroids are indicated by numbers.

Number	Class	Stop notes	Speed notes	Avg mov speed	Avg speed	Stop duration	Stops/km	Acc+ nth	Acc– nth
				m/s	m/s	%	1/km	m/s^2	m/s^2
1	Urban	High stop duration	Unsteady	5.50	1.98	63.9%	3.34	0.57	–0.58
2	Urban	Low stop duration	Very low speed	2.55	2.39	6.2%	4.15	0.32	–0.30
3	Urban	Low stop duration	Low speed	4.19	3.95	5.4%	2.09	0.43	–0.41
4	Urban	Intermediate stop duration	Steady	6.83	4.31	36.7%	2.35	0.58	–0.59
5	Urban	Intermediate stop duration	Unsteady	5.99	4.31	27.8%	3.23	0.65	–0.64
6	Urban	Low stop duration	Unsteady	6.14	5.47	10.6%	2.04	0.65	–0.64
7	Urban	Low Stop duration	Steady	8.26	6.83	17.2%	1.24	0.53	–0.55
8	Urban – Main roads	Flow	Intermediate speed	9.01	8.63	4.0%	0.79	0.60	–0.64
9	Urban – Main roads	Flow, steady	Intermediate speed, steady	11.30	10.92	3.3%	0.44	0.44	–0.52
Manual identified*	Queue, manouvers	high stop duration	Very low speed	1.20	0.50	57.4%	318.00	0.43	–0.37

Table 3 – Summary of main descriptor parameters for each microtrip group. The name of the class and the notes in relation to the speed are assigned after the grouping and are not relevant for analysis.

Considering SAPD values that have been used for the definition of each group, it is possible to notice significant differences between the "patterns" of each cluster, as is shown in Figure 3.

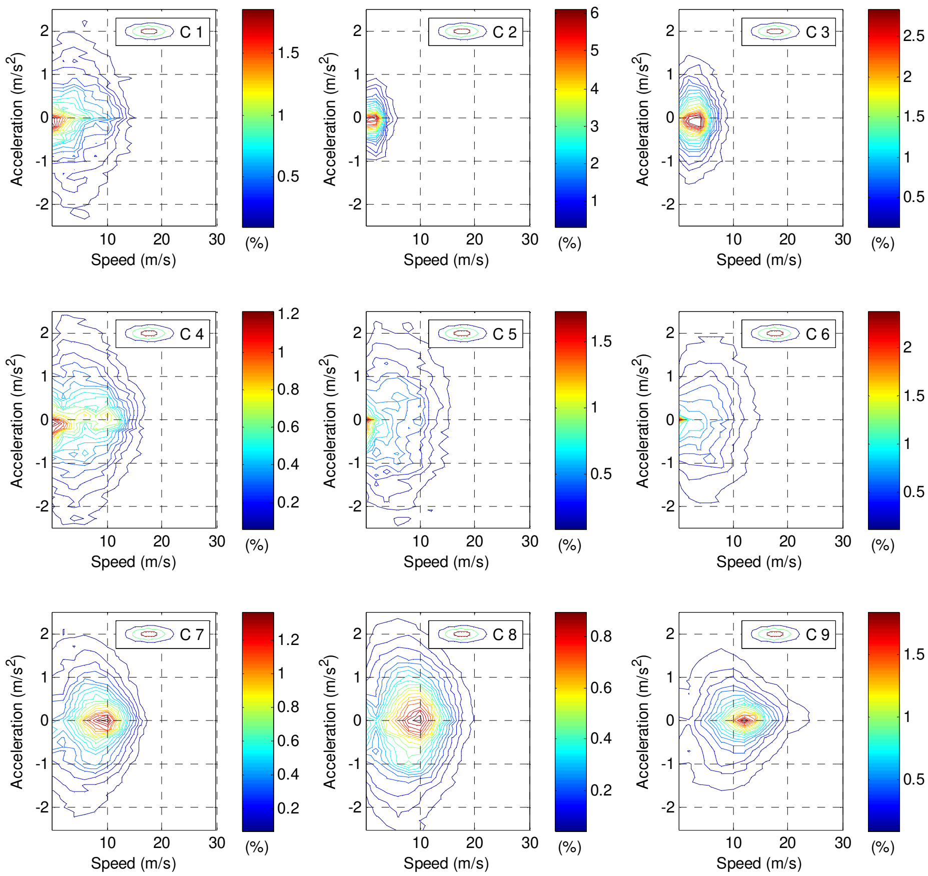

Figure 3 – SAPD contour plot for the microtrip groups described in Table 3; the plots do not include the point corresponding to idle phases (zero speed and acceleration) to avoid distortions due to its predominance.

3.2.2 - Customized driving cycles development

After grouping the microtrips, the creation process of a representative cycle consists of a first phase of "generation":

- the selection of the main group of microtrips to be used (e.g. only a certain vehicle or only a set of clusters)
- the selection of a target distance for the whole cycle
  - for each cluster, a target distance is set in order to maintain the same proportion of the original data set
- random microtrips from each group are selected, until the target distance for that cluster has been reached
  - if the addition of a certain microtrip causes the overcome of target distance, the microtrip is truncated on a random point and glued together with the final portion of another microtrip, maintaining coherence for speed, acceleration and jerk values (threshold being 0.1 m/s, m/s^2 and m/s^3 respectively); the junction between microtrips is repeated in an

iterative process if necessary. New microtrips, different from those part of the database, are therefore generated.

- all the chosen or generated microtrips are put beside each other, thus generating a cycle
- the process is repeated for a number of predetermined attempts.

After the generation of the attempt cycles, the final proposal cycle is selected on the basis of three main criteria:

1. considering the parameters of Table 2 (from number 3 to number 14), the differences between those of the original dataset and of the generated cycles have to be below a threshold (that is, 5%) for at least 11 over 12 values; about 0.5–1% cycles of the generated ones usually respect this condition for a distance of about 10–15km
2. for the reduced number of cycle chosen at the former point, those having similar PV are considered as candidate
3. for the remaining candidate cycles, the final one is that having lower SSD between SAPD matrix.

If a satisfactory cycle cannot be found (e.g. it is not possible to find a cycle having both low PV and low SSD in comparison with other cycles), the whole process is repeated generating new cycles.

Using this procedure, 10 different cycles have been generated. A summary includes:

- depending on the source of the data, 5 vehicle categories are considered:
  - all data from all vehicles are used, so that the cycle is representative of “average” electric vehicles; quadricycles data are included since, especially in urban driving, it is assumed that their performances are comparable with those of the other vehicles;
  - data from N1 passenger vehicles
  - data from M1 light delivery vehicles
  - data from quadricycles, so that the cycle is suitable for low powered vehicles
  - data from N1 and M1 vehicles, using only “unsteady” sequences as identified during clustering phase
- for each category, two different distances have been used:
  - “long” cycles are based on the 95th percentile trip distance; all the microtrip clusters are considered (excluding clusters 1, 2, 4 and 7 for unsteady cycle) and, therefore, also high speed phases can be included
  - “mean” cycles are based on mean trip distance, but clusters 8 and 9 are not used since their data also include quite “long” microtrips, by far exceeding the whole target distance.

Table 4 summarizes the information and the assumptions used for the driving cycle generation. The characteristic of the synthetic cycles are shown in Table 5. Figure 4 and Figure 5 show two of the generated cycles, including a comparison between the SAPD of original and synthetic data. The comparison between All vehicle SAPD and LDV vehicle SAPD highlights the more frequent occurrence of low-speed events for the latter one, as expected considering the typical needs of post services.

Finally, all the cycles are plot in Figure 6.

N.	Cycle name	Vehicles	Groups	Target Distance (km)
1	All long	All	1 to 9	12
2	All mean	All	1 to 7	6
3	Passenger long	N1	1 to 9	15
4	Passenger mean	N1	1 to 7	6
5	LDV long	M1	1 to 9	15
6	LDV mean	M1	1 to 7	4.8
7	Quadricycle long	L7	1 to 9	15
8	Quadricycle mean	L7	1 to 7	6
9	Unsteady long	M1 and N1	3, 5, 6, 8, 9	12
10	Unsteady mean	M1 and N1	3,5,6	6

Table 4 - Summary of the boundary conditions chosen for the cycles generation.

N.	Cycle name	duration (s)	distance (m)	idle %	cruise %	acc %	dec %	avg speed (m/s)	avg mov speed (m/s)	acc+ (m/s^2)	acc– (m/s^2)	stop/km	PKE (m/s^2)	acc+ noth (m/s^2)	acc– noth (m/s^2)
1	All long	1536	11566	13.7%	7.4%	40.6%	38.3%	7.5	8.7	0.60	–0.64	1.0	0.53	0.55	–0.59
2	All mean	1214	5837	24.0%	6.7%	34.6%	34.8%	4.8	6.3	0.63	–0.62	2.2	0.56	0.57	–0.57
3	M1 long	1835	15675	7.3%	7.6%	45.0%	40.1%	8.5	9.2	0.58	–0.65	0.9	0.51	0.54	–0.59
4	M1 mean	1277	6481	17.6%	6.7%	39.2%	36.6%	5.1	6.2	0.65	–0.69	2.2	0.64	0.60	–0.63
5	N1 long	2015	14017	19.3%	7.2%	37.6%	35.9%	7.0	8.6	0.64	–0.66	1.3	0.54	0.59	–0.62
6	N1 mean	1100	4755	31.3%	6.1%	31.7%	31.0%	4.3	6.3	0.64	–0.65	2.1	0.55	0.59	–0.61
7	L7 long	2028	15480	10.4%	7.8%	40.8%	41.1%	7.6	8.5	0.57	–0.56	1.0	0.46	0.52	–0.52
8	L7 mean	1076	6360	17.2%	6.9%	38.3%	37.7%	5.9	7.1	0.56	–0.56	1.7	0.46	0.51	–0.52
9	Unsteady long	1521	12854	6.2%	7.7%	45.5%	40.7%	8.5	9.0	0.61	–0.68	1.0	0.53	0.57	–0.63
10	Unsteady mean	1227	6082	12.7%	7.4%	40.0%	39.8%	5.0	5.7	0.67	–0.67	2.3	0.65	0.62	–0.61

Table 5 – Parameters of synthetized driving cycles

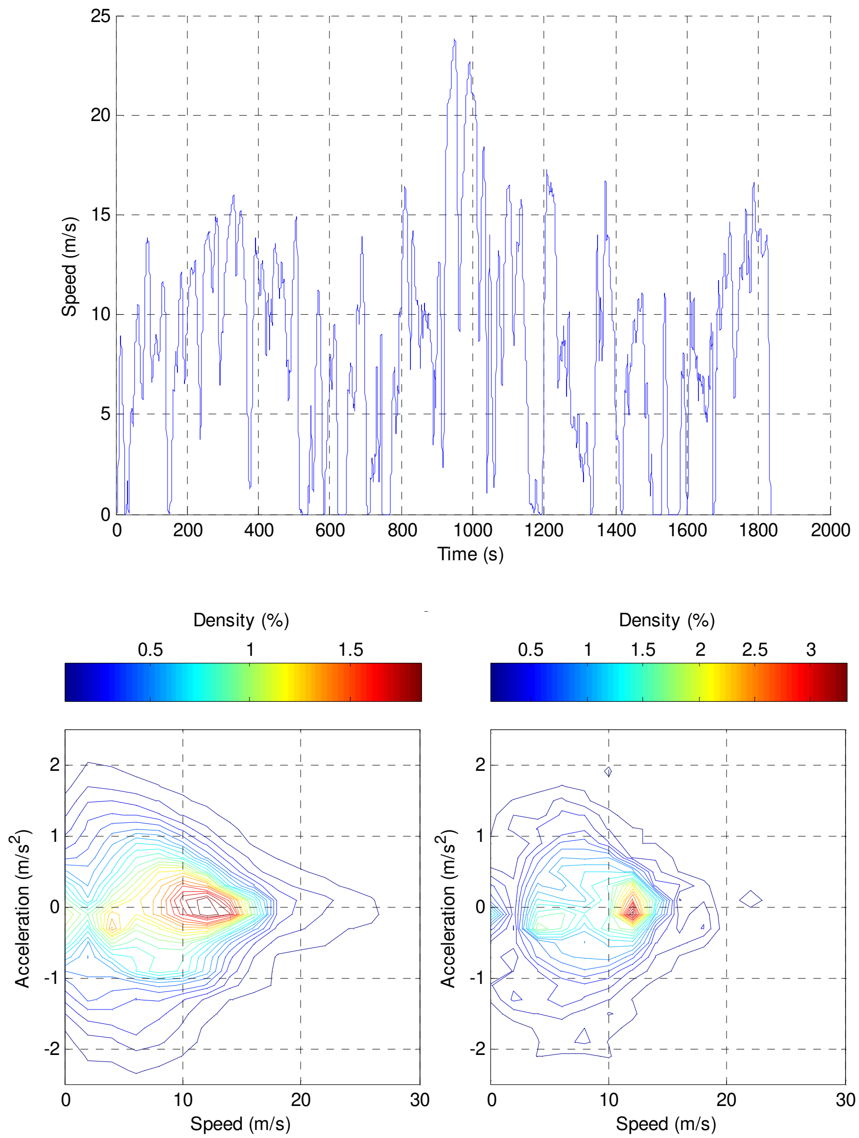

Figure 4 – Upper plot: "Passenger long" cycle. Lower plot: comparison between original SAPD (left) and cycle SAPD (right).

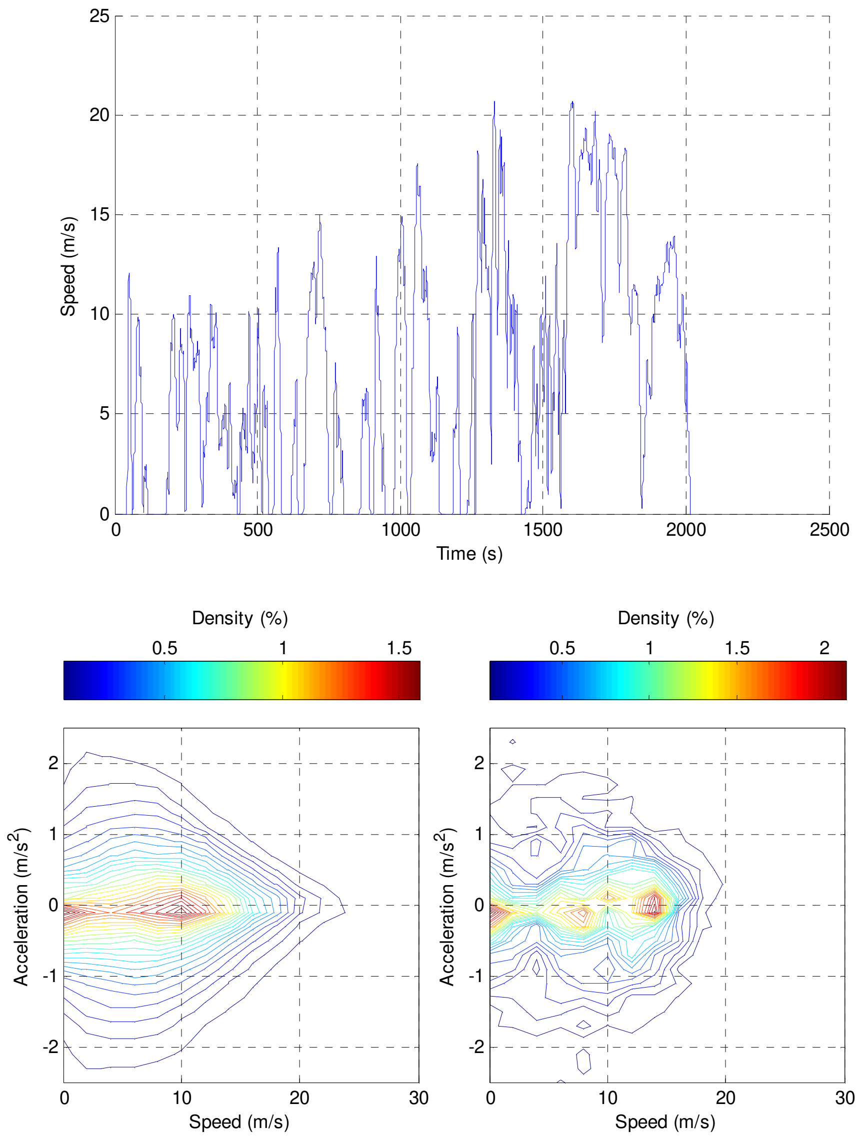

Figure 5 – Upper plot: "LDV long" cycle. Lower plot: comparison between original SAPD (left) and cycle SAPD (right).

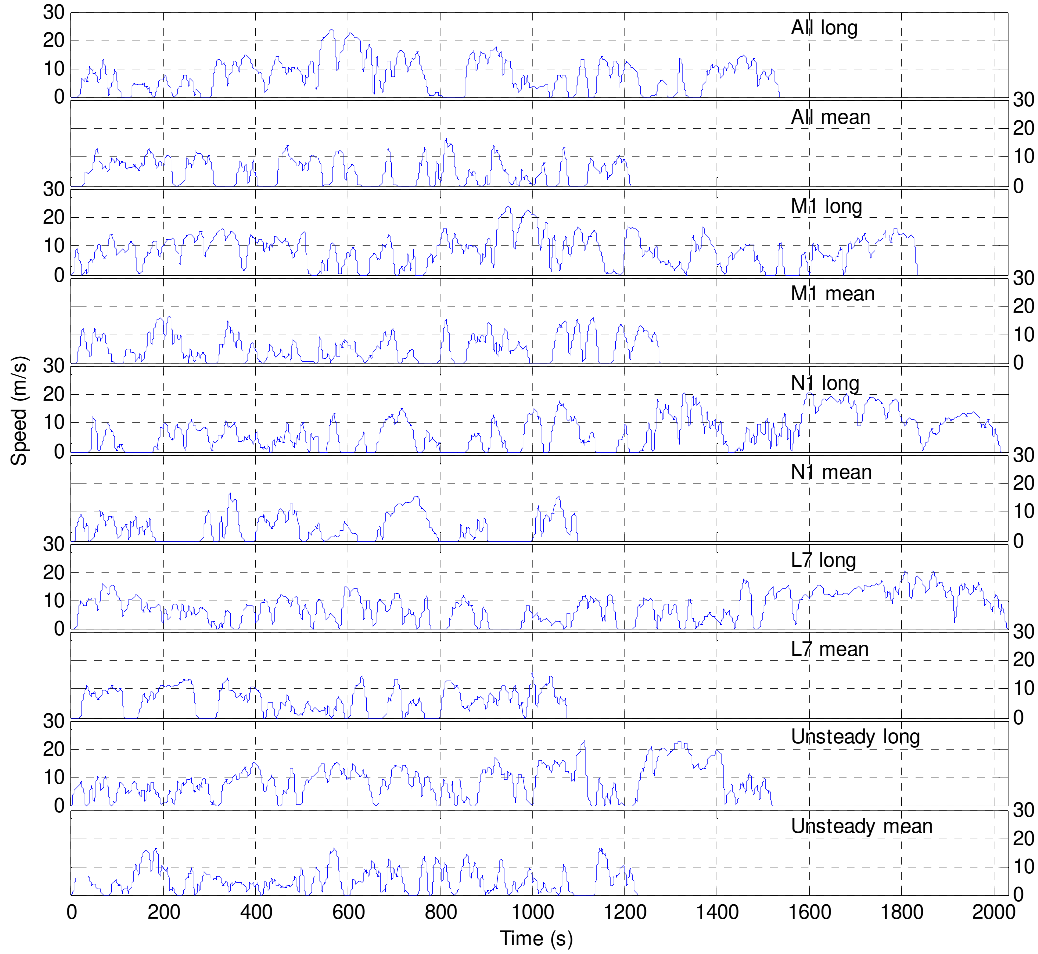

Figure 6 – Time-series plot of all the generated cycles.

3.2.3 - A comparison with existing cycles

As a final outcome, dot plots illustrating the characteristics of generated cycles in comparison with previously available ones are presented. In particular, Figure 7 shows the average speed (including zero phases) in comparison with average positive acceleration, highlighting the proximity between typical urban cycles (NEDC and Artemis Urban) and generated ones (see “All mean” and “All long” dots), as expected due to the typical urban pattern in which the vehicles have been used.

The plot shown in Figure 8 clearly shows that the mean speed and stops per km of the generated cycles fall in the same order of magnitude indicated for legislative cycles such as NEDC and FTP; however, a direct comparison between urban patterns cycle (“All mean” generated cycles) and naturalistic urban driving cycles (Artemis Urban) highlights a lower stop per km number, even if the mean speed is absolutely similar. At this stage, it is not possible to say if this is related to the characteristics of the electric vehicles (which can be driven in a smooth way in intense traffic, limiting start and stop phases) or not.

Similarly, Figure 9 compares the cycles on the basis of Mean Positive and Negative accelerations. As known from previous studies, the trend shows that the values are generally higher for urban pattern cycles in comparison with rural or motorway ones. Negative acceleration values are often slightly higher than positive ones. Regarding the generated cycles, the mean negative values of acceleration are significantly lower than the value related to Artemis Urban naturalistic cycle; again, the difference could be related to the characteristics of the Electric Vehicle which could induce a particular driving behavior during deceleration. It can be noted also that L7 vehicle shows for both "long" and "mean" cycles lower values of mean accelerations, as expected due to its low power characteristics.

Cycle abbreviation	Cycle full name
NEDC	New European Driving Cycle
FTP	US FTP 75 Cycle
Art Urban	Artemis Urban
Art Rural	Artemis Rural
Art MW	Artemis Motorway
Art URM 130	Artemis Mixed cycle 130

Table 6 – List of abbreviations used to indicate the cycles.

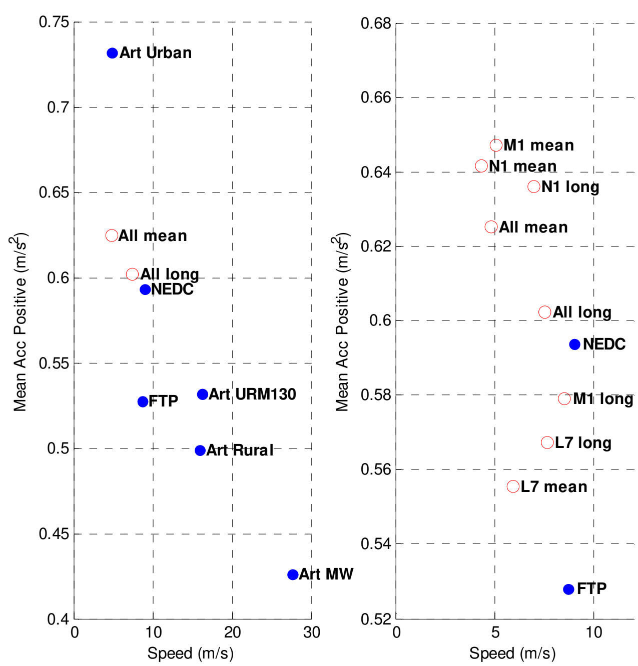

Figure 7 – Speed vs Mean Positive Acceleration for existing and generated cycles. Left side: only "All long" and "All mean" cycles are plot for readability. Right side: all generated cycles are included and the scale is modified to focus on those.

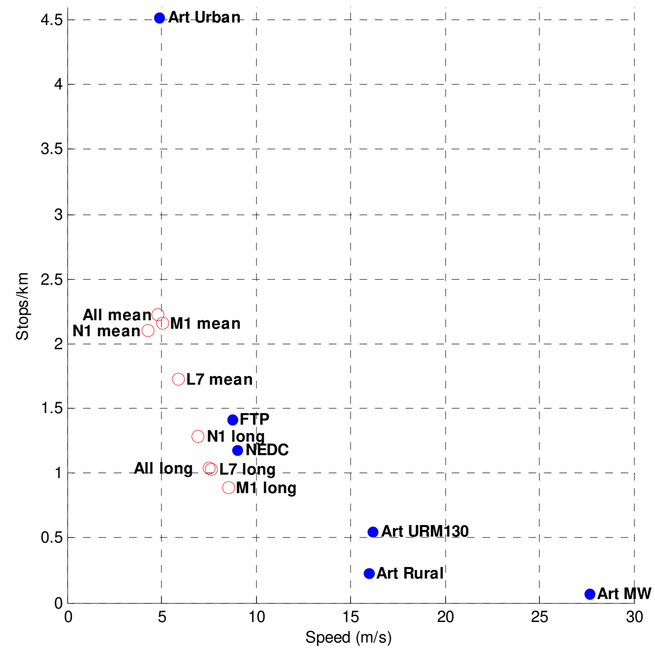

Figure 8 – Speed vs number of stops per km for existing and generated cycles.

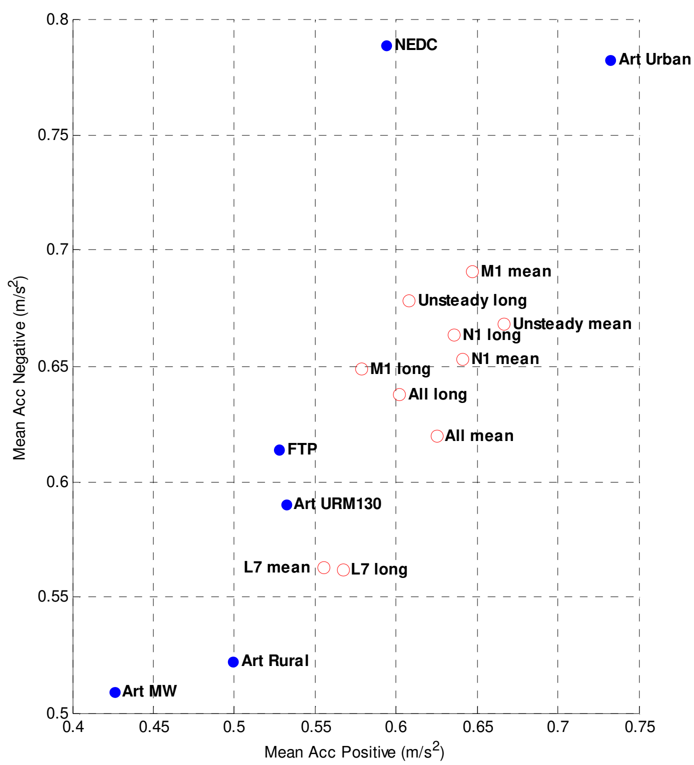

Figure 9 – Dot plots representing Mean Positive and Mean Negative accelerations for existing and generated cycles.

3.2.4 - Extended use of measured driving data

As described in paragraph 2.3.2, the randomization of driving cycles for vehicle development activities is part of recent applied research trends. Such inputs are useful during testing (e.g. for control systems robustness verification in SIL/MIL/HIL environment) or optimization of vehicle characteristics (e.g. for energy management strategies, to be verified over a large number of use cases). A tool for the extraction and the treatment of measured driving data has been developed; it is mainly conceived to be used during batch simulation, extending the variability of the inputs in comparison with “fixed” generated data.

The second main product of driving cycle analysis activity is therefore a “package” for data analysis and cycle synthesis. The package implements the same methodology applied for cycle generation (as described in the former paragraph) and is prepared as a Matlab–based product with Graphical Users Interface (GUI). The tool – “builder” – is an interpreter of data that can be used to generate new cycles and to verify their similarity with original data. The user can set a few parameters (the target distance, the vehicle data to be used, the data “clusters” to be included, the acceptance thresholds), than a number of “attempts” cycles can be generated; if any of the created cycles fits with original dataset, the tools plots the generated “representative” cycle and saves it in a spreadsheet. Saved data include the speed signal, the acceptance results (number of similar parameters, Performance Values – PV – indicator, Sum Square Distance – SSD – of speed–acceleration density matrix – SAPD) and the general describing parameters. The interface of the tool is shown in Figure 10; it is also part of the research products for the project ASTERICS EU FP7. Its typical output is shown in Figure 11. The tool can be used also through command line and is therefore suitable for the integration on simulation environment.

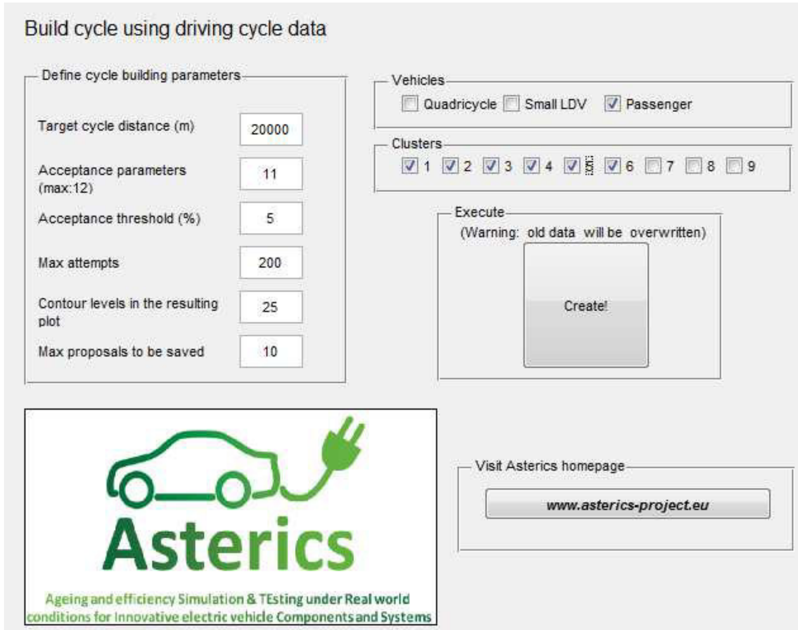

Figure 10 – Driving cycle "builder" tool: main GUI screenshot.

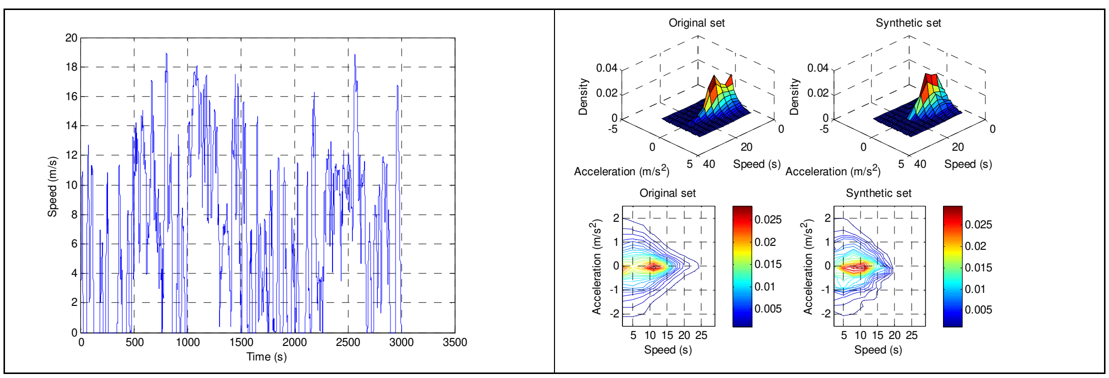

Figure 11 – Output from "builder" tool: cycle plot (left), cycle SAPD plot (right).

4 - Conclusions

Driving cycles are a relevant input for the development of procedures for design, testing and homologation of any kind of vehicles; such topic is particularly relevant considering the high level of attention on vehicles both for pollutants emission and energy use. Considering precedent literature products, in the first part of the present work a summarization of current state of the art on the topic has been proposed. A few main findings emerged from the preliminary analysis of the topic. A large number of synthesis methods have been proposed, most of them being similar on their key points. Literature analysis also highlights a strong need for continuous improvement of the cycles in terms of detail and variety, in order to catch the peculiarities of the vehicle under study and of the area where it is used; such need is therefore the main motivation to propose a new case study. In addition, recent applied research activities show the emerging trend of tools able to generate "on demand" cycles; such data can be used during vehicle development and for simulation and testing activities, as improved input in comparison with synthetic cycles. However, a synthesis method has been prepared considering reference experiences.

In the second part of the work an application case study has been proposed. The activity includes the measurement of driving data within the city of Florence, which is characterized by the presence of restricted traffic and pedestrian areas within its historical center; such areas can be accessed using EVs. A small fleet of EVs used by both professional and private drivers has therefore been monitored within its normal use; the driving sequences obtained can be considered naturalistic, since no predefined itinerary was imposed and since the logging instrumentations was absolutely not invasive. Using the developed method, the data have been therefore processed in order to build up a set of ten synthetic cycles, differing for the type of vehicle used (from low powered quadricycles, to light vans and passenger cars) and for the distance proposed (from typical city route – build up using mainly urban sequences – to mixed route, including fluent driving on longer distances). The cycles represents main outcome of the activity, their peculiarity being the use of data coming exclusively from EVs. In addition, the time-speed vector for each cycle has been defined using four points per second, which is an improved level of detail in comparison with existing cycles; the aim is to offer the possibility to increase the precision of energy consumption and efficiency assessment in simulation activities. The activity is than concluded proposing a short comparison with existing cycles; considering naturalistic cycles, a few differences in typical kinematic indicators are noticeable. A few hypothesis have been proposed; however, at the present stage it cannot be said if the spreading of the data is related to the characteristics of the city, to the relatively small number of drivers involved (a known limitation of the study) or to the peculiarities of electric vehicles, most evident being the regenerative braking capabilities and the fluent traction at very low speed. Both characteristics, in fact, can potentially let the drivers obtain smooth acceleration events even in intense traffic situations. A suggestion for future development, therefore, is to investigate about the attitude of the users in driving EVs in comparison with ICEVs, in order to verify if different powertrain characteristics can induce remarkable modification on driving style. Finally, an interpreter tool for further valorization of the whole dataset has been developed and implemented both as GUI and command-line function. Such activity has been prepared to overcome the limitations of “rigid” representative cycles and extend the representativeness of the data during vehicle development phases, coherently with recent literature experiences and applied research trends.

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http://cordis.europa.eu/fp7/cooperation/home_en.html
http://ec.europa.eu
http://www.asterics.eu
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