Design of Drive Cycle For Electric Powertrain Testing

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Abstract

Drive cycles have been the official way to create standardized comparisons of fuel economy and emission levels between vehicles. Since the 1970s these have evolved to be more representative of real-world driving, with today's standard being the World Harmonized Light Vehicle Testing Procedure. The performance of battery electric vehicles which consist of electric drives, battery, regenerative braking and their management systems may differ when compared to that of vehicles powered by conventional internal combustion engines. However, drive cycles used for evaluating the performance of vehicles, were originally developed for conventional powered vehicles. Moreover, the kinematic parameters that can distinguish the real-world performance of the differently powered vehicles are not fully known. This work aims to investigate the difference between vehicles powered by pure internal combustion engine, electric hybrid and pure electric drive. A route was selected to develop drive cycles with three representative vehicles one for each category and data was collected. Suitable scheme was adopted while carrying out the experiments for minimizing the effect of traffic flow with vehicles with mixed powertrain. A numerical model of Nissan Leaf, was constructed in GT-Suite software and validated against current standard drive cycles data from the Argonne National Laboratory. Two drive cycles were developed using a micro-trip approach, for intermediate and harsh driving conditions. The results from the novel drive cycles show the inevitable distinctions between differently powered vehicles, giving an estimated range prediction that is very similar to the one from the World Harmonized Light Vehicle Testing Procedure.

Introduction

A drive cycle provides a speed-time profile of a driving behavior to test and quantify emissions levels and fuel economy of the vehicles. Standard driving cycles such as the US Federal Test Procedure (FTP) and the European Commission for Europe (ECE) Cycle, introduced in the early 1970s, in Europe, Australia and Asia in the late 1970s [1], have been used to test compliance to regulations and record data for the proper functioning of the common market and marketing purposes [2]. Since the 1970s the US Environmental Protection Agency (USEPA) and the California Air Resources Board (CARB), have been updating the standard driving cycles to conform to regulatory and certification programmed changes. These are now separated between vehicle type (e.g., light duty vehicles, heavy duty vehicles, etc.), and geographical location.

Innovative methods are now used to develop novel drive cycles such as: "quasi-random" approaches that collect micro-trips to form a cycle; Monte Carlo simulations to describe how actual driving behavior occurs; Markov's process, to develop the Germany motorway cycle; Statistical methods [1].

The New European Driving Cycle (NEDC), was introduced in the 1980s to simulate urban driving conditions for light duty vehicles under lab-bench procedures for homologation purposes. The drive cycle has been updated in order to represent the real-world driving conditions and now has been replaced by the WLTP, as it is more representative of real-world driving conditions. Whilst the US has the FTP-75 and Japan the JC08 and more additional cycles have been added to FTP-75 cycle to represent various real-world driving scenarios.

The NEDC has been defined as a cold start cycle, and even though it is not representative of real-world driving conditions it is still used today to test and compare vehicle emissions with the WLTP. The WLTP is the definition of testing procedure used for a Worldwide Harmonized Light Vehicle Test Cycle (WLTC). The WLTC is divided into three power/weight and maximum speed classes. The WLTP is now the EU standard to which all light duty vehicle emissions must comply with [3]. Furthermore, under the WLTC the vehicle is accelerating or decelerating 84% of the time, with only 13% at idle and 4% at constant speed, whilst for the NEDC, 40% is at a steady state condition, 24% is at idle, and 36% is completed accelerating or decelerating [4]. Although this might give the idea that emission limits would be harder to pass with WLTP, Marotta et al., [4] concluded that actually for vehicles over 1100kg in mass, the NEDC produces more particulate matter emissions. This was justified by saying that the engine worked at optimized operating conditions during the WLTP, where cold start emissions (THC and CO particulates) are less prominent then in the NEDC.

With the stringent emission limits, electric vehicles (EVs), and more specifically BEV have now become the main focus of automotive manufacturers. These are currently tested and evaluated using the same drive cycles developed for internal combustion engine (ICE) vehicles. As the regulations have not yet updated the standards (Commission Regulation (EU) 2017/1151; Commission Regulation (EU) 2018/1832), there is a requirement to develop representative drive cycles specific to EVs, to then be adopted as regulatory standards.

BEVs differ from ICE vehicles, in torque, power and braking characteristics; this requires different drive cycles to be developed specifically for BEVs [5; 6]. The choice of an appropriate driving cycle, for a specific vehicle class, is crucial, as power consumption can differ of a factor of 2, depending on the cycle torque demand [7]. Esteves-Booth et al. [8] for Edinburgh; Berzi, Delogu and Pierini [9] for the city of Florence; Kamble, Mathew and Sharma [10] for the city of Pune; Wager, Whale and Braunl [11]; Tahir Baig, M. and Samuel, S. [12] all showed how the effect of geographic location, traffic patterns, ambient temperature and road conditions can affect drastically fuel economy.

Although until now the practice has been to demonstrate that international drive cycle standards, such as the NEDC and WLTP are not adequate to represent EVs driving characteristics, there is still a need to develop BEV standard driving cycles. Similarly to how the current drive cycle standards test emissions and fuel consumption, for ICE vehicles, the new drive cycle is required to test performance and efficiency of BEVs. The speed-time characteristics of this cycle will assess torque and regenerative braking control algorithms, it will test performance, and analyze the battery thermal behavior.

There is a distinct knowledge gap in terms of how ICE vehicles and BEVs are driven differently. To bridge this knowledge gap , it was decided to conduct an experiential analysis on a typical drive cycle of three types of readily available vehicles: FIAT Panda (ICE), Toyota Yaris (hybrid powertrain) and Renault Zoe (BEV) and hence the scope of this work.

Methodology

Experimental Drive Cycle Construction

A drive cycle was constructed to compare the driving behaviors of an ICE, a HEV and a BEV. The drive cycle follows the criteria that were used by many others in constructing real-world cycles. This included driving through urban, extra urban and highway roads. The route chosen for developing the drive cycle is shown in Figure 1 and it is 17.8km long. It is located in the southern part of Rome, Italy (Ciampino Airport can be seen from Figure 1). It consists of 5km of urban, 7km of extra urban and 5.8km of highway driving. This approach follows the RDE [13] standards although in a scaled down version to facilitate the collection of data. It was decided to conduct two cycles, for each type of vehicle, to see the effect of driver aggressiveness. The timing of the experiments were chosen such a way that the trip to trip variation due to traffic flow is minimized and the effect of road geometry and traffic regulations will have maximum influence. The intermediate style is intended as the driving characteristics of the average driver in this part of the country. The three chosen cars used to conduct the tests were the FIAT Panda 2018, the Toyota Yaris hybrid 2016 and the Renault Roe 50.2 2020. These were chosen as where easily accessible, and are commonly seen around these roads. Furthermore, scientific procedures were followed to maintain consistency throughout the driving tests: Traffic variability was mitigated as best as possible by driving after 23:00, time at which traffic is reduced drastically in this area. By driving during the night, temperatures are more manageable and reached a peak of 24°C, and a low of 22°C. This reduced the chances of temperature interference on the test data, mostly for the BEV (as during sunlight hours the temperature reached 33°C that day). Cabin climate control was turned off for all tests.

Data was recorded using a GPS tracker, for every 1s interval, and an OBD2 adaptor connected to a mobile phone with installed the Car Scanner app, used to decrypt and store the incoming data from the car. Furthermore, two special profiles were created, for each vehicle, on the app to extract only the relevant sensor data.

Figure 1, experimental drive cycle map, adapted from: [14].

Mathematical Equations

The GPS data was converted to speed and distance using longitude and latitude equivalences. In Rome 1° of latitude is equivalent to 111km, and 1° of longitude is equivalent to 85km. The speed of the vehicle was calculated using (1)

$$V = \left(\frac{\Delta x_{3D}}{T}\right); \text{(km/h)} \tag{1}$$

Where:

$T = 1hr;$

$\Delta x_{3D} = \sqrt{(\Delta x_{2D})^2 + (\Delta z)^2};$

$\Delta z = elevation\ change\ (km) = z_n - z_{n-1};$

$\Delta x_{2D} = \sqrt{(\Delta x)^2 + (\Delta y)^2};$

$\Delta x = longitude\ change\ (km) = x_n - x_{n-1};$

$\Delta y = latitude\ change\ (km) = y_n - y_{n-1};$

$x_n = \left|\frac{longitude \times 85}{E_{deg}}\right|;$

$y_n = \left|\frac{latitude \times 111}{E_{deg}}\right|;$

$E_{deg} = equivalent\ to\ 1°\ longitude\ or\ latitude = 1;$

The velocity data then was filtered for redundant and noise. The median smoothening method was used for data smoothening. This is commonly used for simple data, with limited changes over time. (2) describes the smoothening process.

$$V_f = \frac{1}{4}V_{n-1} + \frac{1}{2}V_n + \frac{1}{4}V_{n+1}; \tag{2}$$

Drive Cycle Analysis

The procedure developed by TRL [3] is applied for designing and evaluating the characteristics of the drive cycles. They identified that a drive cycle can be distinguished from another using time, speed, acceleration and dynamic related variables, defined as Art.Kinema parameters. Only some variables were identified as useful for the purpose of this drive cycle. The vehicle is considered stopped if the velocity is less then 2km/h, as 70/220/EEC European council directive on the approximations of laws used to measure air pollution produced by ICE vehicles, mentions in section 3.5.2 [15].

GT-Drive Model Construction

A Nissan Leaf model was constructed using GT-Drive. This BEV model follows backward kinematics approach, that takes a target speed (that is stored as a drive cycle in the driver object) and calculates the energy for each stage of the vehicle. Figure 2 shows the general flow chart of the model with the relevant electrical connections between the power demanding components.

The battery controller is used to set the battery minimum and maximum attributes for the battery pack. This holds battery characteristics such as: capacity, cell thermal models and state of charge (SOC) models. The change in open circuit voltage (VOC) and internal resistance (R0) for charge and discharge, due to temperature and SOC. Similarly, a coulombic efficiency map was included as it enabled to represent the efficiency of the battery to convert chemical energy into electrical or vice versa. The battery temperature model was ignored and maintained constant for the simulation, as initial model complexity would have increased the model validation time.

The brake controller signals to the vehicle when only regenerative braking is necessary, or friction brakes need to intervene. The brake demand is given by the backward calculations done from the driver object. This object is used to change the driver or controller settings, such as the PID parameters and the responsiveness.

The vehicle object is used to input specific vehicle mechanical and aerodynamic characteristics. Critical to the validation are vehicle mass and aerodynamic drag and vehicle geometry.

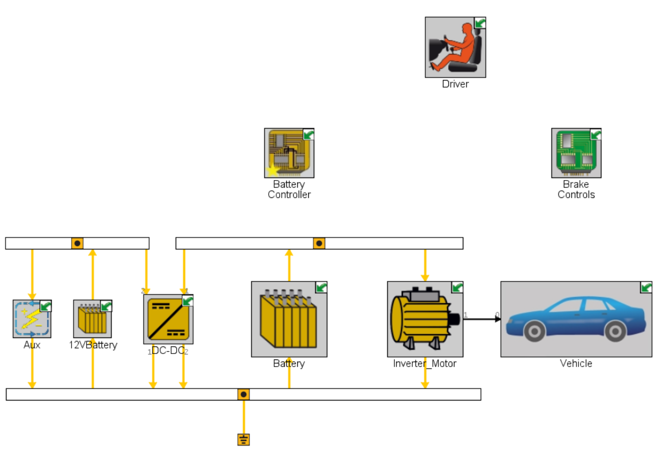

Figure 2, a representative Nissan Leaf Model in GT-Suite

Mathematical Equations

In the SOC model instantaneous current through the open circuit voltage (V_{OC}) is integrated over time to calculate a change in capacity over the duration of the simulation. This change in capacity is subtracted from the initial capacity to calculate an instantaneous capacity.

$$Cap(t) = Cap_{init} - \int_0^t V_{OC}dt; \quad (3)$$

Where:

$$Cap_{init} = SOC_{init} \times Cap_{max};$$

The SOC is then defined as the ratio of instantaneous capacity to maximum capacity.

$$SOC = \frac{Cap(t)}{Cap_{max}}; \quad (4)$$

A coulombic efficiency model is used to include the efficiency at which an electrochemical battery either converts electrical energy into chemical energy (charge scenario) or converts chemical energy into electrical energy (discharge scenario). This efficiency is modelled by placing current source in parallel with the terminal current (Figure 3).

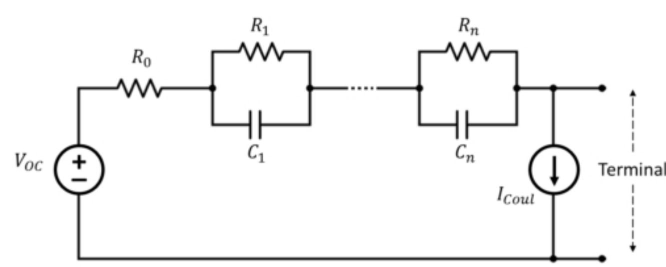

Figure 3, schematic of coulombic efficiency model used.

From Kirchhoff's current law:

$$I_\tau = I_{OC} + I_{Coul}; \quad (5)$$

Where the value of the current through the coulombic efficiency current source is:

- During charge
  $(I_\tau < 0): I_{Coul} = |I_{OC}| \times (1 - \eta_{Coul});$
- During discharge
  $(I_\tau < 0): I_{Coul} = |I_{OC}| \times (1 - \eta_{Coul});$

The last and most critical calculation is carried out by the driver model, that calculates the torque request, by accounting for external resistant forces such as inertia, rolling resistance, aerodynamic drag and road features, and is calculated based on the acceleration request:

$$Acc_{Demand} = \frac{Veh\_Spd_{tar} - Veh\_Spd_{act}}{1s} \times Pre - Control\_Agg; \quad (6)$$

The Accelerator pedal position and brake pedal position outputs are computed using the feed-forward request with the additional PI correlations.

Input Parameters

Input parameters have been taken and cross checked between different sources. The model takes two kinds of inputs: constant and variable, such as vehicle physical properties and SOC maps. Representative maps have been obtained and adjusted from default GT-Suite ones and other online resources. Table A1 in the Appendix shows constant input parameters that reflect the Nissan Leaf specifications. Most importantly the motor speed torque curve in Appendix Table A2 was derived using scaling factors for maximum power, torque, battery VOC and current.

Standard Drive Cycle Construction

A Standard Electric Vehicle Cycle (SEVC) was created using the recorded data from the Renault Zoe experimental drive cycle. Specific speed-time profiles were such as: urban, extra-urban and highway were selected and placed in order. Additionally using the RDE standards the SEVC was created to be 33.3% of each road type, which resulted in duplicating some of the selected profiles from the experimental drive cycle. This method is based on the approach of Lin and Niemeier [16], using micro-trips to develop a summative and larger drive cycle. The difference lies in the fact that instead of having single micro-trips that pinpoint a specific road type, these are individually selected from a larger experimental drive cycle, reducing the amount of data gathering to be done.

This can be observed in Appendix Figure A1, where cyclic elements from the experimental drive cycle can be distinguished. The main drawback of this method is that it is still location specific (Rome area). There are two further adaptations that could be done: (1) create micro-trips from averages of multiple micro-trips recorded at different locations and in different conditions (traffic, weather, etc.); (2) create different micro-trips that describe different conditions (traffic, weather, etc.), forming separate drive cycles. Figure 4 shows the difference in the SEVC between intermediate and harsh driving conditions. Successively a study was conducted using the Art.Kinema parameters so to compare these with the other standard cycles (NEDC, WLTP, etc.). The total distance travelled for the intermediate and harsh cycles is 32km.

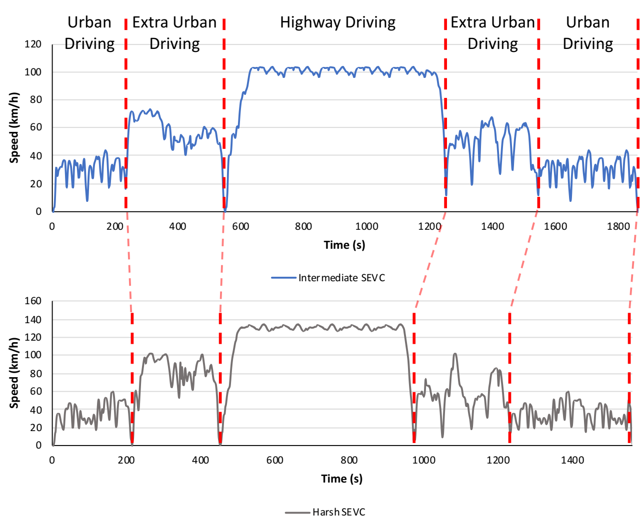

Figure 4, intermediate and harsh SEVC, with the respective urban, extra urban and highway driving.

To further create distinction between new SEVCs a naming convention method should be developed following geographical standards. An initial attempt is proposed in Table 1. It was decided to follow the SEVCI for intermediate and SEVCH for harsh driving conditions.

Table 1, naming standard for the newly developed drive cycle.

Drive Cycle Name	**Location**		**Description**	
	Nation	*Province*	*Duration*	*Driver Behaviour*
SEVC	ITA	RM	1860	I
SEVC	ITA	RM	1560	H

Results

Experimental Drive Cycle

The GPS data from the experimental drive cycle has been used to produce a speed over distance plot as shown in Figure 5. The extra urban, urban and highway driving conditions are separated, and the difference in speed between harsh and intermediate driving characteristics is clearly visible during highway driving.

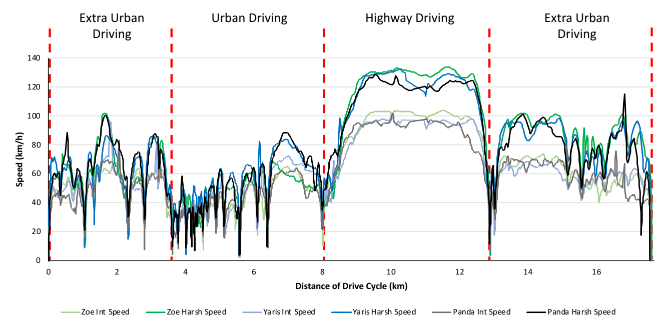

Figure 5, experimental drive cycle, driven with Renault Zoe 2020, Toyota Yaris 2016 and FIAT Panda 2018, under Intermediate and harsh driving conditions.

A more in dept analysis was conducted on particular scenarios in the drive cycle, between the differently powered vehicles. For example, in Figure 6 the road gradient over a small hill with a corner. The acceleration difference between vehicles driving after the corner if very noticeable. In both harsh and intermediate cycles, the Zoe is able to accelerate faster and maintain constant cruise speed, were the road gradient is greater. Whilst since the Yaris has a delay before the engine starts, it lags behind. Also, the stages that the hybrid system needs to go through whilst accelerating, reduce the acceleration potential, decreasing the velocity slope. This difference is also given whilst the ICE of the hybrid system is running at low RPM delivering reduced torque. Likewise the Panda has a similar behavior to the Yaris. Interestingly even the gear shifts are clearly visible in the velocity slopes for both intermediate and harsh conditions.

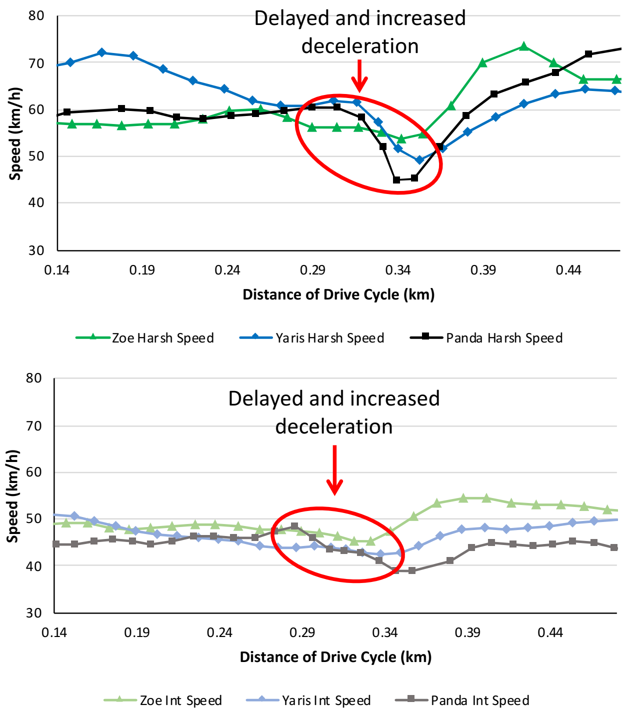

Figure 6, velocity slope characteristics for an extra urban road with a hill ascent. (a) harsh driving conditions, (b) intermediate driving conditions.

Comparative behavior can be seen in Figure 7. Here the vehicles are experiencing high deceleration after driving at motorway speed to a “STOP” sign. Both for intermediate and harsh conditions the deceleration seems to be longer and the final velocity lower for the Zoe. In the initial stages deceleration is constant in all cycles, but as the “STOP” sign approaches in the Yaris friction brakes are applied earlier, whilst on the Zoe these are delayed until 10m before the stop. This causes the Zoe speed curve to be delayed and more consistent over time. The effect of friction brakes being applied earlier in the braking event can be seen in Figure 8. Here the deceleration is maintained constant for the Zoe as the regenerative braking is calibrated to maintain constant deceleration (regenerative braking deceleration power reached a maximum of 44kW on the Zoe). Whilst on the Yaris the friction brakes are used more frequently, even during the initial phases of regenerative braking, since this is reduced to only 5kW in the Yaris. Whilst on the Panda the behavior is mostly affected by gear shifting, which causes oscillations in the braking curve.

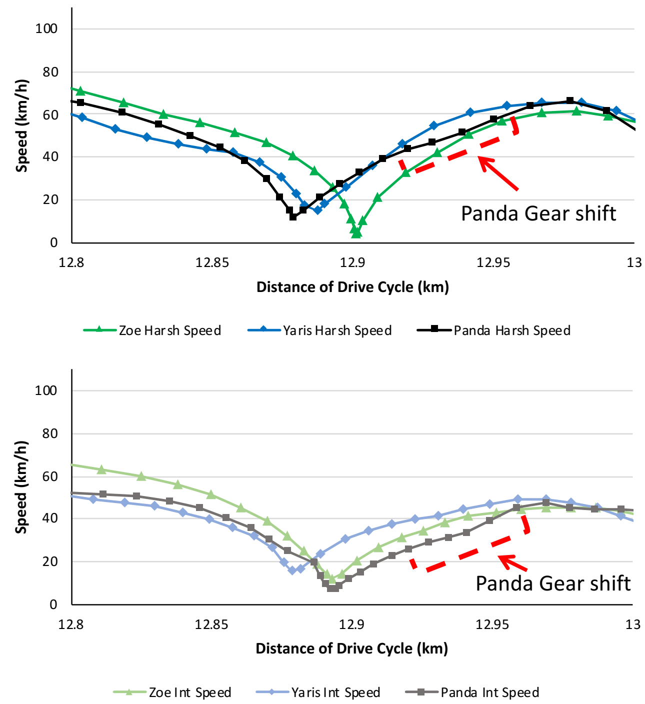

Figure 7, braking characteristics after driving at highway speeds; the graph shows speed-distance curve adjusted to start at the equivalent distance for the vehicles. (a) harsh driving conditions, (b) intermediate driving conditions.

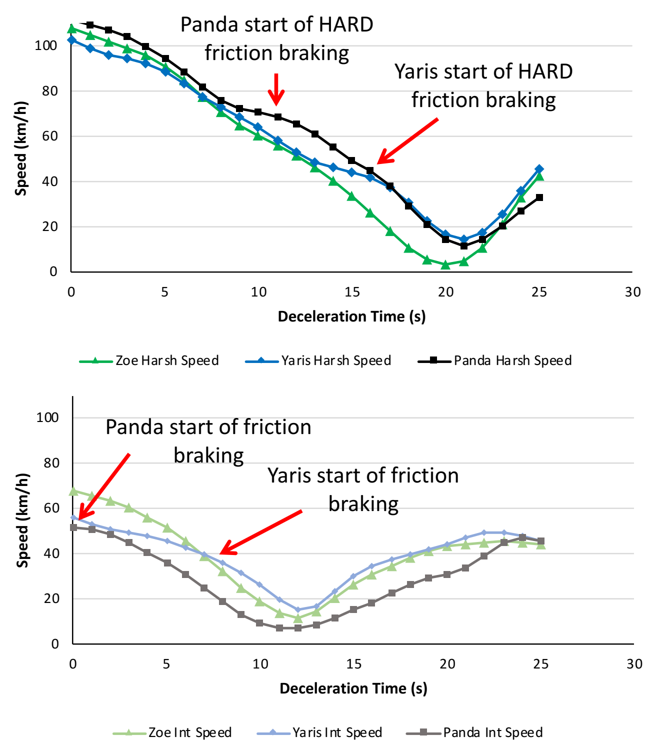

Figure 8, braking characteristics after driving at highway speeds; the graph shows speed-time curve adjusted to start at the equivalent speed for the vehicles. (a) harsh driving conditions, (b) intermediate driving conditions.

The experiments have shown how differently a BEV behaves compared to other ICE vehicles. The difference is mostly noticeable in braking and accelerating, as the driver takes full advantage of regenerative braking (more consistent braking) and high torque at low speed. On the Yaris braking consistency is interrupted by the influence of friction brakes operated by a human. Additionally, the control systems that allow the braking to operate smoothly, from regenerative to friction, disrupt braking consistency.

The kinematic parameters [3] show an even deeper insight into how the three different types of vehicles behave. Table A3 and Table A4 in the Appendix compare some selected parameters from the TRL analysis, for intermediate and harsh conditions respectively. The differences between the vehicles are minimal and the only consistent differences are positive and negative average acceleration. A more precise analysis on the acceleration behavior, shows how for 75% of the time, under intermediate conditions, the Zoe is accelerating at a slower 0.21 rate, compared to the others which are instead 0.24 for the Yaris and 0.26 for the Panda. The same happens for harsh conditions. This is probably due to the fact that the Zoe reaches faster the required velocity due to the motors high output torque, and maintain a constant speed for a prolonged period of time. Likewise the Yaris has a hybrid system, where the time spent at lower acceleration rates is higher than the Panda. The results show how a BEV such as the Zoe has much higher acceleration rates, for shorter periods, compared to other powertrain types.

GT-Drive Model Validation

Validation of the GT-Drive model was carried away using ANL data [17] recorded on dynamometer testing for the Nissan Leaf. It was decided to use four standard drive cycles to validate the model to: (1) NEDC, because it was the most adopted cycle in industry and in research ; (2) the WLTP, that is currently the industry standard drive cycle; (3) the US06, to validate the model on high speed sections; (4) the UDDS, to validate the model for intermittent driving since the UDDS has may starts and stops.

The validation was achieved by scaling parameters such as: coulombic efficiency, and tuning PID controller increment values, driver ability to look forward, driver responsiveness and aggressiveness. The model was initially well calibrated, but errors resulted in higher SOC differences over time. With tuning of the previously mentioned parameters the validation was achieved with errors, at the end of the cycle, of: 1.7% for the NEDC, 3.3% for the WLTP, 3.1% for the US06 and 0.3% for the UDDS as shown in Figure 9.

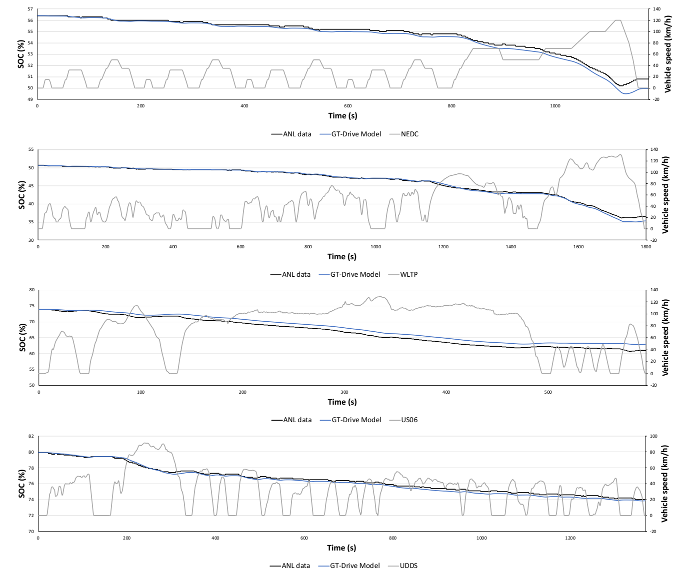

Figure 9, Nissan Leaf GT-Drive model validation; (a) validation to the NEDC cycle; (b) validation to the WLTP cycle; (c) validation to the US06 cycle; (d) validation to the UDDS cycle.

It is important to mention that with the tuning of driver responsiveness, and ability to look forward, there is a noticeable delay in the SOC curve compared to the ANL test data.

To further increase model validation major steps need to be taken in changing the model structure and including thermal losses for battery and motor objects. These losses have been included in the powertrain efficiency but temperature variations for battery and motor would further alter the overall system efficiency. Another consideration is that driver weight was not included in the simulations.

Standard Drive Cycle

The two cycles produced with the proposed variation of the micro-trip method, were tested using the validated GT model of the Nissan Leaf. Figure 10(a) clearly shows the difference between the decline in SOC between the SEVCI and SEVCH, caused by the acceleration and velocity differences between the two. The patterns in the SOC decline are also similar. The unexpected result is that the high speed extra urban driving, in the first half of the cycle, majorly reduces SOC. This is probably caused by the elevated speed and the low efficiency of the Leaf at high speeds. This effect is increased even more during highway driving, where SOC drastically decreases. The difference in output motor power is visible in Figure 10(b). Undoubtably there is a noticeable disparity between the cycles. The more demanding SEVCH compels higher torque to drive the wheels. The variability of power states is similar for both cycles, although the SEVCH has evident higher spikes in power output, due to higher demands.

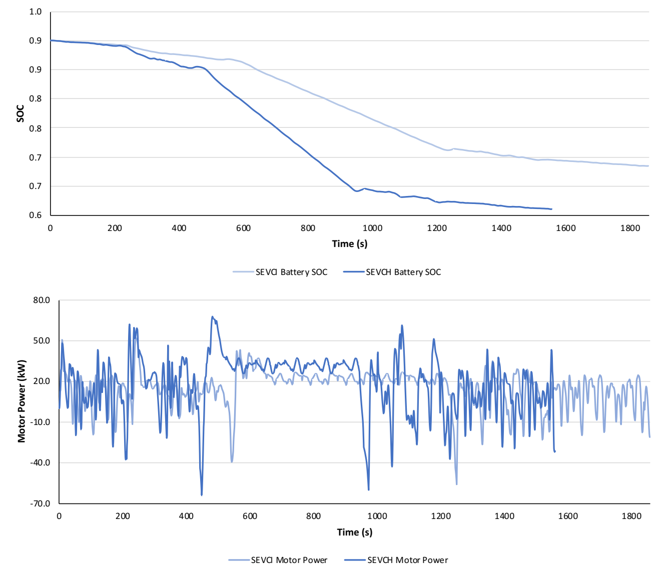

Figure 10, performance difference between SEVCI and SEVCH. (a) the SOC decline during the cycle, higher for the SEVCH, and (b) the motor power output, greater variability for the more demanding SEVCH.

The results have been compared to the NEDC and WLTP standards. In Appendix Figure A2, the NEDC demands much less from the vehicle compared to the SEVCH. This is why the adoption of the more representative WLTP was important for better performance analysis and range prediction. A deeper look in the deceleration and acceleration characteristics between the NEDC, WLTP, SEVCI and SEVCH (Appendix, Figure A3a), shows that the NEDC requires the least maximum acceleration, although its average acceleration is similar to the others. Likewise the WLTP in Appendix Figure A5b, demands less maximum deceleration and its average deceleration is similar to the others. The result is that the SEVCI is a very well balanced average that fits between the WLTP and the NEDC in terms of maximum values, whilst the SEVCH is extreme for all variables.

The NEDC Leaf range was estimated by Nissan in 2012 to be 175km [18]. This result is very similar to the one calculated using the GT model. From Table 2 the average speed is distinctively different between the cycles. Although in terms of acceleration the SEVCI sits between the NEDC and the WLTP, the average velocity is higher, meaning that highway driving is more influential as there is a longer highway section compared to the WLTP. It is also interesting to notice how although the WLTP is similar in total time to the SEVCI, it consumes less energy.

An important variable that is used in industry to compare EVs economy is kWh/100km which can be related to the ICE equivalent: l/100km. The result from the economy analysis shows that the WLTP and SEVCI are very similar, whilst the SEVCH is far less efficient, due to the high accelerations and velocities.

Finally, the estimated range calculation confirms how the NEDC is completely overshooting, whereas the WLTP and SEVCI are a good representation of the expected range that can be achieved (Table 2). The SEVCH is instead a representation of the range that can be anticipated by driving faster and more aggressively, a decrease of 26%. It is important to say that these results are for standard ambient conditions, and during winter and summer season the range is expected to decrease at least another 20% for all cycles [18].

Table 2, drive cycle comparison and final essential results

	NEDC	**WLTP**	**SEVCI**	**SEVCH**
Average Speed *(km/h)*	33.4	46.3	62.4	73.9
Energy *(kWh)*	1.46	3.47	4.90	6.58
Economy *(kWh/100km)*	13.3	15.0	15.2	20.5
Estimated Range *(km)*	180.3	159.9	157.9	116.8

Discussion

The experimental drive cycle shows how different powertrains are driven uniquely to their characteristics. High torque at low RPM allows the vehicle to reach the demanded speed faster, reducing the average acceleration throughout the cycle, giving higher instantaneous acceleration. Constant speeds and accelerations are maintained more easily as gear shifts and other powertrain transitions are absent. Regenerative braking allows the vehicle to slow down without the intervention of friction brakes. This is controlled by computer algorithms that associate at a velocity a generator braking force required, which means that during deceleration, as velocity is decreasing braking power is decreasing as well (this is why the intervention of friction brakes, actuated by the driver, is required at low speed). The result is constant deceleration until friction brakes are applied, that are usually used just for low speed braking or for stopping the vehicle. These observations can be made for both the intermediate and the harsh driving conditions. Showing that driver aggressiveness will not influence how the inbuilt features of the vehicle operate.

It is difficult to predict what influence traffic might have on how the vehicles would be operated since the testing was completed under minimum traffic conditions. It is expected that most vehicles are driven during rush-hours which means that low speed sections and start-stop events would increase compared to the equivalent non-traffic route. This entails a completely different case study, resulting in distinctive performance and range predictions.

Another element to analyze is that modern-day EVs have multiple driving modes such as Eco, Comfort, Sport modes, these can alter the vehicle responsiveness. For the experimental test done with the Zoe under harsh conditions, the Eco mode was switched off. This was decided so that there wouldn't be a speed limiter, as there is one for the Eco mode (limits at: 100km/h). During day to day driving this is the element that will affect the range of the vehicle the most; high acceleration and high speed reduce vehicle range and battery life. Figure 12(a) illustrates how demand and discharge currents affect the SOC.

The Nissan Leaf model was used to show how the SEVCI and SEVCH differ from the standard industry adopted cycles. The results demonstrate that the now outdated NEDC is not representative of a rea-world scenario, due to the low amount of cycle variation, the low speeds and the short duration. The simulation showed that the NEDC predicted 13% more range than the WLTP. The NEDC prediction is similar to the ANL results and the manufacturer estimation for the same cycle [18]. The WLTP estimate closely matches the SEVCI prediction, showing how although it is a cycle produced specifically to test ICE vehicles it is still viable for EV range estimation. Thus, the constructed SEVCI is a viable cycle as a standard testing cycle, containing all the specific acceleration and deceleration features that characterize EVs, which are not in the WLTP. Figure A4 in the Appendix, shows the difference between the SEVCI and the WLTP output battery current which can be directly associated with acceleration/deceleration. The SEVCI low average acceleration is visible by looking at the amount of time the vehicle is accelerating. For the WLTP the accelerating instances are prolonged but less aggressive as the cycle was built for ICE vehicles, whereas the SEVCI is accelerating more often but for minor durations. The most probable reason why these two cycles give a very similar result is because the SEVCI compensates the lack of prolonged accelerations with the amount of time spent at high speed, as the WLTP has a very short highway section.

The SEVCH instead is a representative case of what happens to an EV's range if for example the Eco mode is turned off and the vehicle is driven faster and more aggressively. This is what happens commonly with EVs as during extra-urban and highway driving, where the limitations on power imposed by the Eco mode are restrictive. It is expected that most EVs are driven in-between these two scenarios, with the use of Eco modes for city and possibly extra-urban driving. It needs to be mentioned that this might be the case only for light-duty vehicles and different studies should be done for higher powered vehicles such as Tesla's, Porsche's, etc.. Higher power, means that limiters can be applied for higher speeds (130km/h instead of 100km/h), although the overall economy of more powerful vehicles is reduced as their weight increases. The Zoe achieved 13kWh/100km, the Leaf model estimated 15kWh/100km, whilst a Tesla, should achieve 18kWh/100km [19].

The factor that should become more relevant for drive cycles is elevation. This is a major element that contributes to vehicle range. High elevation changes can affect EV range by 50%, reducing the predicted SEVCI to 130km assuming that the vehicle is regenerating 2/3 of the energy downhill. The reality is that this is the case only for constant elevation change.

To construct a novel drive cycle that is actually viable for industry and research, it has to be futureproof, and has to follow standards and procedures that distinguish today's. It is believed that traffic flow will be affected by the introduction of more EVs on the road. Furthermore, the manufacturers implementation of autonomous driving functionalities, the change in roads, roads are on average becoming bigger with higher speed limits, the change in mobility and how people move around cities, and the incremental adoption of shared means of transport, are all factors that will change how EVs are driven. City center driving is being restricted throughout the globe to mitigate pollution, traffic and accidents. Meaning that city driving will be severely reduced compared to today's RDE standards (33% city driving, which could become 15% of the cycle be 2030).

The methodologies used to construct the SEVCs are recommended to be used for further research and possibly for real-world applications. As these drive cycles reflect the altering driving styles, caused by the previously mentioned changes. Cycles are becoming more specific and the adoption of a standard methodology used to construct novel EV cycles is more relevant than a worldwide adopted standard one, such as the WLTP. This is not to say that the estimations from the SEVCI and SEVCH cannot be considered viable worldwide. These actually derive from an EV which means that they retain the inherit EV characteristics and would give a much better performance test benchmarking.

Summary/Conclusions

1. The drive cycle developed using a representative electric vehicle showed that the WLTP is not adequate for estimating the range or fuel economy of the electric vehicles.

2. The methodologies that where adopted for the drive cycle development have shown to be adaptable and simple, and are recommended to be used for future EV drive cycle development.

The findings from this work highlighted that the difference in powertrain affects radically how vehicles are driven, and driving modes allow for further distinction. Therefore, adoption of more pertinent drive cycle is critical for testing and evaluating the performance and range of electric vehicles. This work though it is based on limited number of vehicles and number of trips, it demonstrates that the kinematic parameter and micro-trip approach can be used to distinguish the powertrain and constructive suitable drive cycle for evaluating real-world performance of the electric and hybrid vehicle.

References

[1] Hung, W., Tong, H., Lee, C., Ha, K. and Pao, L., 2007. Development of a practical driving cycle construction methodology: A case study in Hong Kong. Transportation Research Part D: Transport and Environment, 12(2), pp.115-128.

[2] Watson, H.C., Milkins, E.E., Braunsteins, J., 1982. The development of Melbourne peak cycle, SAE-A and ARRB Traffic Energy and Emissions Conference Paper 82148, Melbourne.

[3] Assets.publishing.service.gov.uk. 2022. [online] Available at: <https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/4247/ppr-354.pdf> [Accessed 16 February 2022].

[4] Marotta, A., Pavlovic, J., Ciuffo, B., Serra, S. and Fontaras, G., 2015. Gaseous Emissions from Light-Duty Vehicles: Moving from NEDC to the New WLTP Test Procedure. Environmental Science & Technology, 49(14), pp.8315-8322.

[5] Dang, L., Bernard, N., Bracikowski, N. and Berthiau, G., 2017. Design Optimization with Flux Weakening of High-Speed PMSM for Electrical Vehicle Considering the Driving Cycle. IEEE Transactions on Industrial Electronics, 64(12), pp.9834-9843.

[6] Oleksowicz, S., Burnham, K., Southgate, A., McCoy, C., Waite, G., Hardwick, G., Harrington, C. and McMurran, R., 2013. Regenerative braking strategies, vehicle safety and stability

control systems: critical use-case proposals. Vehicle System Dynamics, 51(5), pp.684-699.

[7] Pfriem, M. and Gauterin, F., 2016. Development of real-world Driving Cycles for Battery Electric Vehicles. World Electric Vehicle Journal, 8(1), pp.14-24.

[8] Esteves-Booth, A., Muneer, T., Kirby, H., Kubie, J., Hunter, J., 2001. The measurement of vehicular driving cycle within the city of Edinburgh. Transportation Research Part D, 209–220.

[9] Berzi, L., Delogu, M. and Pierini, M., 2016. Development of driving cycles for electric vehicles in the context of the city of Florence. Transportation Research Part D: Transport and Environment, 47, pp.299-322.

[10] Kamble, S., Mathew, T. and Sharma, G., 2009. Development of real-world driving cycle: Case study of Pune, India. Transportation Research Part D: Transport and Environment, 14(2), pp.132-140.

[11] Wager, G., Whale, J. and Braunl, T., 2016. Driving electric vehicles at highway speeds: The effect of higher driving speeds on energy consumption and driving range for electric vehicles in Australia. Renewable and Sustainable Energy Reviews, 63, pp.158-165.

[12] Tahir Baig, M. and Samuel, S., "Numerical Simulation of Electric Powertrain for Examining Real World Performance of EVs at Sub-Zero Temperatures," SAE Technical Paper 2021-01-1245, 2021, doi:10.4271/2021-01-1245.

[13] Theicct.org. 2022. [online] Available at: <https://theicct.org/sites/default/files/publications/EU-RDE_policy-update_18012017_vF.pdf> [Accessed 28 February 2022].

[14] Sunearthtools.com. 2022. View GPS file on map, GPX, KML, TCX, CSV, KMZ on line free tool. [online] Available at: <https://www.sunearthtools.com/tools/gps-view.php#top> [Accessed 3 July 2022].

[15] eur-lex.europa.eu. 2022. [online] Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31970L0220&from=EN> [Accessed 13 October 2022].

[16] Lin, J., Niemeier, D.A., 2002. An exploratory analysis comparing a stochastic driving cycle to California's regulatory cycle. Atmospheric Environment 36, 5759–5770.

[17] Anl.gov. 2022. D3 2013 Nissan Leaf SV | Argonne National Laboratory. [online] Available at: <https://www.anl.gov/taps/d3-2013-nissan-leaf-sv> [Accessed 19 October 2022].

[18] EV Database. 2022. Nissan Leaf. [online] Available at: <https://ev-database.org/car/1011/Nissan-Leaf> [Accessed 13 September 2022].

[19] Tesla.com. 2022. European Union Energy Label. [online] Available at: <https://www.tesla.com/en_EU/support/european-union-energy-label> [Accessed 16 September 2022].

[20] Tesla.com. 2022. [online] Available at: <https://www.tesla.com/sites/default/files/blog_attachments/the-slipperiest-car-on-the-road.pdf> [Accessed 3 July 2022].

[21] Hayes, J. and Davis, K., 2014. Simplified Electric Vehicle Powertrain Model for Range and Energy Consumption based on EPA Coast-down Parameters and Test Validation by Argonne National Lab Data on the Nissan Leaf. Department of Electrical and Electronics Engineering, University College Cork, Ireland, (IEEE Explore).

[22] EVSpecifications. 2022. 2014 Nissan Leaf SL - Driving range. [online] Available at: <https://www.evspecifications.com/en/model-driving-range/f290a> [Accessed 3 July 2022].

[23] guide, N., 2022. Nissan Leaf 2014 - Wheel & Tire Sizes, PCD, Offset and Rims specs. [online] Wheel-Size.com. Available at: <https://www.wheel-size.com/size/nissan/leaf/2014/> [Accessed 3 July 2022].

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Definitions/Abbreviations

T	Time
Δx_{3D}	3D distance change
Δz	Elevation change
Δx_{2D}	2D Distance change
Δx	Longitude change
Δy	Latitude change
x_n	1deg of longitude
y_n	1deg of latitude
V_f	Final smoothened velocity
$Cap(t)$	Battery capacity over time
Cap_{init}	Instantaneous capacity
V_{OC}	Open circuit voltage
SOC_{init}	Instantaneous change in capacity
Cap_{max}	Maximum capacity
I_{τ}	Kirchhoff's current law
I_{OC}	Open circuit current
I_{Coul}	Coulombic current
η_{Coul}	Coulombic efficiency
Acc_{Demand}	Acceleration demand
Veh_Spd_{act}	Actual vehicle speed
Veh_Spd_{tar}	Target vehicle speed
ANL	Aragonne National Laboratory
BEV	Battery Electric Vehicle
CARB	California Air Resources Board
EV	Electric Vehicle
ECE	European Commission for Europe
FTP	Federation Testing Protocol
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
JC	Japanese Cycle
NEDC	New European Drive Cycle
RPM	Revolutions Per Minute
SEVC	Standard Electric Vehicle Cycle
SOC	State of charge
USEPA	US Environmental Protection Agency
WLTC	Worldwide Harmonized Light Vehicle Test Cycle
WLTP	World Harmonized Light Vehicle Testing Procedure

Appendix

GT-Model Input Parameters

Table A1, constant parameters extracted from various sources to construct the Nissan Leaf model.

Parameter	Value	Units	References
Mass	1521	kg	[20]; [21]; [22]
Drag Coefficient	0.32	-	[20]; [21]; [22]
Frontal Area	2.276	m^2	[20]; [21]; [22]
Wheelbase	2.7	m	[20]; [21]; [22]
Centre of Mass	1.35	m	[20]; [21]; [22]
Tire Rolling Radius	315	mm	[23]
Tire Rolling Resistance	0.013	-	[20]; [21]; [22]
Final Drive Ratio	7.9377	-	[20]; [21]; [22]
Max Motor Power	80	kW	[20]; [21]
Max Motor Torque	254	Nm	[20]; [21]; [22]
Battery VOC	350	V	[20]; [21]; [22]
Battery Capacity	68.5	Ah	[20]; [21]; [22]

Table A2, adjusted motor speed-torque curve.

Motor Speed-Torque Curve			
Accelerating		Braking	
0	252	0	-252
2000	252	2000	-252
4000	252	4000	-252
4500	224	4500	-224
5000	202	5000	-202
5500	183	5500	-183
6000	168	6000	-168
6500	155	6500	-155
7000	144	7000	-144
7500	134	7500	-134
8000	126	8000	-126
8800	115	8800	-115
8810	0	8810	0

Standard Drive Cycle Constriction

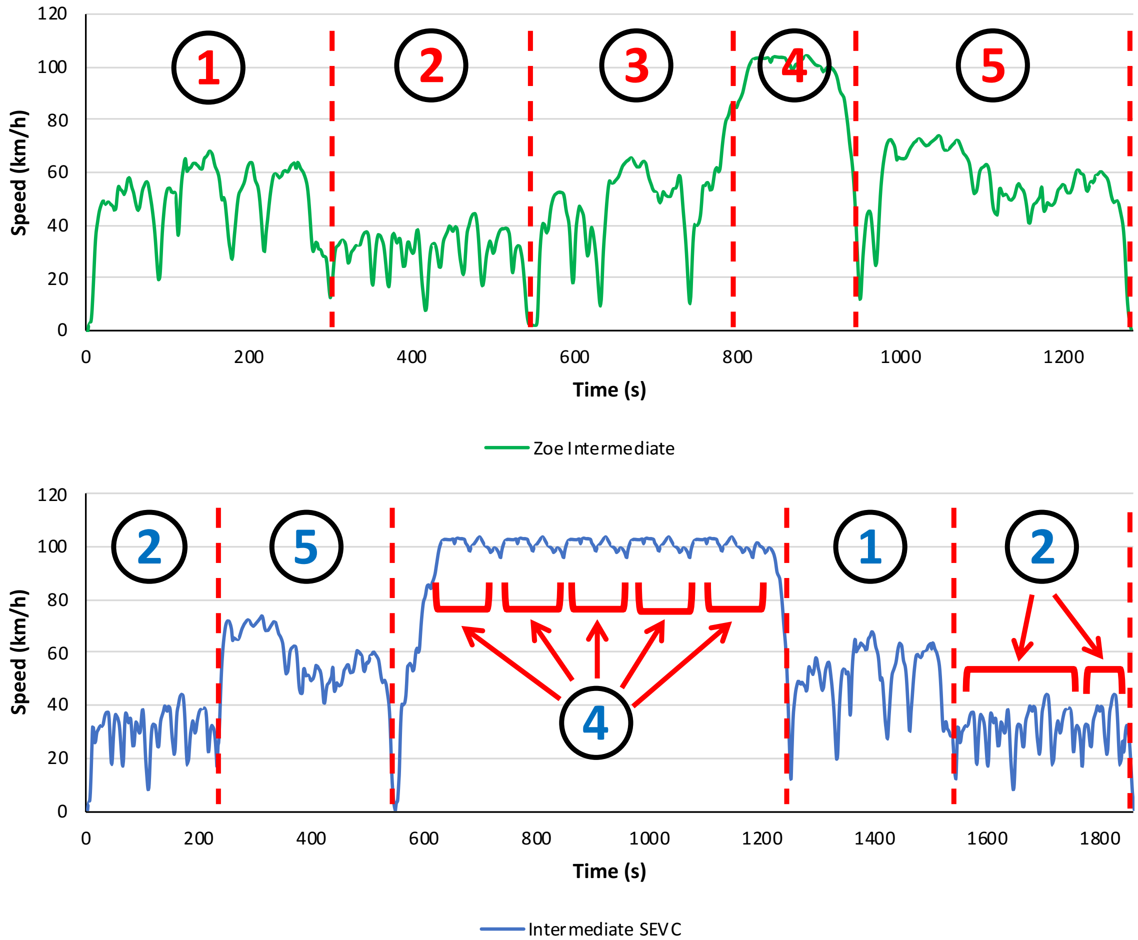

Figure A1, standard drive cycle construction; comparison between the experimental and the constructed drive cycle. The only real variability in the naming standard might be the driving condition. For this project "I" was used for intermediate and "H" for harsh, but it might be necessary to include other letters such as: "A" for aggressive and "P" for passive.

Results and Discussions

Table A3, TRL parameters used to make cycle analysis for intermediate driving conditions.

Parameter	Zoe	Yaris	Panda
	Intermediate		
Total Distance (m)	18674.4	18166.0	18361.6
Total Time (s)	1283	1233	1321
% of time driving	99.6%	99.8%	99.8%
% of time cruising	23.1%	25.3%	25.6%
% of time accelerating	39.2%	38.9%	37.3%
% of time decelerating	37.3%	35.5%	36.9%
V trip (km/h)	52.4	53.0	50.0
V drive (km/h)	52.6	53.2	50.1
V_sd (km/h)	57.1	56.8	54.4
Speed 75th percentile (km/h)	62.8	63.4	62.2
Speed 25th percentile (km/h)	36.2	39.2	36.4
V max (km/h)	104.0	101.2	101.9
Average positive acc (m/s^2)	0.49	0.6	0.6
Average negative acc (m/s^2)	-0.5	-0.6	-0.6
a_sd (m/s^2)	0.6	0.7	0.6
positive a_sd (m/s^2)	0.4	0.5	0.4

Table A4, TRL parameters used to make cycle analysis for intermediate driving conditions.

Parameter	Zoe	Yaris	Panda
	Harsh		
Total Distance (m)	18891.7	18284.0	18506.6
Total Time (s)	1061	1010	1048
% of time driving	99.6%	99.7%	99.6%
% of time cruising	40.3%	45.5%	48.3%
% of time accelerating	29.3%	28.0%	27.0%
% of time decelerating	30.0%	26.1%	24.3%
V trip (km/h)	64.1	65.2	63.6
V drive (km/h)	64.3	65.4	63.8
V_sd (km/h)	71.4	71.5	70.5
Speed 75th percentile (km/h)	83.5	83.7	82.9
Speed 25th percentile (km/h)	43.1	45.6	40.0
V max (km/h)	133.9	132.2	128.7
Average positive acc (m/s^2)	1.0	1.3	1.3
Average negative acc (m/s^2)	-1.0	-1.4	-1.4
a_sd (m/s^2)	0.91	1.0	0.92
positive a_sd (m/s^2)	0.69	0.78	0.63

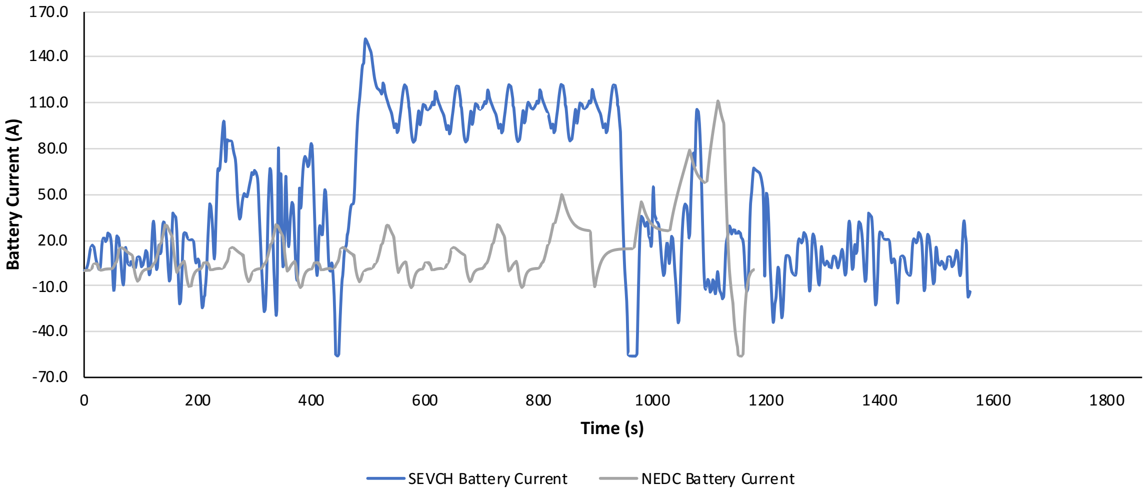

Figure A2, SEVCH and NEDC battery current comparison, data from the GT model.

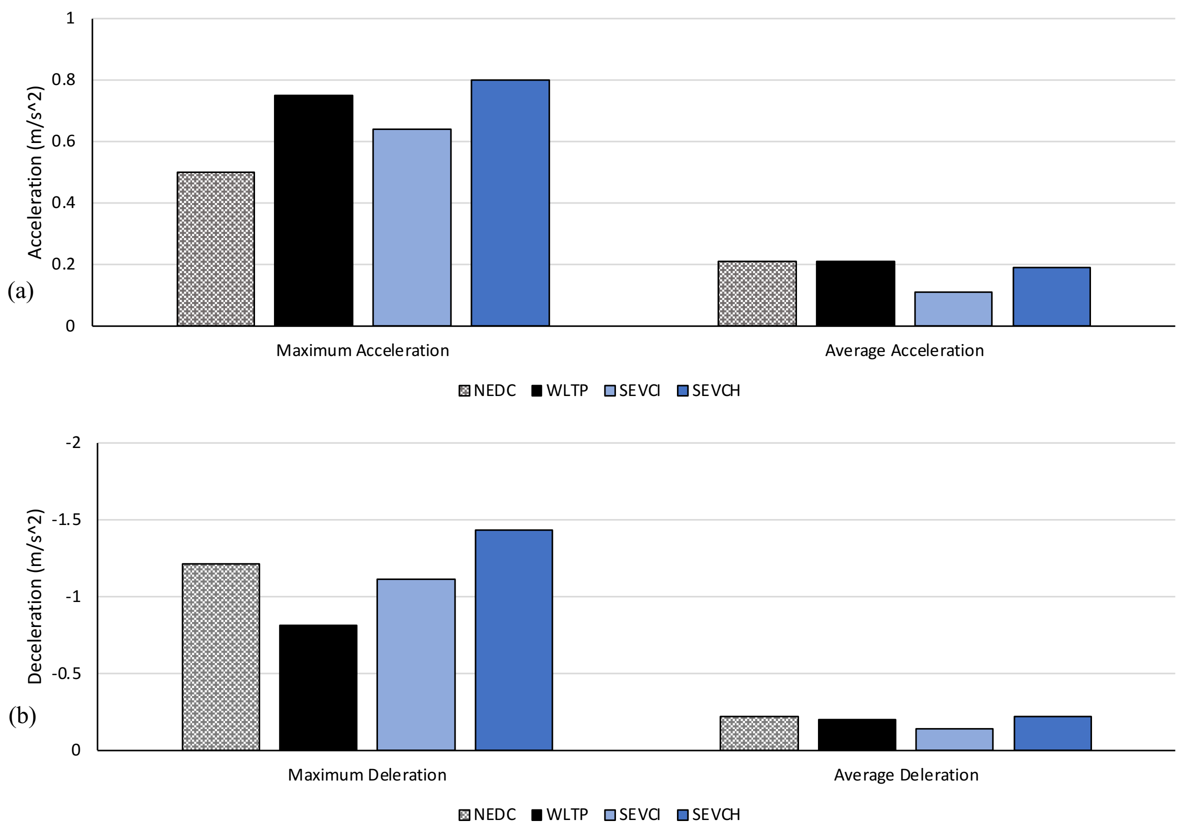

Figure A3, maximum and average acceleration/deceleration comparison between NEDC, WLTP, SEVCI and SEVCH.

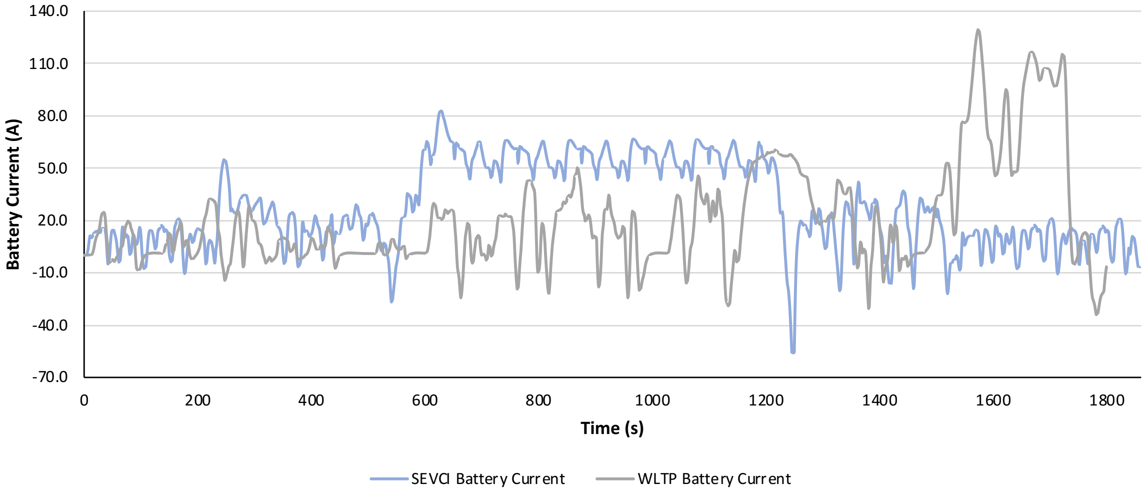

Figure A4, battery current output during the SEVCI and WLTP cycle, data from GT model.