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Albert Boretti

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Albert Boretti *

Department of Mechanical and Aerospace Engineering, Benjamin M. Statler College of Engineering and Mineral Resources, West Virginia University, Morgantown, WV, USA.

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Abstract

The use of kinetic energy recovery systems (KERS) is the best solution presently available to dramatically improve the energy economy of passenger cars. The paper presents an experimental analysis of the energy flow to and from the battery of a MY 2012 and a MY 2013 Nissan Leaf covering the Urban Dynamometer Driving Schedule (UDDS). The two vehicles differ for the integration of the electric drivetrain component, plus a different use of the electric motor and the regenerative brakes, in addition to a different weight. It is shown that while the efficiency propulsive power to vehicle / power from battery are basically unchanged, at about 87-89 %, the efficiency power to the battery / braking power to vehicle are significantly improved from values of about 70-80 % to values of 72-87 %. The analysis provides a state-of-the-art benchmark of the propulsion and regenerative braking efficiencies of electric vehicles.

Keywords: electric vehicles, regenerative braking, vehicle efficiency

1. Introduction

An Electric Vehicle (EV) is propelled by one or more electric motors that use the electrical energy stored in rechargeable batteries. The EVs are plugged into an electric power source to charge the batteries storing the electricity powering an electric motor. Though the most part of the electricity production contributes to air pollution, some organizations, as for example the U.S. Environmental Protection Agency, label the EVs as zero emission vehicles because they produce no direct emissions. As the EVs use no petroleum fuel, their widespread use is promoted as a way to dramatically reduce petroleum consumption, omitting the inconvenient truth that carbon and hydrocarbon fuels are the most relevant contributors to the electricity production worldwide and in the U.S. Both heavy-duty and light-duty EVs are now commercially available and they are typically much more expensive than the similar conventional vehicles. The additional cost is not presently recoverable trough tax credits or incentives. However, the loss of payload and more than that driving range is what makes the uptake of EVs still minimal.

Currently available EVs have a much shorter range per charge than the conventional vehicles have per tank of gasoline, diesel or alternative fuel. In the best case, the EVs have a range of 160 km on a fully charged battery requiring for longer trips or more use during a day to charge the vehicle or swap the battery. The efficiency and the driving range of an EV varies substantially based on the driving schedule and the environmental parameters. The interest towards electric cars is growing since the mid-2000s mostly thanks to the advances in the batteries' technology, historically the Achilles' heel of this mobility

* Corresponding author. E-mail address: alboretti@mail.wvu.edu

solution. Political reasons are pushing the technology well above the most reasonable expectations through tax credits, subsidies, and other incentives, plus penalties to use passenger cars based on internal combustion engines fueled with hydrocarbon fuels. The major issue the electric vehicles are presently facing are the high costs both economic and environmental of construction, maintenance and disposal, with the batteries playing a key role. The limited range, the limited load, the high weight, the long times to recharge, the limited places to recharge, and finally, the upstream consumption of carbon and hydrocarbon fuels (the energy statistics says renewables as solar and wind only account a few percent of the total electricity mix) are the additional downfalls.

If we do consider the 2014 electricity production in the Organization for Economic Co-operation and Development (OECD) countries [1], 59.88% of the electricity is generated by burning combustible fuels, and 18.44% is from nuclear. The remaining is 14.93% hydroelectric, and the contribution of geothermal/wind/solar and other renewables is only 6.75%. These numbers are marginally more favorable to wind and solar than the years before. Their contribution is certainly growing, but still very far from becoming substantial no matter which are the investments. Biomass is included in the combustible fuels. Within the Non-OECD countries, the role of wind and solar is reduced in terms of both contribution and trend. Therefore, apart from the weight, load and especially range and recharging penalties, there are still significantly larger economic and environmental costs to produce, use and dispose of electric vehicles making the electric mass transport absolutely not competitive with the internal combustion engine based on combustible fuels mass transport.

Despite these downfalls still preventing mass uptake, the electric vehicles are certainly experiencing significant improvements as demonstrated by the latest Nissan Leaf (acronym for "Leading, Environmentally friendly, Affordable, Family car") that even if not certainly the car we do use for moving the family is certainly much more than a technology demonstration exercise. This paper reports on the latest advances in energy recovery of the 2013 model vs. the 2012 model, adopting the approach described in [2] to clear the results of the weight advantage of the 2013 model. Worth of mention, the advances in battery pack and electric motor/generator are beneficial not only to the EVs, but they may also help improving the hybrid electric vehicles (HEVs) that are certainly a much better answer to today's needs in terms of mass transport, being these two components the core of the kinetic energy recovery and internal combustion engine buffering of HEVs. The HEV is indeed becoming more and more popular, in both motorsport (see all the F1 or the Le Mans prototype hybrid power trains) as well as in the passenger car market.

2. Nissan Leaf MY2012 vs. MY2013

The Nissan Leaf is an electric vehicle (EV) introduced in December 2010 [3]. The Leaf uses an 80 kW (110 hp) and 280 N•m (210 ft•lb) 10500 rpm max AC synchronous electric motor powering the front axle feed by a 24 kW·h (86 MJ) Lithium-ion (Li-Ion) battery pack rated to deliver up to 90 kW (120 hp) power. The Lithium-Ion has a cathode made of Lithium-Manganese Oxide and an anode of Carbon. With 192 cells (2 parallel series of 92), the nominal cell voltage is 3.7 V, the nominal system voltage is 364.8 V and the rated pack capacity is 66.2 Ah. The pack located underneath the passenger floor pan is air cooled within the sealed pack enclosure. The weight of the pack is 290 kg.

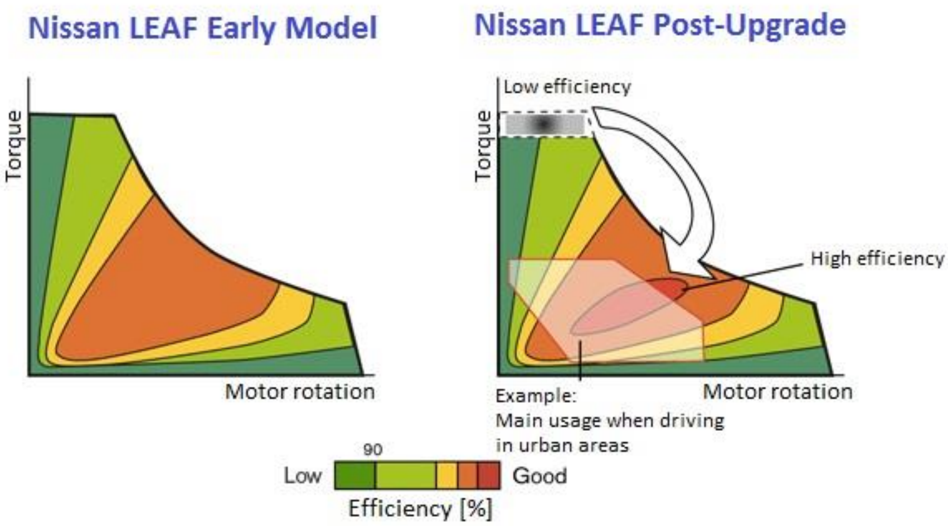
The MY2012 and MY2013 vehicles differing for the integration of the electric drivetrain component, plus a different use of the electric motor and the regenerative brakes were extensively tested at the Advanced Powertrain Research Facility (APRF) [4, 5] at three ambient test temperatures (20F, 72F, 95F) with the use of various drive cycles including the Urban Dynamometer Driving Schedule (UDDS) with cold and hot start [6].

The changes between the MY2012 and the MY2013 are summarized in [7, 8]

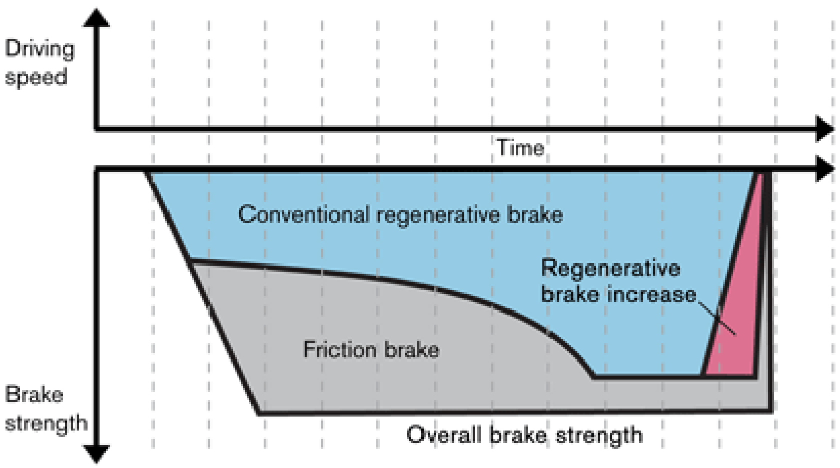
EVs use regenerative braking converting via the motor the vehicle kinetic energy into electrical energy during decelerations. The integration of regenerative and friction braking is optimized to recover the most part of the braking energy during the certification tests where decelerations are usually not dramatic, while the friction brakes are used for sharpest decelerations. The energy regeneration outcome is maximized.

The EV powertrain main components are motor, inverter, converter and reduction drive. The motor generates the power for propulsion or the electricity during regenerative braking. The inverter transforms direct current DC electricity to alternate current AC electricity during acceleration and cruise of the vehicle. It also transforms alternate current to direct current during deceleration. The converter is used to converts DC high voltage to DC low voltage electricity (14V). A junction box distributes high voltage to every unit. The reduction drive finally controls the rotations of the motor and the wheels similar to a conventional transmission.

For the MY2013 version, the main components were integrated into one single unit making a lighter and more compact powertrain. In addition to this integration, the MY2013 version also has some differences in the use of the motor and the regenerative braking as detailed in Fig. 1.



(a) Operating points of the motor, torque – speed map (image from [7]), left MY2012, right MY2013



(b) Regenerative and friction brakes intensity, brake strength – time map (image from [7]), MY2013 vs. MY2012

Fig. 1 MY2012 and MY2013 motor torque-speed and brakes strength-time maps

Fig. 1 (a) presents the changes in the operating points of the motor in the torque – speed map plane (image from [7]). The motor is optimized for better efficiencies in the area of more common use during city driving. The operation in the low efficiency high torque low speed range is prevented. Stepping on the brake, the supply of current from the battery stops, and the wheels then rotate the motor producing electricity to the battery. While the electric current charges the battery, the force reducing the rotation brakes the tires. Fig. 1.b presents the changes in the regenerative and friction brakes map of strength vs. time (image from [7]). Regenerative braking is generally more effective the higher is the rotation of the motor, i.e. the faster is the vehicle. In the MY2013, the regenerative braking is extended to even smaller vehicle speed.

3. Energy Flow Analysis

The MY2012 and MY2013 Nissan Leaf EVs have been recently tested at Argonne [5, 6]. These results are analyzed here to provide the energy flows of the two vehicles while covering the UDDS cycle by solving the Newton's equation of motion for the car.

The EPA Urban Dynamometer Driving Schedule (UDDS) [4] represents city driving conditions. The UDDS cycle has a length of 7.44 mi or 11,971 m. The tests made in Argonne [5, 6] provide the EV operating parameters vs. time for the car covering the prescribed velocity schedules of the UDDS, with cold and hot start, and with different room temperatures. Only the UDDS cycle cold (CS) and hot (HS) at 20, 72 and 95 F test cell temperatures are considered here. Other results are available in [5, 6]. The results of Argonne [5, 6] include the battery voltage [V] and the battery current [A]. The battery power P_b is computed as the product of the two. The analysis method described hereafter has been previously used in [2].

To analyze the energy flow, propulsive and braking powers and energies are computed from the velocity schedule. This is done by using a simplified car dynamics equation only accounting for the mass of the car and the aerodynamic and rolling resistances. The accessory loads are disregarded in the analysis.

If $F_{P/B}$ is the propulsion or the braking force and F_R is the retarding force due to the aerodynamic drag and the rolling resistance [N], then $(F_{P/B}-F_R)=m\cdot a$, where m is the mass of the car [kg] and a is the acceleration [m/s^2].

The weight of the MY2012 car during tests is 1699 kg. The weight of the MY2013 car during tests is 1498 kg. The aerodynamic drag force is taken as $½\cdot\rho\bullet v^2\bullet C_D\bullet A$, where ρ is the air density, C_D is the drag coefficient and A is the frontal car area. I assume ρ=1.29 kg/m^3, C_D=0.29 and reference area A=2.74 m^2.The rolling resistance is taken as $0.01\cdot m\cdot g\cdot(v/44.69+1)$ where g is the gravity acceleration, v is the velocity [m/s] and m is the mass of the car.

The propulsive and braking powers are the product of propulsive and braking forces by velocity $P_{P/B}=F_{P/B}\cdot v$ [W]. The computation returns reference propulsion and braking powers from the velocity schedule. The propulsive and braking energies E [J] are finally obtained by integrating in time t [s] the powers' results.

Sample results are presented in Fig. 2, Fig. 3, and Fig. 4. Fig. 2 presents the velocity schedule v(t) and v(s), where t is the time, s is the distance covered, and the resulting acceleration schedule a(s). Fig. 3 presents the computed reference propulsive (positive) and braking (negative) power $P_w(t)$ and $P_w(s)$ plus the measured battery power $P_{HV}(t)$ and $P_{HV}(s)$ in one of the different cases considered, namely the MY2013 version run with test cell temperature 72 F and hot start.

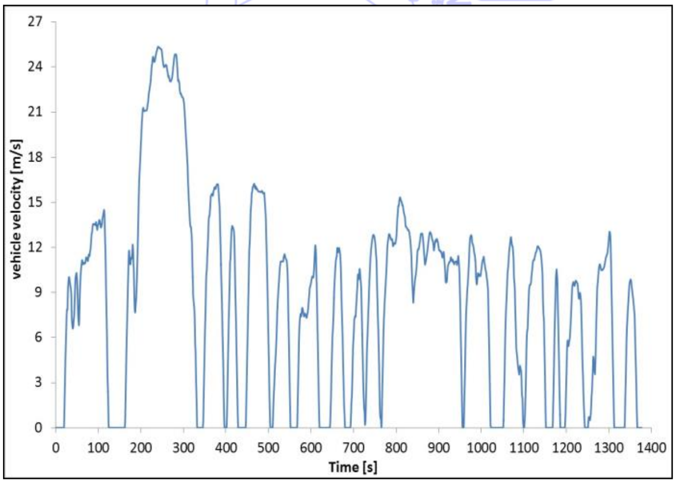
Fig. 4 presents the computed battery energy, from and to the battery, $E_{HV}(s)$, for this same test case. The positive and negative energies are shown on the top; the net energy is shown on the bottom. The ratio of these energies to the propulsive and braking energies from the Newton analysis is a measure of the efficiency of the propulsive and regenerative braking events.

The test and analysis results are summarized in Table 1.

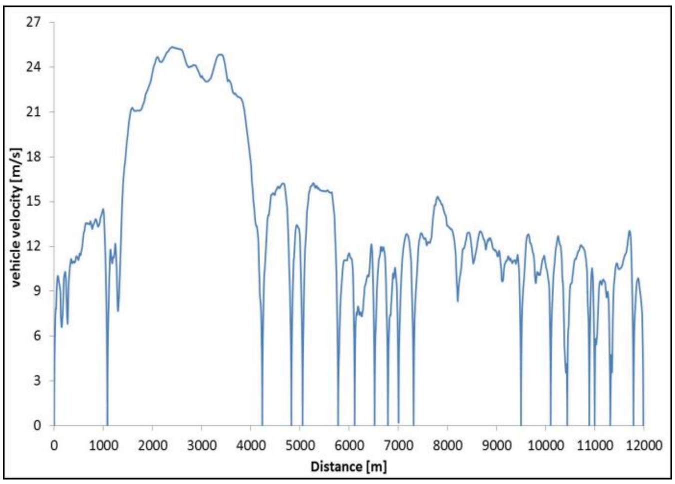
The vehicle climate control settings are 72 F for the 20 F and the 95 F tests, and climate control off for the 72 F tests. Solar radiation of + 850 W/m^2 is considered for the 95 F tests. Further details about the tests may be found in [5, 6 and 10].The battery roundtrip efficiency, calculated by dividing the DC energy out of the battery (A+) by the DC energy from the on-board charger into the battery (D), have values of 95-98% [10].

The On-Board Charger Efficiency, calculated by dividing the DC energy from the on-board charger into the battery (D) by the AC energy from the Electric Vehicle Supply Equipment (EVSE) (C) has values of 86-87% [10]. The Overall Vehicle Efficiency, calculated by dividing the DC energy out of the battery (A+) by the AC energy from the EVSE (C) have values of 82-85% [10].

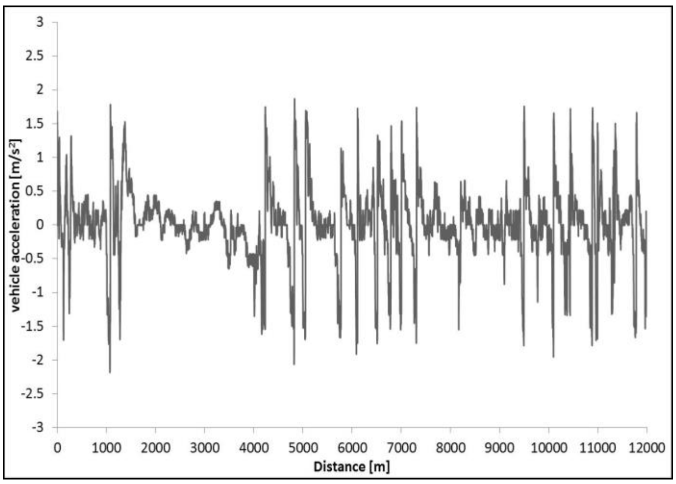
The energy rating of an EV in MJ/km should therefore be corrected by accounting for the Overall Vehicle Efficiency. The efficiency in charging and discharging a Li-ion battery depends on many parameters as the charging and discharging parameters, the temperature and the life of the battery, and this ultimately impact on the actual electric energy consumed.



(a) prescribed velocity vs. time

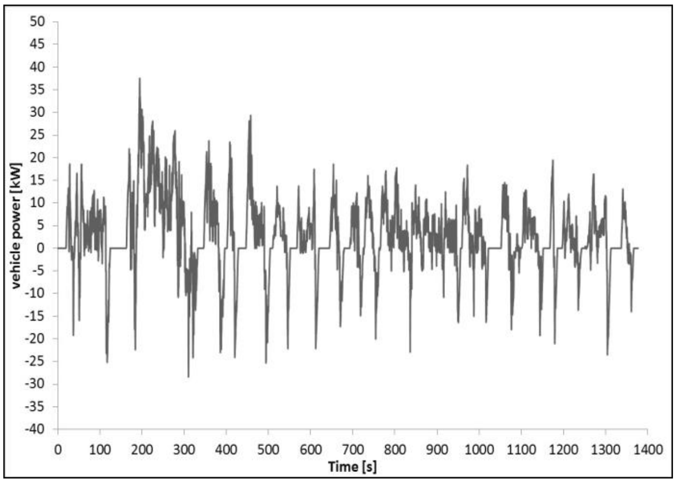


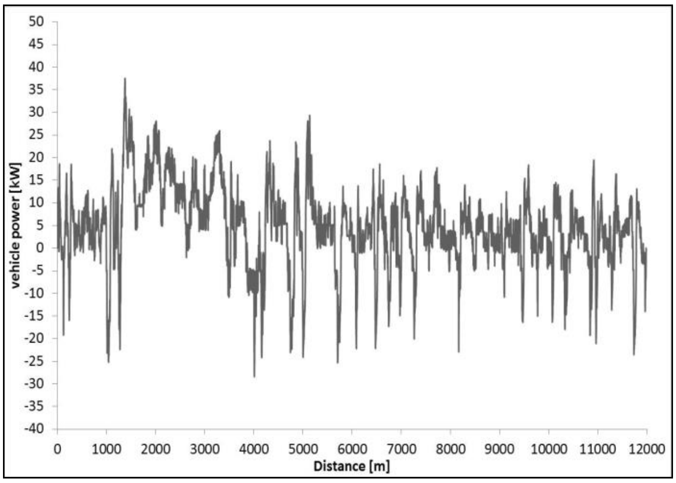
(b) prescribed velocity vs. space



(c) computed acceleration vs. space

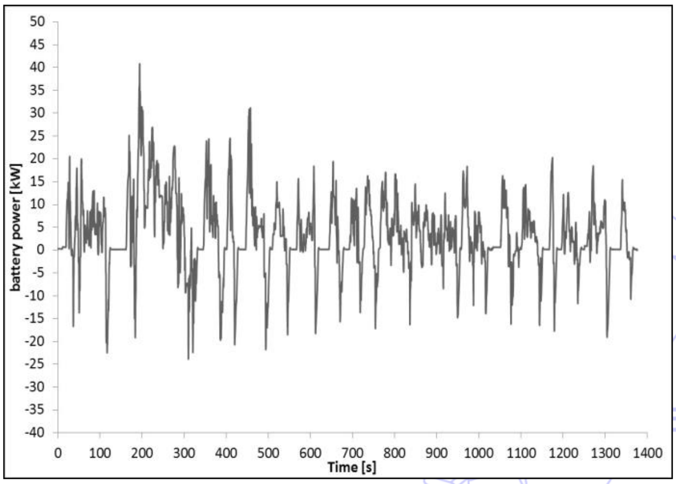
Fig. 2 UDDS

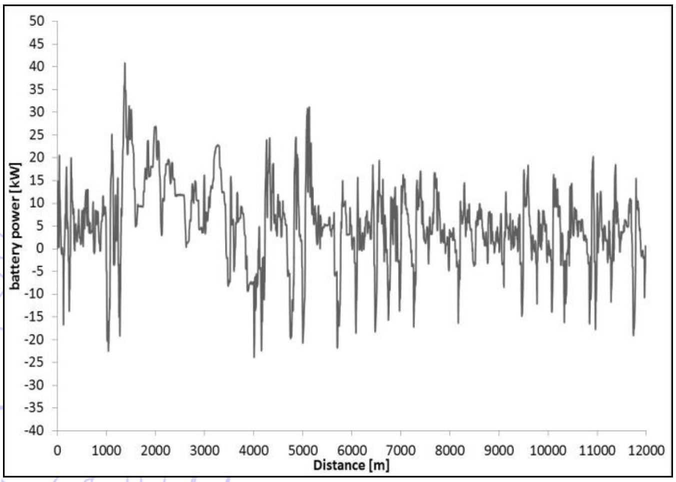




(a) computed vehicle reference propulsive and braking power vs. time

(b) computed vehicle reference propulsive and braking power vs. space

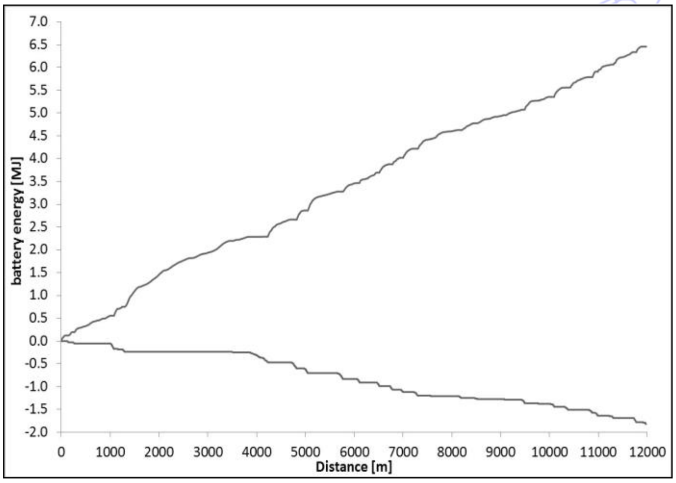


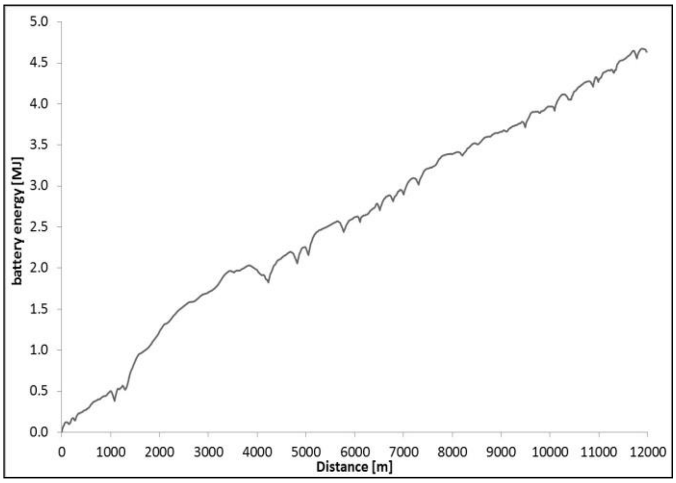


(c) measured battery power vs. time

(d) measured battery power vs. space

Fig. 3 UDDS, Test cell temperature 72 F, Hot Start, MY2013 version





(a) measured energy from and to battery

(b) measured net battery energy

Fig. 4 UDDS, test cell temperature 72 F, Hot Start, MY2013 version

Table 1 Test and analysis results, UDDS cycle

		MY2012						MY2013					
Temperature		20 F	20 F	72 F	72 F	95 F	95 F	20 F	20 F	72 F	72 F	95 F	95 F
Starting conditions		cold	hot	cold	hot	cold	hot	cold	hot	cold	hot	cold	hot
Reference propulsive energy	MJ	6.37	6.37	6.38	6.37	6.37	6.37	5.78	5.78	5.76	5.78	5.78	5.78
Reference Braking energy	MJ	-2.38	-2.38	-2.39	-2.38	-2.38	-2.38	-2.09	-2.09	-2.08	-2.09	-2.09	-2.09
Battery energy out	MJ	12.01	11.20	7.29	7.15	8.69	8.04	11.20	9.55	6.57	6.46	7.86	7.46
Battery energy in	MJ	-0.72	-1.12	-1.68	-1.91	-1.52	-1.70	-0.81	-1.20	-1.70	-1.82	-1.37	-1.50
Battery energy net	MJ	11.28	10.08	5.62	5.25	7.17	6.34	10.39	8.35	4.87	4.63	6.49	5.96
Actual distance	m	11966	11970	11958	11967	11964	11975	11997	12018	11972	11982	12012	12023
Specific Energy Consumption	MJ/km	0.94	0.84	0.47	0.44	0.60	0.53	0.87	0.69	0.41	0.39	0.54	0.50
Propulsive efficiency	%	53.08	56.90	87.45	89.08	73.35	79.26	51.62	60.54	87.57	89.52	74.03	77.55
Regenerative braking efficiency	%	30.42	47.10	70.21	80.09	63.72	71.37	38.69	57.52	82.01	87.30	65.06	71.73

The battery charging and discharging efficiency is on average about 85% for Li-ion batteries [9], perfectly in line with the 82-85% in the specific of the Nissan Leaf for the conditions considered in [10].

3.1 20 F (6.7 ℃) tests

The MY2012 car has a reference propulsive energy of 6.37 MJ and a reference braking energy of -2.39 MJ. During the cold and hot start tests, the battery energy out are respectively 12.01 and 11.20 MJ, while the battery energy in are respectively -0.72 and -1.12 MJ, for a battery energy net flux of 11.28 and 10.08 MJ. The specific energy consumption in MJ/km are respectively 0.94 and 0.84.

The propulsive braking efficiencies, defined as the ratio of reference propulsive energy to battery energy out are 53.08 and 56.90 % for cold and hot start. The regenerative braking efficiencies defined as the ratio of battery energy in to reference braking energy, are 30.42 and 47.10% for cold and hot start.

The MY2013 car has a reference propulsive energy of 5.78 MJ and a reference braking energy of -2.09 MJ. During the cold and hot start tests, the battery energy out are respectively 11.20 and 9.55 MJ, while the battery energy in are respectively -0.81 and -1.20 MJ, for a battery energy net flux of 10.39 and 8.35 MJ. The specific energy consumption in MJ/km are respectively 0.87 and 0.69.

The propulsive braking efficiencies are 51.62 and 60.54 % for cold and hot start. The regenerative braking efficiencies are 38.69 and 57.52 % for cold and hot start.

The MY2013 has therefore much better specific energy consumptions in both cold and hot start tests. This is the result of the significant mass reductions and the much higher efficiency of the regenerative braking process.

3.2 72 F (22.2 ℃) tests

The MY2012 car has a reference propulsive energy of 6.37 MJ and a reference braking energy of -2.39 MJ. During the cold and hot start tests, the battery energy out are respectively 7.29 and 7.15 MJ, drastically reduced vs. the 20 F tests, while the battery energy in are respectively -1.68 and -1.91, drastically increased vs. the 20 F tests, for a drastically reduced vs. the 20 F tests battery energy net flux of 5.62 and 5.25MJ. The specific energy consumptions in MJ/km are down to respectively 0.47 and 0.44.

The propulsive braking efficiencies are 87.45 and 89.08% for cold and hot start. The regenerative braking efficiencies are 70.21 and 80.09% for cold and hot start.

The MY2013 car has a reference propulsive energy of 5.78 MJ and a reference braking energy of -2.09 MJ. During the cold and hot start tests, the battery energy out are respectively 6.57 and 6.46 MJ, while the battery energy in are respectively -1.70 and -1.82 MJ, for a battery energy net flux of 4.87 and 4.63 MJ. The specific energy consumptions in MJ/km are respectively 0.41 and 0.39.

The propulsive braking efficiencies are 87.57 and 89.52 % for cold and hot start. The regenerative braking efficiencies are 82.01 and 87.30 % for cold and hot start.

The MY2013 has therefore much better specific energy consumptions in both cold and hot start tests also working at 72 F, similarly to what was found in the 20 F tests. This is the result of the significant mass reductions and the much higher efficiency of the regenerative braking process.

3.3 95 F (35 ℃) tests

The MY2012 car has a reference propulsive energy of 6.37 MJ and a reference braking energy of -2.39 MJ. During the cold and hot start tests, the battery energy out are respectively 8.69 and 8.04 MJ, increased vs. the 72 F tests, while the battery energy in are respectively -1.52 and -1.70, reduced vs. the 72 F tests. This translates in an increased battery energy net flux vs. the 72 F tests of 7.17 and 6.34 MJ. The specific energy consumptions in MJ/km are up to respectively 0.60 and 0.53.

The propulsive braking efficiencies are 73.35 and 79.26 % for cold and hot start. The regenerative braking efficiencies are 63.72 and 71.37 % for cold and hot start.

The MY2013 car has a reference propulsive energy of 5.78 MJ and a reference braking energy of -2.09 MJ. During the cold and hot start tests, the battery energy out are respectively 7.81 and 7.45 MJ, while the battery energy in are respectively -1.36 and -1.50 MJ, for a battery energy net flux of 6.45 and 5.96 MJ. The specific energy consumptions in MJ/km are respectively 0.54 and 0.50.

The propulsive braking efficiencies are 74.03 and 77.55 % for cold and hot start. The regenerative braking efficiencies are 65.06 and 71.73 % for cold and hot start.

The MY2013 has therefore reduced benefits in terms of specific energy consumptions in both cold and hot start tests when working at 95 F. The regenerative braking process does not seem to be more efficient at higher temperatures, and only the weight reduction makes differences. Propulsive and regenerative braking efficiencies are indeed both very close to the MY2012 values.

4. Discussion and Conclusions

The novelty of the present work is to provide propulsive and regenerative braking efficiencies from the measurements of battery power in and out of two Nissan Leaf MY2012 and MY2013 covering the UDDS cycles at different temperatures cold and hot. The Nissan Leaf MY2013 is a benchmark for today’s electric vehicles.

The energy flow in a latest Nissan Leaf has been analyzed to assess the single propulsive trip battery-to-wheels and the regenerative braking round trip wheels-to-battery and battery-to-wheels.

Covering the hot start 72 F UDDS, the MY2012 Nissan Leaf has a specific consumption of 0.44 MJ/km. The propulsive efficiency is almost 90%, and the regenerative braking efficiency is about 80%. Covering the hot start 72 F UDDS, the MY2013 Nissan Leaf has a specific consumption of 0.39 MJ/km. The propulsive efficiency is about the same of the MY2012 car at almost 90%, but the regenerative braking efficiency is now about 87%. This is the result of the weight reduction and the more complete recovery of the braking energy.

During a cold start the energy efficiency decreases. Reducing the operating temperature to 20 F or increasing the temperature to 95 F, but in this case also accounting for the air conditioning to 72 F, the energy efficiency deteriorates. The advantages of the MY2013 version are still evident working at 20 F, but they are reduced working at 95 F where only the mass reduction seems to pay. The specific consumption of 0.39 MJ/km in the best case scenario drastically increases working in different conditions to values almost double this number.

The information of Fig. 1 is provided by the manufacturer and cannot be verified during this work that is solely based on the measured battery energy flow plus a Newton's equation analysis of the vehicle dynamics. This paper only discussed propulsive and regenerative braking efficiencies, i.e. ratio of battery energy out to reference propulsive energy from Newton's analysis, and ratio of battery energy in to reference braking energy from Newton's analysis.

In terms of propulsive efficiency the differences in between MY2012 and MY2013 are quite small. From Table 1, the average improvement with MY2013 is a not significant +0.28%, well below the inaccuracy of the assessment.

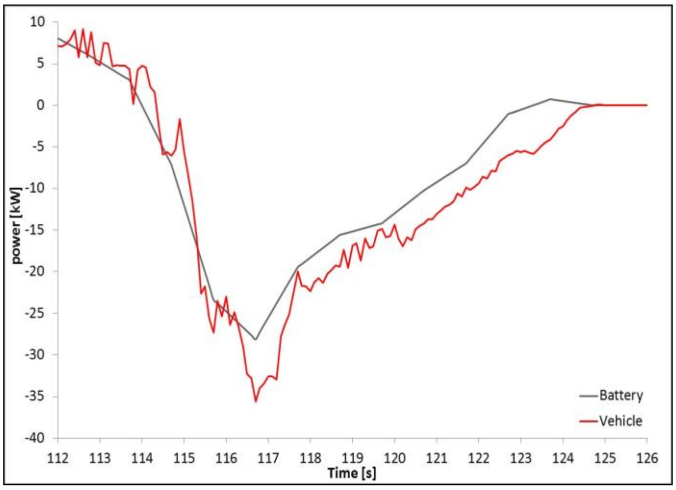
In terms of regenerative braking efficiency, the differences in between MY2012 and MY2013 are significant. From Table 1, the average improvement with MY2013 is +6.57%.

Therefore, over the UDDS tests considered, there is no improvement of the propulsive efficiency, but only of the regenerative braking efficiency. This improvement results from the arguments proposed in Fig. 1, translating in a more complete recovery of the braking energy as shown in the details for MY2012 and MY2013 of the 112 to 116 s from start and the 300 to 335 s from start braking events of Fig. 5.

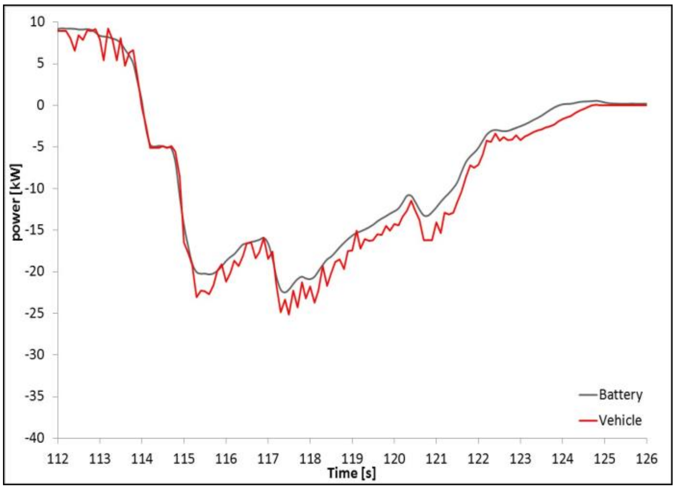
Apart from the "static" differences mentioned by the manufacturer in the images proposed Fig. 1, the control of the vehicle seems much more sophisticated in the MY2013, as nominally the same velocity schedule produces a much more detailed vehicle and battery power time series, with the reduced deviations in between the vehicle and the battery powers that then translates in the improved regenerative efficiency that also follow the modified time series.

Further information of the battery characteristics, motor efficiency improvement and regenerative braking strategies cannot be inferred from the available data, as the measured voltage and current vs. time for the vehicle covering a prescribed, recorded driving cycle and the few parameters known or guessed to set up the Newton's analysis do not permit to provide any further explanation.

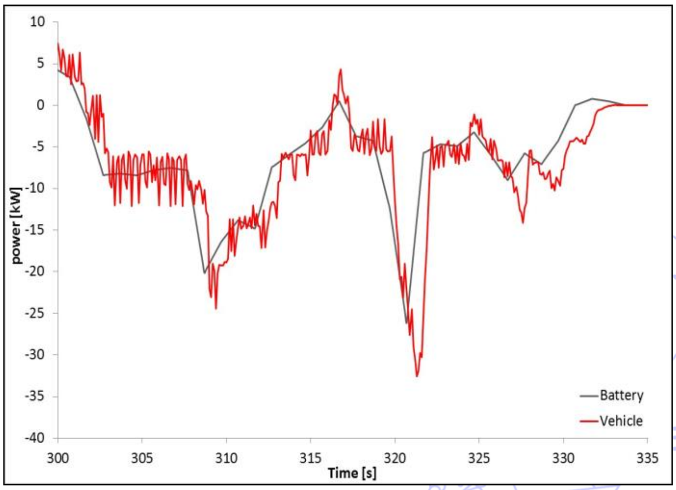
The analysis does not include the actual efficiency of the charging and discharging the battery. As the efficiency in charging and discharging a Li-ion battery depends on many parameters as the charging and discharging parameters, the temperature and the life of the battery, the above specific consumptions increase accordingly.



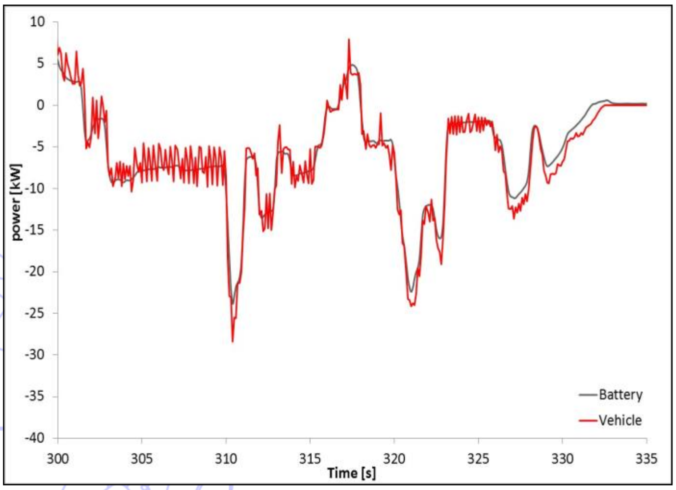
(a) power vs. time braking event 112 to 116 s from start MY2012



(b) power vs. time braking event 112 to 116 s from start, MY2013



(c) power vs. time braking event 300 to 335 s from start, MY2012



(d) power vs. time braking event 300 to 335 s from start, MY2013

Fig. 5 UDDS, Test cell temperature 72 F, Hot Start, Computed vehicle reference propulsive (positive) and braking (negative) power Pw(t), and measured HV battery power out (positive) and in (negative) $P_{HV}(t)$

If the charging and discharging efficiency of the battery is neglected, purely electric kinetic energy recovery systems are competing with purely mechanical kinetic energy recovery system [11, 12, 13, 14 and 15]. The energy conversion mechanical to electric and electric to mechanical is therefore occurring very efficiently with today's motors and generators. The conversion electric to chemical and chemical to electric that generally occur to and from the battery is the critical part of the round trip efficiency of purely electric kinetic energy recovery systems.

While the long term future of the electric vehicles still depends on the opportunity presently not available to produce endless renewable electricity without any consumption of carbon and hydrocarbon fuels, from an engineering perspective the building blocks of an electric vehicles are subjected to rapid improvements.

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