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Efficiency and performance testing of electric vehicles and the potential energy recovery of their electrical regenerative braking systems

PEC624 M.Sc. Renewable Energy Dissertation

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Abstract

Fossil fuels are the main energy source used in the transport sector and as such significantly contribute to pollution and health issues, particularly in large cities. Furthermore, relying on a single energy source can lead to supply issues and problems with energy security. Electric vehicles (EVs) are a viable alternative to address these issues. EVs have the potential to be operated using a clean, renewable energy source. However, one of the main disadvantages of EVs is their short vehicle driving range. To address this issue an efficient design and operation of EVs are important. The aim of this project was to investigate the efficiency of two EV-converted Ford Focus, a Lotus Elise and one factory-built Mitsubishi MiEV. The efficiency of these 4 cars was compared by driving them on a chassis dynamometer in a controlled test environment according international standards. The first sets of experiments were carried out using the Ford Focus under different gearing to investigate the effect of gearing on energy consumption and driving range. The second part of the project investigated the efficiency improvement by regenerative braking systems (RBS) from the Lotus and MiEV driving the cars under different RBS settings and different speed profiles. The results have shown that the energy consumptions and drivable range between identical cars driving under different gearing varied significantly. This finding showed than an appropriate gearing of EVs is an important factor for their efficient operation.

The efficiency improvement and RBS performance of the two different EVs with RBS varied considerably. Under certain conditions, an appropriate gearing can operate an EV more efficiently than the support of an RBS. The results showed that for an efficient operation an RBS must be optimized, finetuned and calibrated to match the load. To maximise the RBS performance it should be interfaced with an antilock braking system (ABS).

In summary, the investigations of this project have shown that the design and configuration of EVs are very important factors for its efficient operation. Further investigations on EV efficiency and RBS performance might include real road testing and taking topographical and traffic conditions into account.

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Table of Content

Acronyms

ABS	**Antilock Brake System**
Ah	**Ampere Hours**
ECE	**Economic Commission for Europe**
EPA	**Environmental Protection Agency**
EUDC	**Extra Urban Drive cycle**
EV	**Electric Vehicle**
FTP	**Federal Test Procedure**
NEDC	**New European Drive cycles**
NI	**National Instrument**
RBS	**Regenerative Braking System**
SOC	**State of Charge**
UWA	**University of Western Australia**

1. Introduction

A large amount of energy used in the transport sector is based on fossil fuels. In the U.S. for example, 25% of the total energy used in 2009 was for transport and based on fossil fuels [1]. Besides potential issues with future supply, the burning of fossil fuels in motor vehicles is a significant contributor to air pollution in large cities. The International Energy Agency IEA claims transport accounts for about 25% of the total global CO_2 production [2]. In addition, air pollution causes health issues and increased mortality in people through the exposure to exhaust gas emissions and particulate. An air quality study has shown that emissions from the burning of fossil fuels caused around 13000 premature deaths in the UK per year. According to this study, the number of premature death from the transport sector is comparable to the number of death due to road accidents [3]. Electric vehicles (EV) are a viable alternative to motor vehicles and can contribute to reduce both fuel supply risks and air pollution, provided the energy to run EVs is supplied from local, renewable energy sources. However, the mainstream use of EVs has been hindered by issues such as high purchase costs, short vehicle driving range, limited recharging stations and time consuming recharging of the batteries [4].

The idea of the EV is not new. In place of a combustion engine an EV uses one or more electric motor for propulsion. EVs first appeared in the mid 19th century. During these years motor vehicles required some effort to be hand started. EVs required no combustion engine start and provided comfort and ease of operation. After the invention of the electric starter motor for combustion engines many EVs disappeared from the market and the internal combustion engine became the dominant propulsion method for cars. In 1997, Toyota appeared with its Prius, the first mainstream hybrid EV [5]. These hybrid cars were developed for a better fuel economy or performance. A hybrid car combines a combustion engine and an electric motor for propulsion. The interconnection and configuration of hybrids varies depending on the demanded properties of the car. Toyota reached a cumulative sale of 2 million Prius vehicles by 2010 making it the world's best selling hybrid car. CNN claims that by the end of 2012 most major car manufacturers will have a plug-in car available for sale [6]. Some EV enthusiasts did not want to wait so many years until major car manufactures provide EVs. For example, already in 1973 the Australian Electric Vehicle Organisation was founded [7]. The organisation provides forums for social and technical communication to support local car conversion industry such as EV works in Lansdale W.A. [8] or Electric Vehicle Conversions in Balcatta W.A. [9]. These companies offer the conversion of a standard car into an EV. Further trend towards manufacturing EVs are outlined in a report by the U.S. department of energy. President Obama's goal of one million EVs by 2015 should represent a milestone to reduce dependency of oil [10].

To reduce the issue of the short vehicle driving range of a pure EV, major manufacturers of EVs are incorporating regenerative braking system (RBS) into EVs to increase their efficiency and range. In contrast to a friction brake, which is converting the vehicle's kinetic energy into heat, a RBS is converting kinetic energy into a storable form of energy such as electricity. During regenerative braking, the electric motor acts as a generator. The generated electricity can be stored in the battery and the electricity can be reused later on demand [11]. Disadvantages of an electric RBS include the potential of load matching, higher manufacturing costs and in some instants increased vehicle weight [12]. Measuring the performance and efficiency of RBS in EVs is a complex task as there are many, constantly changing environmental factors such as changing wind speed and direction, temperature, ascending and descending slopes, which provides an unstable test environment. The changing environmental conditions might negatively influence results such as the vehicles energy consumption and the electricity generated by the RBS. This problem can be overcome by using a chassis dynamometer. A chassis dynamometer is a device capable of measuring forces on a cars wheels or engine. Some advanced chassis dynamometers are computer controlled and are capable of simulating the driving of a car as it would be driven on a real road. A main benefit of a chassis dynamometer is that provides a stable testing environment in which the performance of the EV and its RBS can be measured and characterized. The measured energy consumption of the vehicle allows the calculation of the efficiency improvements by the RBS by comparing the energy recovered to the energy consumed. A study about the general performance of RBS on a city bus and about different charge efficiencies driving under different battery state of charge (SOC) by Junzhi Zhang [13] lead to the research question of what is the actual energy consumption, drivable range of EVs and the overall efficiency of an RBS implemented in an EV. Some of these questions will be addressed in this research project and outlined in the following thesis.

After outlining the project aims and objectives in the remainder of the introduction, Chapter 2 provides background information about previous studies on RBS and vehicles energy recovering systems used in EVs. Chapter 3 provides an overview of the test methods, the vehicles and the experiments involved in this project. Chapter 4 presents the results from the vehicle testing which are further discussed in Chapter 5. Finally, Chapter 6 presents the conclusions and recommendations.

1.1. Project Aims and Objectives

The objective of this project was twofold. The first aim was to compare the electricity consumption of two cars driving under different gearing by measuring the electrical energy consumption of two converted pure-EVs under the same driving patterns. One of the cars was designed with an automatic gear dive and the other car with a manual gear drive. In addition, the second aim was to determine how much electricity can be regenerated by an RBS and its overall efficiency implemented in two different cars. This was achieved measuring the regenerated electricity and comparing the improvement of the energy consumption of the two different EVs by driving them under different vehicle configurations, driving patterns and different SOC.

To meet these two aims the following objectives were defined:

- Conduct tests to see whether a different gearbox or a more appropriate gear selection can save more energy than a costly RBS.
- Conduct tests to see how much energy can be recovered by a RBS during different international drive cycles and different SOC.
- Examine the data to see how different vehicle configurations and different driving patterns influence energy consumption and vehicle driving range

The testing was conducted on a chassis dynamometer at the Orbital facilities in Balcatta. The project involved 4 different fully electrical cars provided by the University of Western Australia and a Mitsubishi dealership in Osborne Park W.A. The custom made instrumentation system was used to measure the electric current, voltage and the distance driven during the experiment. For cars with a RBS, the electric energy used and produced by the RBS was calculated from the logged data. The overall efficiency was the energy recovered as a ratio of total energy consumed by the EV.

The project was restricted to the testing of pure EVs on chassis dynamometer. Hybrid cars were not considered as were other test procedures such as Advanced Vehicle Testing Activity (AVTA) [14]. Furthermore, all the driving for the measuring of the energy consumptions was conducted on a computer controlled chassis dynamometer with road load simulation and therefore the effect of driver behaviour is not included in this study.

2. Background and Literature Review

The following literature review describes the kinetic energy recovery systems that are currently implemented in passenger cars. The review also describes how researchers try to improve the efficiency and overcome the limiting factors of RBS by testing and implementing complex strategies for the control of a RBS. Furthermore, international drive cycles used in industry for homogeneous performance and RBS tests are introduced and the importance and disadvantages of drive cycle analyses are discussed. Finally, the review discusses previous EV evaluation testing with its pitfalls and lessons learnt from these studies.

2.1. Theory

Motor vehicles have limited driving range before they require refuelling. For vehicles with combustion engines there is a wide-spread refilling infrastructure available. The vehicles can be refuelled within a couple of minutes. Current options for recharging an EV are limited to homes, some workplaces and to a few official charging stations. A further disadvantage is that current recharging times for EV are relatively long. For an optimized EV range, an efficient EV design and operation is important. The energy from the fuel or electricity is used to move a vehicle and is used to overcome the rolling resistance, the aerodynamic drag, the friction of the vehicle's drive train and the vehicle's inertia. Slowing down a vehicle requires braking. Conventional friction brakes convert the vehicle kinetic energy into heat and hence the energy is lost and not reusable any more. One option to reduce heat loss and increase efficiency is to recover some of the kinetic energy from the moving vehicle by an RBS. The energy *E* in Joules in a moving object is defined by:

$$E = \frac{1}{2}mv^2 \qquad (1)$$

Where *m* is the mass in kg and *v* the speed in meters per second [15]

The following shows an example of a Mitsubishi MiEV with a mass of 1125kg driving at 120km/h.

$E = 1/2 * 1125\text{kg} * (120 * (1000\text{m}/3600))^2$

$E = 625 \times 10^3$ Joules or 0.174 kWh

If the vehicle would be slowed down by a brake it would convert 0.174 kWh into heat, ignoring drive train friction and the losses due to the car's air resistance. The same kinetic energy would be available to an RBS and hence would be available or later reuse. But as with any other energy conversion system not all of the energy can be recovered due to losses in the energy conversion system.

2.2. Vehicle Kinetic Energy Recover Systems

Today, conventional vehicles use mechanical friction brakes that convert the vehicle's kinetic energy directly into heat. This heat energy cannot be used by the vehicle and is considered waste energy. Braking systems that convert energy into a reusable and storable form are known as RBS [11]. During deceleration a vehicle energy recovering system converts available kinetic energy into a reusable form and preferably into a form that can be stored and used later as demanded. The energy recovery system contains an energy conversion device and preferably an energy storage system. The available kinetic energy from the moving vehicle can be converted in to another form of kinetic energy or into potential energy. To safely slow down a vehicle, its relatively large kinetic energy needs to be converted in a controlled manner to prevent stress on the vehicle, its equipment and passengers. Where some modern cars with combustion engines implement fly wheel technology to recover energy [16], a more common technology in EVs is to convert kinetic energy into electro-mechanical energy and store the generated electricity in batteries or super capacitors, as is done in an RBS. A disadvantage of this approach is that a RBS cannot be operated on a vehicle as a single braking system only. For the case of emergency braking, as a backup braking system and for parking the vehicle needs to have a conventional friction braking system as well.

Other, less common RBS technologies used in automotive industry, are mechanical springs or compressed air absorber in which the kinetic energy is stored as potential energy in a spring or compressed air are not further discussed in this report [17] [18].

2.3. Electro-Mechanical RBS

An electro-mechanical RBS converts the kinetic energy into electricity by using its driving motor in reverse and operating it as a generator during deceleration. The more electric current produced by the generator the faster the rate of deceleration of the vehicle. The generated energy is used to charge the vehicle's batteries or capacitors such that the energy can be used later on demand. The design and performance of an electro-mechanical RBS was investigated by Zhang Junzhi [13]. This study involved the design and performance testing of an electro-mechanical RBS system on a hybrid electric bus. The aim of the study was to model and test the RBS system under real road conditions. The testing was conducted according to a Chinese urban bus drive cycle profile. The theoretical available kinetic energy from the driving bus was compared with the energy recovered from the RBS. The efficiency of energy regeneration from real road braking was a considerable 64%.

Despite the efforts of the authors in designing and testing the RBS, the overall energy recovery compared to the total energy consumption over the entire drive cycle was not investigated. The potential of a high efficient electric RBS and the lack of information about the overall efficiency during a whole drive cycle are motivating the research questions and demonstrate the need for the experiments carried out in this thesis.

One of the limiting factors of an electric RBS is the friction between the wheels and the road, given as the friction factor. The maximum available friction of a wheel is influenced by environmental factors such as temperature, rain or snow on the road. It is not possible to recover more energy than what can be transmitted by the friction of the wheels. A fully applied electrical RBS can cause the wheels to slip or lock and can create unstable and dangerous driving situations. Modern electric cars with RBS transmit data between the antilock braking system (ABS) and the RBS system to utilize the maximum possible energy transfer through the wheels without the wheels locking up. As a consequence, the design of RBS systems is very complex and involves additional costs for the design of software and hardware. This additional cost is a disadvantage of RBS and can form a major hurdle to their implementation. The complexity and design efforts for such an optimised system are the subject of a study by D.Peng [19]. This study investigates the limiting factor associated with slipping or locking wheels during braking of a vehicle. The challenge was to control the hydraulic pressure applied to the frictional brakes but also the level of interaction of the RBS during the braking process. The developed strategy was first modelled in simulation software and then tested in a real vehicle. To prove the modelled data in practice and to investigate the efficiency of the RBS, the vehicle was driven and tested on a chassis dynamometer driving a New European Drive cycle (NEDC) as well as on a real road. Figure 1 has been reproduced from Peng et al. and shows an example of a drive cycle profile and the results of a NEDC drive cycle test. The velocity traces recorded the vehicle speed over time. During deceleration of the vehicle a regenerative braking torque, as indicated by the negative trace, reaches up to

1000Nm. In addition to validating the data from the simulation and the chassis dynamometer test, the road testing provided real road data about wheel slip and vehicle safety. The results showed that the data from modelling of an RBS strategy agreed with the results of chassis dynamometer and real road driving and hence demonstrated that chassis dynamometer testing can provide valuable and realistic data for system design and performance testing.

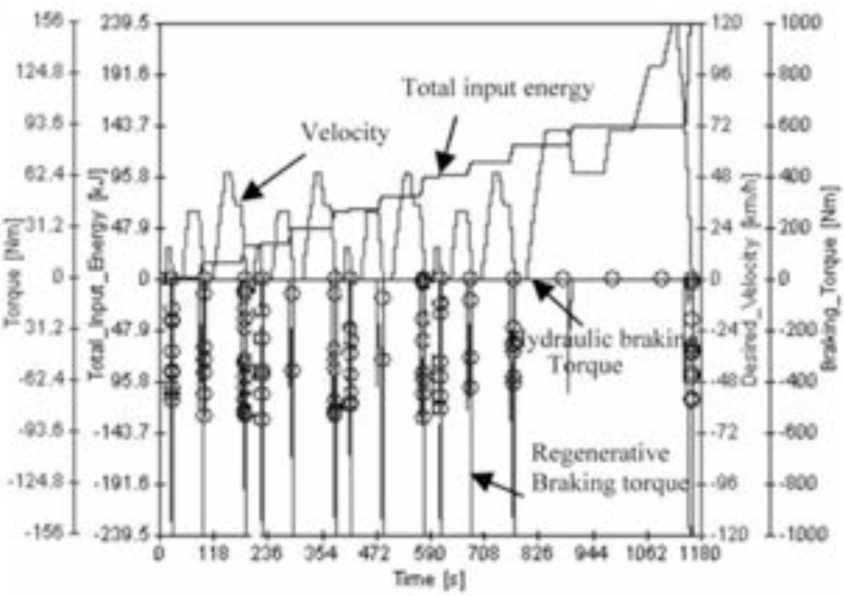


Figure 1: Results of a NEDC indicating vehicle speed and the available potential kinetic energy of the car [Source: [19]]

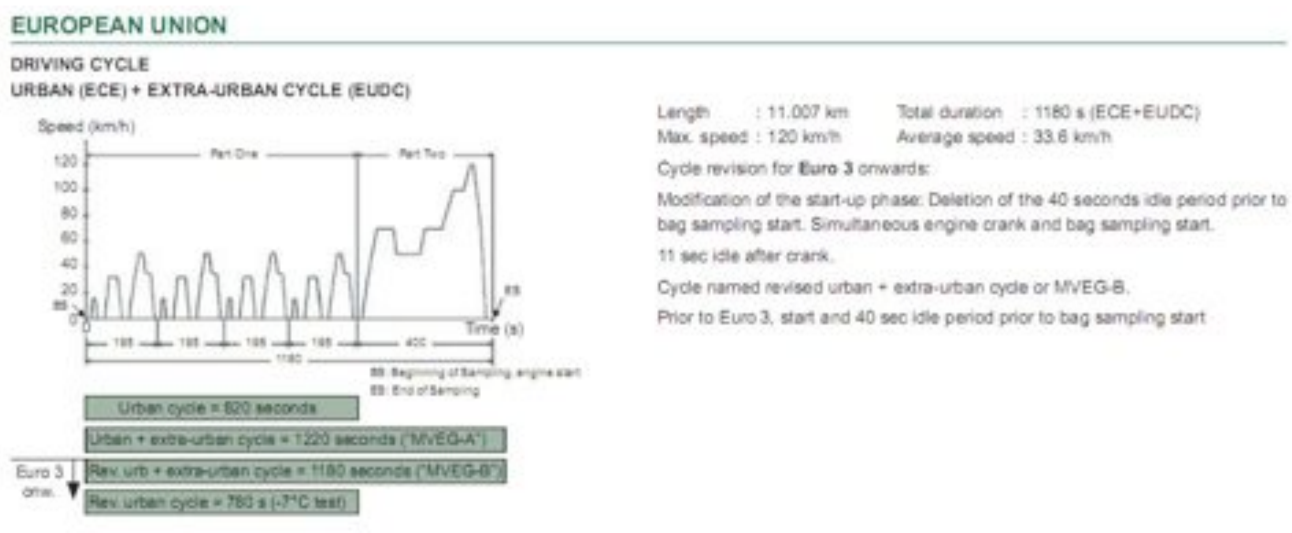
In addition to the limited traction of a wheel, another limiting factor of the RBS performance is the electrical system design in the EV. Electric motors, controllers, batteries and cable size are limiting the amount of energy transferred from the wheels to the electrical system. Systems with load mismatch put stress on under-designed components, create heat and hence cause a loss of efficiency. Furthermore, RBS efficiency is limited by the SOC of the vehicle’s battery. Lithium-Ion batteries currently used in EVs are sensitive to overcharging [20]. Therefore a fully charged battery cannot absorb any more electrical energy from an electrical RBS. Another limitation of a RBS is the vehicles driving pattern. Vehicles with RBS driven on a highway without slowing down cannot recover usable energy and hence there is no benefit of an installed RBS.

2.4. Drive cycles

Drive cycle testing was developed in the late 1960's [21] for uniform emission testing on passenger cars with combustion engines [22]. A drive cycle should represent a common driving pattern of motor vehicle users. Testing is usually performed on a calibrated chassis dynamometer following such a drive cycle. This provides vehicle testing in a stable, climate controlled and traffic free environment. A drive cycle is a predefined speed and acceleration profile. For a specific vehicle test, the test driver of the motor vehicle is required to follow the profile. To drive at the required speed along the profile a computerized driving aid supports the driver by indicating the rate of acceleration and deceleration of the vehicle. Figure 2 shows a typical computer driving aid used in industry for vehicle testing. The blue line in the centre of the track is the indication of required speed to be driven. The red lines show the driver the maximum allowed speed deviation for a valid test drive. This tolerance is critical because the rate of acceleration, deceleration and vehicle speed influences emissions and the energy consumption of a vehicle, thus influencing the test results.

Figure 2: Computerized driving aid for a test driver required to follow a predefined drive cycle used during the testing at Orbital.

There are several international standards for chassis dynamometer drive cycles designed for combustion engine cars for different countries. For example Figure 3 shows the New European Drive cycles (NEDC), introduced in 2000 [23], containing the European Union Urban Drive cycle and the extra urban cycle (EUDC) applied for emission testing for Euro 3 standards and onwards. The first section represents the European Union Urban drive cycles from the Economic Commission for Europe (ECE) section with a slow suburban driving for 780 seconds. The second part represents a high way driving speed pattern for another 400 seconds at much higher speeds and no stopping.



Length : 11.007 km Total duration : 1180 s (ECE+EUDC)
Max. speed : 120 km/h Average speed : 33.6 km/h

Cycle revision for **Euro 3** onwards:

Modification of the start-up phase: Deletion of the 40 seconds idle period prior to bag sampling start. Simultaneous engine crank and bag sampling start.

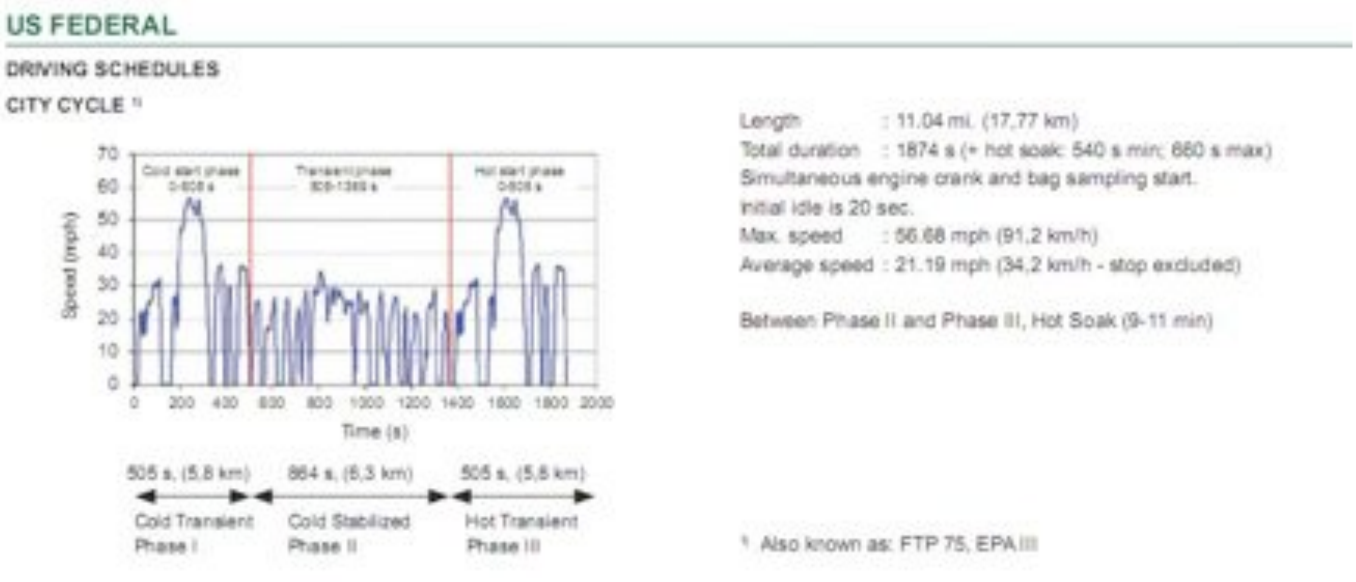
11 sec idle after crank.

Cycle named revised urban + extra-urban cycle or MVEG-B.

Prior to Euro 3, start and 40 sec idle period prior to bag sampling start

Figure 3: A speed profile for the European Union Urban Drive Cycle (ECE) and the extra urban cycle (EUDC) [Source: [22]]

Figure 4 and Figure 5 show other common drive cycles. Figure 4 is the first part of the US Federal city driving pattern for vehicle testing also known as FTP 75 (Federal Test Procedure) and EPA III. Its steeper curves and higher speed indicate a more aggressive acceleration than the ECE. Figure 5 shows the second part, of the US Federal driving, the highway driving, that represents driving on a freeway with no stopping and little deceleration. The above mentioned drive cycles contain different pattern and properties. The high dynamic variation in the US city cycle probably represents a more real world driving scenario than the Urban ECE cycle with its flat shaped profile.


US FEDERAL

DRIVING SCHEDULES

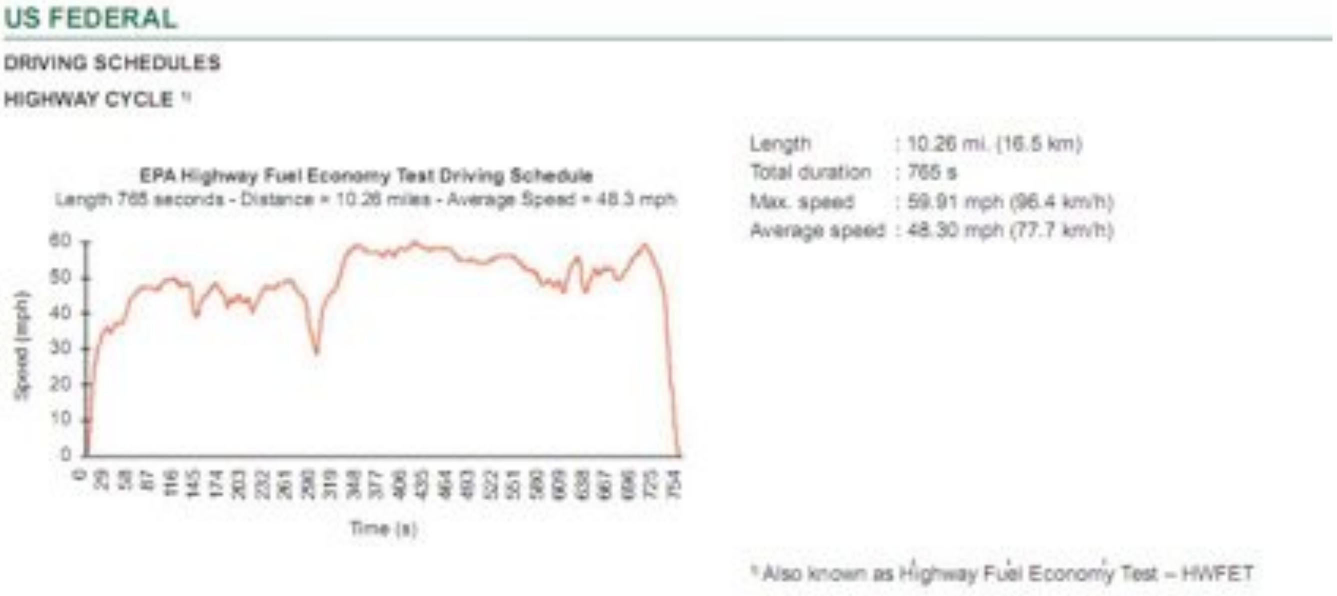
CITY CYCLE [1]

Length : 11.04 mi. (17.77 km)
Total duration : 1874 s (+ hot soak: 540 s min; 660 s max)
Simultaneous engine crank and bag sampling start.
Initial idle is 20 sec.
Max. speed : 56.68 mph (91.2 km/h)
Average speed : 21.19 mph (34.2 km/h - stop excluded)

Between Phase II and Phase III, Hot Soak (9-11 min)

[1] Also known as: FTP 75, EPA III

Figure 4: US Federal drive cycle for vehicle testing [Source: [22]]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DRIVING SCHEDULES

HIGHWAY CYCLE [1]

Length : 10.26 mi. (16.5 km)
Total duration : 765 s
Max. speed : 59.91 mph (96.4 km/h)
Average speed : 48.30 mph (77.7 km/h)

[1] Also known as Highway Fuel Economy Test – HWFET

Figure 5: The second part of the US Federal drive cycle representing a driving on a Hwy [Source: [22]]

Current drive cycle standards are also used for EV testing [24]. Drive cycles provide not just a uniform testing procedure for range testing and energy consumption testing but also for other performance testing including the evaluation of RBS and ABS.

Although the predefined driving pattern provides a stable test procedure and vehicles with different systems and configurations can be compared, it might not always reflect a real road situation. In the real world there might be hills and different traffic patterns influencing the performance, efficiency and energy consumption of a vehicle. Therefore under certain conditions results from such a laboratory test environment can vary from real world driving. Performance results also can be influenced by the driver's driving style [25]. A study conducted by the University of Sheffield [26] investigated energy consumptions on pure EVs driven on chassis dynamometer and real road driving. The vehicle was a factory Smart-ed. Part of the project was a range test and an energy consumption test. For the laboratory range test vehicles were driven on a chassis dynamometer over certain drive cycles until the battery capacity was exhausted and the total recorded distance considered as the vehicles' range. The test was repeated for different driving patterns. The range for the Smart-ed in laboratory testing was between 105.66km and 114.68km depending on the selected driving pattern. These results demonstrated how different drive cycles influence the range and performance of the vehicle. The real road testing with three different drivers showed an even bigger variation in vehicles range. The maximum drivable distance between the three drivers ranged from 61.2km to 74.0 km. [11]. Further investigations confirmed results of inconsistent fuel consumptions by test driving vehicles on real roads with different drivers. On a real road electric car range tests including a pool of 25 different drivers the vehicles drivable distance showed a large range from 56km to 107km, or a 52% variation in range. [26]

This study highlighted, that there is a significant deviation between drivers on real road testing and how this affects the range and fuel consumption of the vehicles tested. It emphasises the importance of chassis dynamometer testing for benchmark range and energy consumption tests to achieve realistic, stable range results. For example, for official and uniform energy consumption testing and labelling the Australian government requires vehicle testing according the Australian Design Rule 81/02 [27].

2.5. Electric Vehicle Evaluation Testing

In 2010 an infield EV evaluation study was conducted by the University of Western Australia (UWA) [28]. The objective of the project was to investigate and document the vehicle performance of a standard petrol operated Hyundai Getz, a EV converted Hyundai Getz and a converted EV Lotus Elise. In addition, the study aimed to investigate the relationship between real roads testing and chassis dynamometer testing and hence vehicle testing was conducted on a real road as well as using a chassis dynamometer according to a predefined speed profile. The testing of the vehicles was conducted according to the Australian Design Rule 81/02, driving a NEDC drive cycle. Analysis of the chassis dynamometer testing has shown that the chassis dynamometer was not able to simulate road loads such as vehicle mass, friction and air resistance. Without the simulated loads the chassis dynamometer was acting just as a brake and test conditions did not agree with real road driving conditions. The missing road load simulation on the chassis dynamometer had a significant impact on the results and underestimated energy consumption. Furthermore, the project results were negatively influenced by factors such as vehicle accessory power consumption due to e.g. air-conditioning, fluctuating real road driving conditions from changing traffic, and inappropriate instrumentation and testing equipment. The project also faced problems in the availability of the Lotus car due to road licensing issues. The project has shown that a stable, reliable, test environment is very important for reliable energy consumption measurement.

The report provided the current research project with valuable information and raised warning flags about the pitfalls in addressing technical, vehicle construction and measurement issues for such a project.

3. Methods and Test Equipment

All vehicle testing was conducted at the facilities of Orbital Engines in Balcatta, which provided calibrated test equipment and instrumentation in particular a chassis dynamometer with the capability of road load simulation. The test facilities fulfil the requirements for the testing of motor vehicles according to international standards. The facilities were adapted to be suitable for EV testing by installing additional equipment as described below. The existing chassis dynamometer instrumentation was able to log the following parameters during the drive cycle analyses.

- Exhaust gas analysers (not used in this project)
- Ambient temperature
- Vehicle speed
- Dynamometer force

The computer of the chassis dynamometer contained pre-programmed drive cycles that represent internationally recognized drive cycles as outlined in section 2.4.

3.1. Vehicle Instrumentation

In addition to the existing dynamometer instrumentation systems a custom made data acquisition system was designed, build, programmed and calibrated by the author to log the following data:

- Date and time
- Vehicles main battery voltage (V)
- Main battery charge current (-A)
- Main battery discharge current (+A)
- Motor controller temperature (°C)
- Brake light status information (on/off)
- Brake pedal foot pressure (Kg)

Figure 6 shows the hardware and user interface for the custom built instrumentation. The core of the system was a National Instrument (NI) data acquisition unit. The user graphical interface software was designed for the particular task of measuring, displaying and logging vehicle data. The software was an open source application programmed in Labview and provided the option to modify the system during the project if required. The data sampling rate was 500Hz, averaged and stored on a text file every second. For example driving 1180 seconds an NECD drive cycle produced a text file with 1180 averaged data points. For analysing the data the text file was imported to Microsoft Excel.

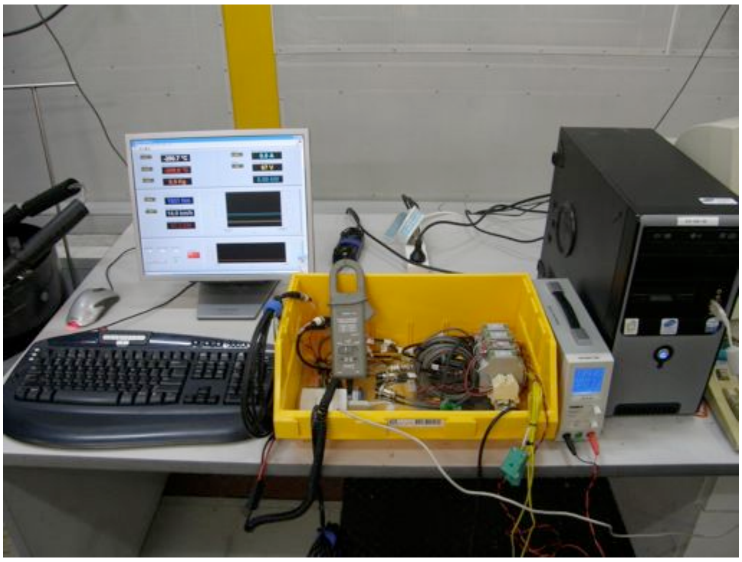


Figure 6: The custom built instrumentation hardware and user interface used for testing at Orbital test facilities

In addition to the custom built instrumentation, the two electric Fords were equipped with an installed energy meter from tbs-electronics [29] as shown in Figure 7. The measuring unit reported the main battery voltage (V), instantaneous current (A), accumulated ampere hours (Ah) and battery charge level in percentage (%) to the driver through a multi functional display. The inbuilt energy meter was an additional important instrument. The standard R101 [24] states that the vehicles recharge energy for the calculation of the vehicle’s electricity is measured on the wall socket. This has proved to be impractical for this experiment and the recharge energy was therefore measured by the TBS energy meter. This technical issue is further discussed under 4.1.1.

Figure 7: TBS energy meter indicating electrical system parameters [Source: [29]].

An additional instrumentation system was available for the Lotus. The EV was equipped with a highly developed, programmable EV motor controller and provided options for measuring and logging of the vehicle's performance data The main parameters include battery voltage (V), current (A) and motor speed (km/h).

3.2. Test Vehicles

Four fully EVs were used for the experiments in this project. Table 1 provides an overview of the four different EV vehicles and their configurations for testing:

Table 1: An overview of the EVs available for testing

Model	Gearbox	Battery	Motor	RBS	Factory EV
1.Ford Focus [30]	Manual	144V, 23kWh	80kW	No	No
2.Ford Focus [30]	Automatic	144V, 23kWh	80kW	No	No
3.Lotus Elise [31]	Manual	320V, 19kWh	54kW	Yes	No
4.Mitsubishi MiEV [32]	Automatic	330V, 16kWh	49kW	Yes	Yes

3.2.1. Ford Focus

Figure 8 shows an image of one of the first two cars. Both were standard factory motor vehicles that were converted by EV-Works in Landsdale W.A. [33], into fully electrical cars. Both vehicles have identical electric main drive motors, controllers and batteries. The only difference is the gearing of the cars. Car 1 had a manual factory gearbox whereas car 2 had a factory automatic gearbox installed.

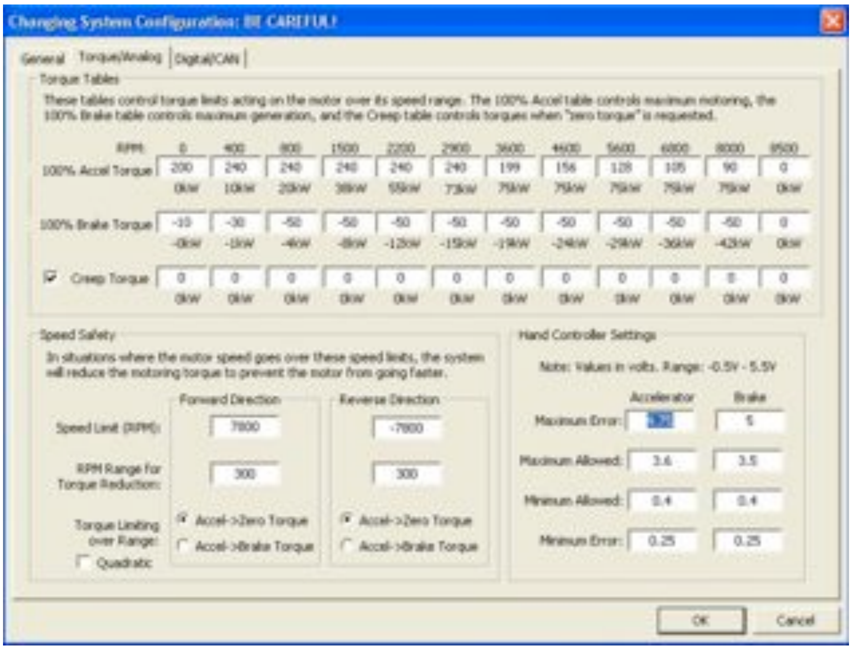
Figure 8: A Ford Focus converted EV [Source: [34]]

3.2.2. Lotus Elise

Figure 9 shows the third car, a Lotus Elise, designed and converted to a full electrical car by researchers at UWA [35]. It is equipped with a fully configurable electrical RBS. The motor controller provided connectivity to a PC for data logging and was configured before testing. The data were logged internally and downloadable in to an Excel spread sheet after the test.

Figure 9: Lotus Elise designed and converted by UWA [Source: [35]]

Figure 10 shows the GUI for programming the RBS settings. Due the risk of altering the settings to a level of dangerous wheel lock up the settings were left unaltered for testing.



Torque Tables

These tables control torque limits acting on the motor over its speed range. The 100% Accel table controls maximum motoring, the 100% Brake table controls maximum generation, and the Creep table controls torques when "zero torque" is requested.

RPM	0	400	800	1500	2200	2900	3600	4600	5600	6800	8000	8500
100% Accel Torque	200	240	240	240	240	240	199	156	128	105	90	0
	0kW	10kW	20kW	38kW	55kW	73kW	75kW	75kW	75kW	75kW	75kW	0kW
100% Brake Torque	-10	-30	-50	-50	-50	-50	-50	-50	-50	-50	-50	0
	-0kW	-1kW	-4kW	-8kW	-12kW	-15kW	-19kW	-24kW	-29kW	-36kW	-42kW	0kW
☑ Creep Torque	0	0	0	0	0	0	0	0	0	0	0	0
	0kW	0kW	0kW	0kW	0kW	0kW	0kW	0kW	0kW	0kW	0kW	0kW

Speed Safety

In situations where the motor speed goes over these speed limits, the system will reduce the motoring torque to prevent the motor from going faster.

	Forward Direction	Reverse Direction
Speed Limit (RPM):	7800	-7800
RPM Range for Torque Reduction:	300	300
Torque Limiting over Range:	● Accel->Zero Torque ○ Accel->Brake Torque	● Accel->Zero Torque ○ Accel->Brake Torque

☐ Quadratic

Hand Controller Settings

Note: Values in volts. Range: -0.5V - 5.5V

	Accelerator	Brake
Maximum Error:	[illegible]	5
Maximum Allowed:	3.6	3.5
Minimum Allowed:	0.4	0.4
Minimum Error:	0.25	0.25

Figure 10: User interface software for configuring the RBS performance though a PC interface from UQM [Source: [36]]

3.2.3. Mitsubishi MiEV

The fourth car shown on Figure 11, a Mitsubishi MiEV, is a fully electrical car factory built by a major car manufacturer.

Figure 11: Mitsubishi MiEV [Source: [32]]

In the MiEV the driver can choose between three pre-set factory RBS options as shown in Figure 12 . The RBS setting selection is available to the driver by a gear stick similar to that commonly used in automatic transmission designed cars. RBS setting mode C configured the

RBS with little braking effect while setting D provided a medium braking and B the most powerful regenerative braking.

Figure 12: The driver's options for the RBS settings [Source: [32]]

3.3. Vehicle Testing and Standard R101

The test method for the energy consumption and range tests were conducted according to the United Nations ECE Regulations R101 standard [24]. For the energy consumption test the standard requires the vehicles and the battery to be conditioned prior to testing. Such conditioning should provide uniform testing conditions for all types of vehicles and batteries. The key requirement included the vehicle's main battery to be in operation for at least seven days and have undergone driving of a minimum of 300km. Furthermore, the main battery was required to be discharged and fully charged prior to a performance test. In addition, the vehicles were required to be conditioned at a temperature between 20 °C to 30 °C and the vehicles tires inflated to the pressure specified by the vehicle manufacturer. For the test drive, the vehicle was required to be driven with all auxiliary devices such as heater and air-conditioner to be switched off. The test drive required two consecutive NEDC drive cycles with a maximum deviation of +/- 2km/h in the speed profile. After the test the vehicle was required to be recharged and the charge energy *E* to be measured. The electric energy consumption *C* is defined by the equation:

$$c = \frac{E}{D_{test}} \quad \textit{(expressed in Wh/km and rounded to the nearest whole number)} \tag{2}$$

where D_{test} is the distance covered during the test (km) [24]

For the range test the vehicles and batteries where required to be conditioned as for the fuel consumption test described above. The vehicle was required to drive continuous NEDC drive cycles until the battery was discharged. The end of the range test is defined by the standard as occurring when the vehicle cannot maintain 50km/h or an indication from the car informing the driver the vehicle must be stopped due to a low battery level [24].

3.4. Experiments

The first aim of the project was to determine the electrical energy consumption and the vehicles range of the two Fords, which is described in Experiments 1 and 2. The second aim was to measure the energy recovered by the RBS for the Mitsubishi MiEV and the Elise Lotus, covered by Experiments 3 and 4.

Prior to conducting the experiments the test vehicles were prepared as described above except the full discharging and recharging of the battery prior to testing was not possible due to the time restriction on the chassis dynamometer. The time on the chassis dynamometer was restricted due other ongoing projects and test driving conducted by the host company Orbital Engines. As other cars required access to the test area the electric cars were removed from the chassis dynamometer and recharged over night in a dedicated charging area. Therefore battery conditioning was limited to a full charge prior to testing. Furthermore the chassis dynamometer computers were configured with the individual vehicle curb weight and for the requested drive cycles. The curb weight is defined as the total weight of the vehicle equipped with essentials to operate [37].

3.5. Experiment 1: Ford Focus Manual, Energy Consumption and Range Test

The experiment investigated the energy consumption and the vehicle driving range under different gear selections. For the energy consumption test the vehicle was driven for two consecutive NEDC drive cycles in gear 2 and 4 where the city cycle and the highway cycle were driven in second and fourth gear, respectively. After fully recharging the batteries over night the vehicle was driven again for the same pattern in gear 3 and 4. After the completion of the energy consumption test the vehicle's battery was fully recharged and prepared for the range test. The range test involved driving continuous NEDC drive cycles in gear 2 and 4 until the battery was exhausted. After an overnight full battery charge the range test was repeated in gear 3 and 4.

3.6. Experiment 2: Ford Focus Automatic, Energy Consumption and Range Test

The experiment investigated the energy consumption and the vehicle driving range. Figure 13 shows the Ford Focus on an energy consumption test on the chassis dynamometer. The vehicle was driven for two consecutive NEDC drive cycles in automatic gear mode D. After the completion of the energy consumption test the vehicles battery was fully recharged over night before the range test was conducted. The range test involved driving continuous NEDC drive cycles until the battery was exhausted.

Figure 13: Ford Focus on a chassis dynamometer under test conditions at Orbital test facilities

3.7. Experiment 3: Mitsubishi MiEV RBS Performance Testing

This experiment investigated the energy consumption and RBS efficiency while driving under different drive cycles and using different RBS settings. Due to technical issues further discussed under 4.3.1, it was not possible to record voltage and current simultaneously and therefore these parameters were measured from two individual drive cycles. Table 2 shows the experiments in chronological order. Figure 14 shows the Mitsubishi MiEV under test.

Table 2: The experiments conducted on the Mitsubishi MiEV

Date and Time	**Drive cycle**	**RBS Settings**
12/4/2012, 12:44:58 PM	NEDC	D Mode
12/4/2012, 1:15:17 PM	NEDC	C Mode
12/4/2012, 1:47:48 PM	NEDC	B Mode
12/4/2012, 3:47:35 PM	US Federal HWY	D Mode
13/04/2012,8:26:08 AM	FTP75	D Mode
13/04/2012, 8:58:55 AM	FTP 75	B Mode
13/04/2012, 9:29:01 AM	FTP 75	C Mode
13/04/2012,10:59:00 AM	US Federal HWY	B Mode

Figure 14: The Mitsubishi MiEV under testing

3.8. Experiment 4: Lotus Elise RBS Performance Testing

Experiment 4 investigated the energy consumption and RBS efficiency driving under different drive cycles. Furthermore, the experiment investigated the influence of driving the car with a different battery SOC on the recharge efficiency. Figure 15 shows the Lotus on the first test which involved an NEDC drive cycle with a near fully charged battery with a SOC of ~90% and standard RBS settings. Continuing without recharging the second test involved an FTP75 drive cycle driving with standard RBS settings. The third driving test repeated the NECD driving but this time the SOC was ~30%.

Figure 15 Lotus prepared for testing on the chassis dynamometer.

4. Results

The overall aim of this project was to investigate the efficiency performance of 4 different EVs using chassis dynamometer tests. The experiments investigated the energy consumptions and maximum vehicle range on an automatic and a manual Ford Focus car. The performance and efficiency of the RBS was investigated by comparing a Mitsubishi MiEV and Lotus car. The following section presents the data collected during the drive cycles using the chassis dynamometer. The vehicles with RBS systems did not only use energy from the battery but also generated energy that was fed back into the battery. For this report, currents and energy with negative signs are currents generated by the RBS flowing in reverse, into the battery. Positive currents are currents flowing out of the battery into the motor.

4.1. Ford Focus Manual

This experiment involved the Ford Focus manual tested using an NEDC drive cycle according to the R101 standard. The aim was to measure the energy consumption and the maximum vehicles driving range.

4.1.1. Energy consumption

Finding the vehicle's energy consumption by just measuring the energy required to recharge the battery, as stated by the standard R101, has proved to be impractical for this experiment. This was due the restricted time available on the chassis dynamometer which meant the batteries were required to be charged unsupervised over night. This resulted in the problem that with available test equipment, the end of the charge process could not be exactly determined. Even after the batteries were fully charged the battery charger still used some energy for the battery charger and vehicles standby power. The battery charging data from a UWA REV project [38], logged from a Ford Focus showed how significant the energy consumption of a charger and standby power can be, even after the battery was fully charged. Figure 16 has been reproduced from the UWA research and shows an initial, relative high, charge current. At the end of the battery recharging process, the cumulative energy used for charging was 7.4kW. After this time the charger does not charge the battery anymore but uses energy for the battery charger and vehicle standby power. At the end of logging the charge currents, the cumulative energy used was 15.1 kW. This shows that over the three days 7.7 kW was just for the vehicles standby power and for the battery charger itself [39].

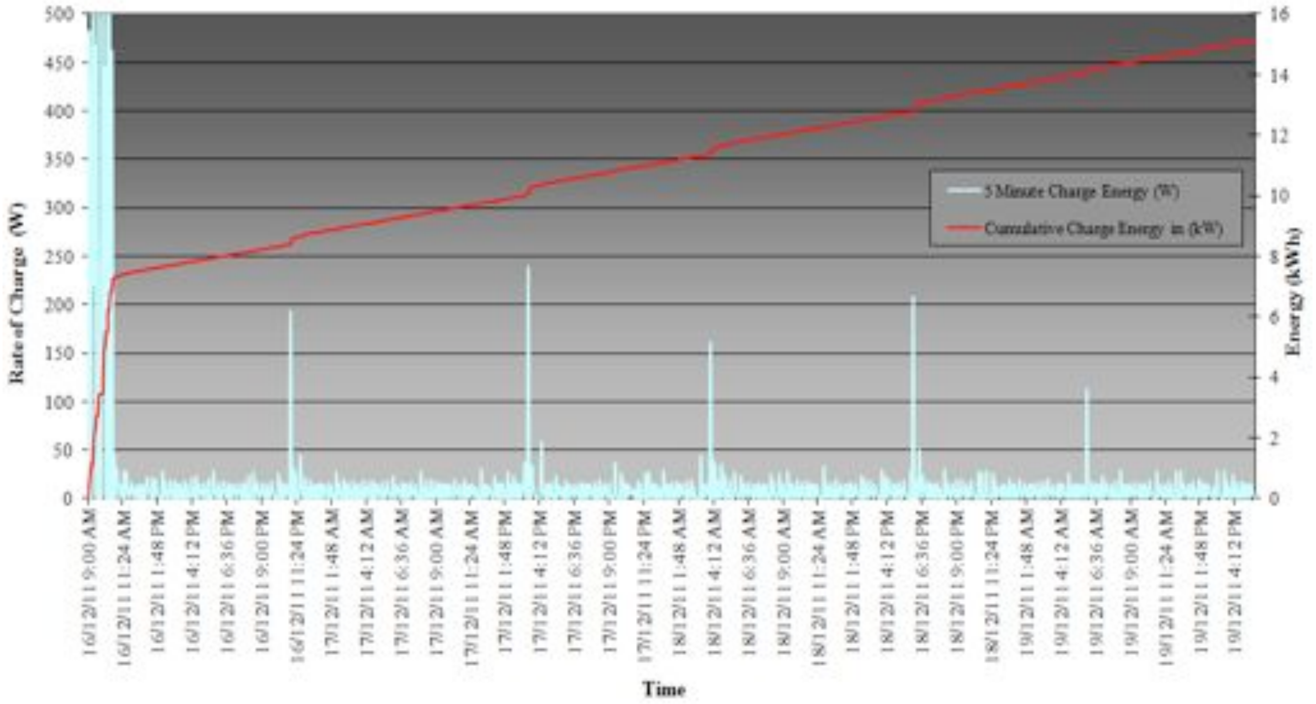
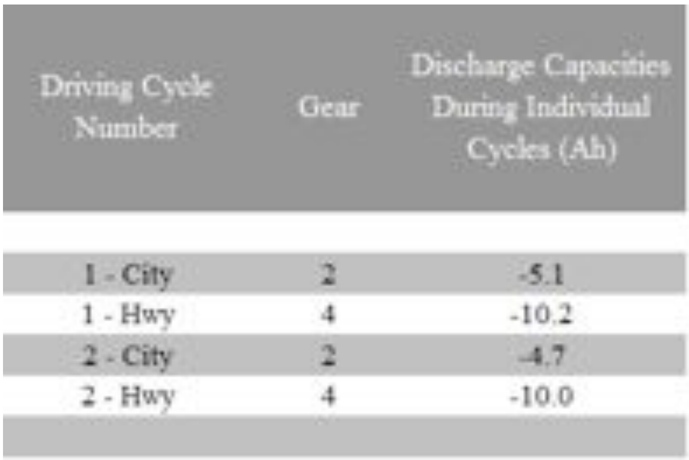


Figure 16: Cumulative energy used for battery charge and conditioning [Source: [38]]

Excessive energy used by the charger and vehicles standby power would influence the vehicles energy consumptions results. To overcome this problem the vehicles energy consumption was manually recorded from the cars internal TBS energy meter after the completion of each individual drive cycle. Table 3 shows the current used as indicated by the TBS energy meter during the driving of two consecutive NEDC drive cycles driven in second and fourth gear. After the first city cycle the reading was -5.1 Ah whereases after the following Hwy cycle the discharge capacity was -10.2 Ah. The lower discharge capacity for the second city and Hwy cycle of -4.7Ah and -10Ah respectively is assumed to be due to less friction of the driving train such as gearbox, bearings and tyres after warming up. This reduced discharge capacity on the second cycle was noticed on all other EV experiments.

Table 3: The discharge capacity (Ah) over two NEDC drive cycles driving the Ford Focus in gear 2 & 4



Driving Cycle Number	Gear	Discharge Capacities During Individual Cycles (Ah)
1 - City	2	-5.1
1 - Hwy	4	-10.2
2 - City	2	-4.7
2 - Hwy	4	-10.0

The car’s internal energy meter provided the discharge capacity in Ah. The energy consumption unit commonly used in the automobile industry and required by the R101 standard is Wh/km. For an approximation of the vehicle energy consumption in Wh/km the required voltages from the cars main battery was logged over the two drive cycles, averaged and multiplied by the recorded Ah displayed by the TBS meter. This technique was assumed to be within an acceptable accuracy since the voltage discharge curve of a Lithium-Ion cell or Lithium Polymer cell is relatively flat up to a discharge capacity percentage of about 80 %, as shown in Figure 17.

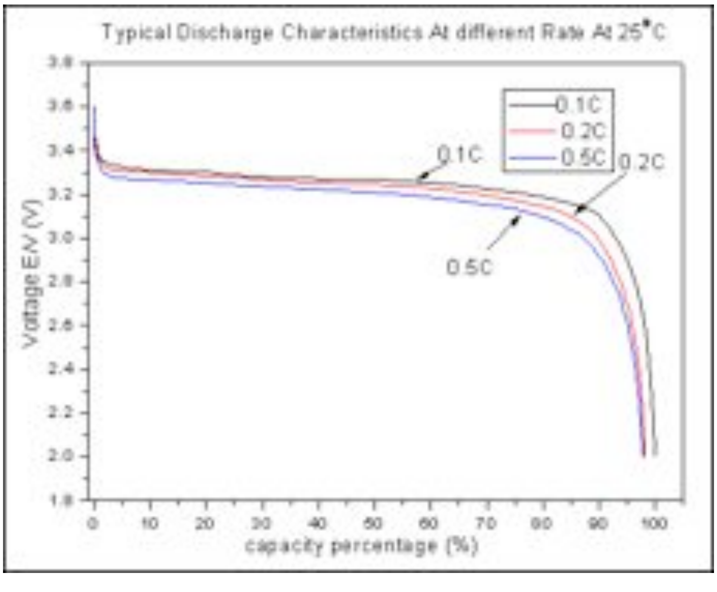
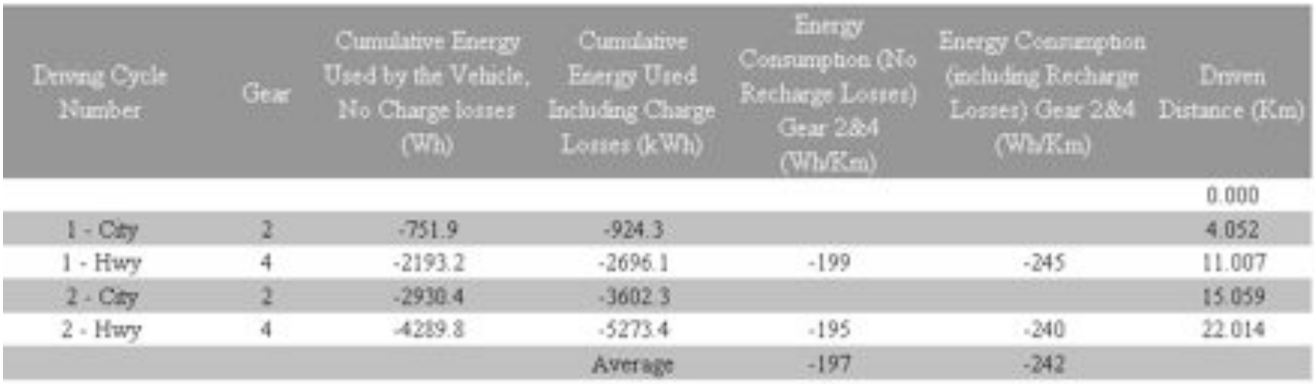


Figure 17: Typical discharge characteristic of Lithium ion cells [Source: [40]]

The charge energy (*C*) was then calculated using Equation 2 and multiplied by an assumed charging system efficiency of 0.81. The charging efficiencies were assumed to be 0.88 for the battery charger [41], 0.99 for the battery recharge efficiency [20] and 0.99 for the vehicles wiring system. The total cumulative energy was then divided by the driven distance in km for the energy consumption in Wh/km. Table 4 shows the calculated energy consumptions from two consecutive drive cycles in gear 2 and 4 without charge losses. After including the charge efficiencies the energy consumption was 242 Wh/Km compared to 197 Wh/Km without charge losses. The significant difference shows the effect of just measuring energy used by the car and energy used to recharge the car.

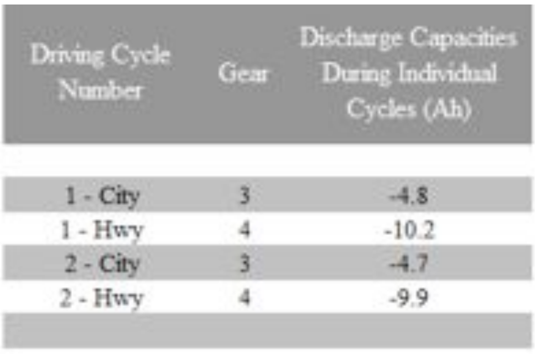
Table 4: The calculated energy consumption in Wh/km driving in gear 2 and 4



Driving Cycle Number	Gear	Cumulative Energy Used by the Vehicle, No Charge losses (Wh)	Cumulative Energy Used Including Charge Losses (kWh)	Energy Consumption (No Recharge Losses) Gear 2&4 (Wh/Km)	Energy Consumption (including Recharge Losses) Gear 2&4 (Wh/Km)	Driven Distance (Km)
						0.000
1 - City	2	-751.9	-924.3			4.052
1 - Hwy	4	-2193.2	-2696.1	-199	-245	11.007
2 - City	2	-2930.4	-3602.3			15.059
2 - Hwy	4	-4289.8	-5273.4	-195	-240	22.014
			Average	-197	-242	

Table 5 shows the discharge capacity from driving two consecutive NEDC cycles in gear 3 and 4. The discharge capacity for driving the first city cycle was -4.8 Ah whereases the car used -10.0 Ah for the subsequent Hwy cycle. As for the previous results, the lower discharge capacity for the second city and Hwy cycle of -4.7Ah and -9.9 Ah, respectively, is assumed to be due to less friction of the driving train such as gearbox, bearings and tyres after warming up.

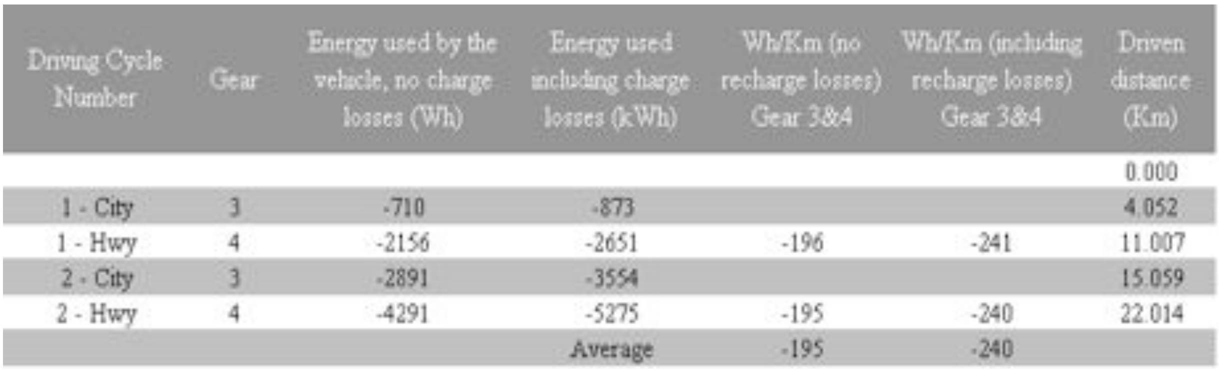
Table 5: The discharge capacity (Ah) over two NEDC drive cycles driving the Ford Focus in gear 3 & 4



Driving Cycle Number	Gear	Discharge Capacities During Individual Cycles (Ah)
1 - City	3	-4.8
1 - Hwy	4	-10.2
2 - City	3	-4.7
2 - Hwy	4	-9.9

Table 6 shows the calculated energy consumptions of 195 Wh/Km without recharge losses. Including the recharge losses in to the vehicles energy consumptions increases the calculated energy consumption to 240 Wh/km.

Table 6: The calculated energy consumption from driving in gear 3 and 4



Driving Cycle Number	Gear	Energy used by the vehicle, no charge losses (Wh)	Energy used including charge losses (kWh)	Wh/Km (no recharge losses) Gear 3&4	Wh/Km (including recharge losses) Gear 3&4	Driven distance (Km)
						0.000
1 - City	3	-710	-873			4.052
1 - Hwy	4	-2156	-2651	-196	-241	11.007
2 - City	3	-2891	-3554			15.059
2 - Hwy	4	-4291	-5275	-195	-240	22.014
			Average	-195	-240	

4.1.2. Range Test and Energy Consumption

This experiment involved driving the car continuously on NEDC drive cycles until the battery was exhausted. The achieved distance was the vehicle's maximum range. Over the 5 h and 15 min driving, the range test provided data of the maximum vehicle range. In addition, during the continuous driving, the individual discharge capacities for each drive cycle were recorded. Table 15 in the Appendix shows the individual discharge capacity and energy consumptions over the whole range test driving in gear 2 and 4 and the maximum achieved distance of 143 km when the battery was exhausted. During the course of the range test the energy consumption was stable. The significant higher current consumption during the last drive cycle was because the vehicles battery level was very low and was not able to maintain the maximum required speed of 120 km/h. The car was not able to complete the last Hwy cycle, marked with an asterisk (*) in Table 15. During the vehicles acceleration to the required speed of 120 km/h the battery level was too low to maintain the rate of acceleration and the manufacturing warning signal indicated to the driver to slow down the vehicle and stop.

Figure 18 shows the individual discharge capacities during the consecutive drive cycles until the battery was exhausted. The energy consumptions of the first drive cycles were slightly higher which is likely to be due less friction of the driving train such as gearbox, bearings and tyres after warming up. Towards the end of the range test the current consumptions during the

Hwy cycles increased. This was due to the lower battery voltage towards the end of the range test. The vehicles motor compensated the low battery voltage level by drawing more current from the battery to provide the same power.

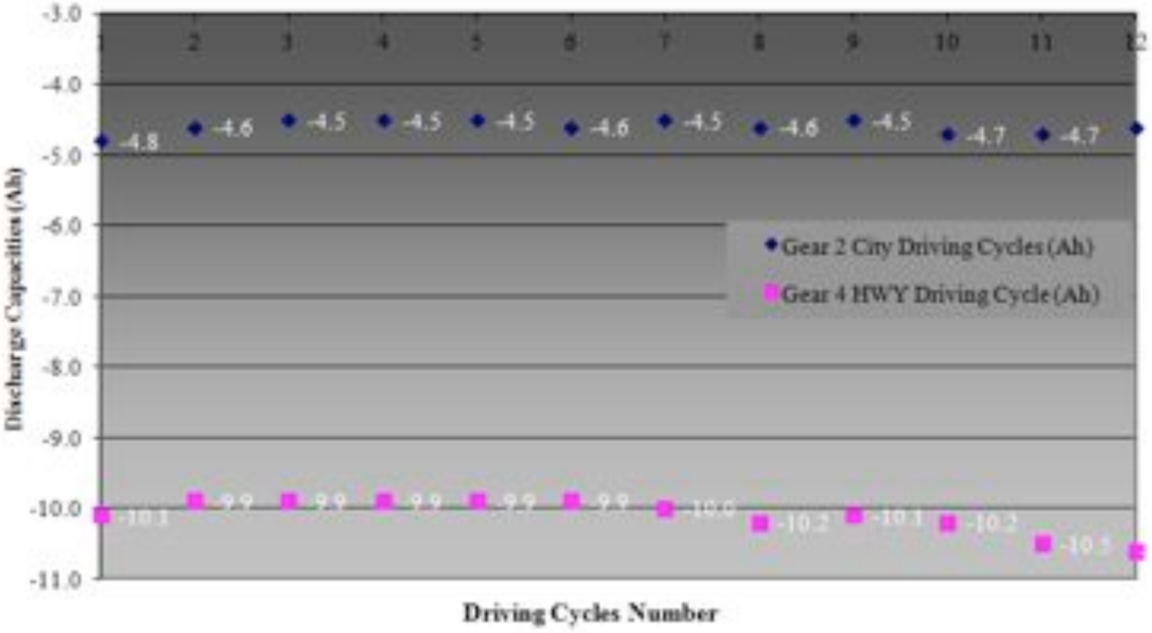


Figure 18: The individual discharge capacity versus the number of repeated drive cycles driving in gear 2 and 4 until the battery was exhausted

Table 16 in the Appendix shows the individual discharge capacity, energy consumptions and the vehicle's maximum range driving in gear 3 and 4. Over the 5 h and 30 minutes of driving the vehicle achieved a distance of 141 km. The graph on Figure 19 shows the individual discharge capacity during the drive cycles for the repeated drive cycles until the battery was exhausted. As during the previous experiment the discharge capacities of the first drive cycles where slightly higher than during the course of the range test. Towards the end of the range test the Ah readings during the Hwy cycles increased. This was also due the lower battery voltage level towards the end of the range tests. The vehicle's motor was required to draw more current from the battery to provide the same power for the required demand speed.

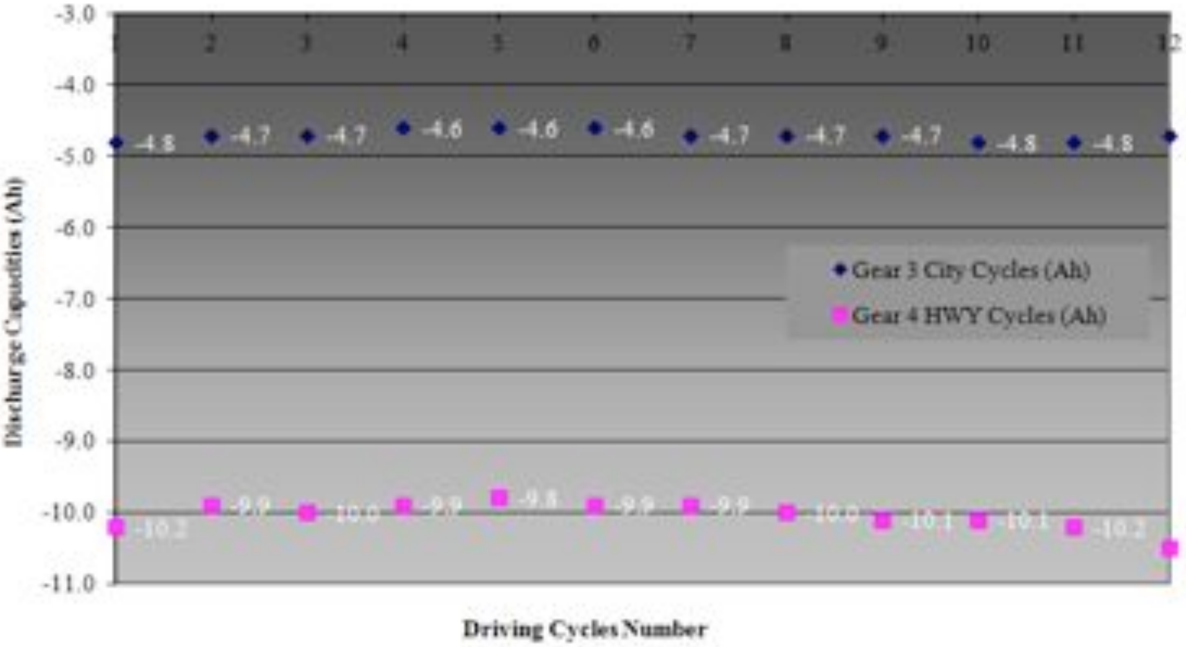


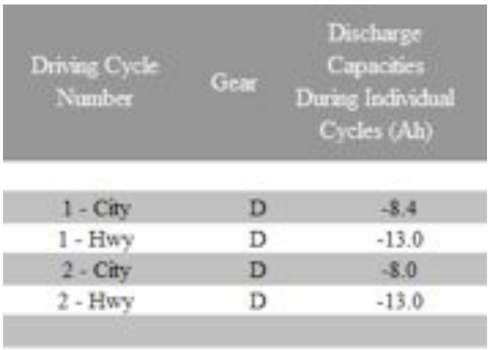
Figure 19: The individual discharge capacity versus the number of repeated drive cycles driving in gear 3 and 4 until the battery was exhausted

4.2. Ford Focus Automatic

4.2.1. Energy consumption

Table 7 shows the current (Ah) recorded from the TBS energy meter during the driving of two consecutive NEDC drive cycles driving in the standard automatic transmission gear selection D. After the first city cycle the Ah reading was -8.4 Ah whereases after the following Hwy cycle the reading was - 13.0 Ah. The lower discharge capacity for the second city cycle of -8.0 Ah is assumed to be due less friction of the driving train after warming up, as in previous experiments. The second Hwy cycle did not show a difference in current consumption compared to the first Hwy cycle.

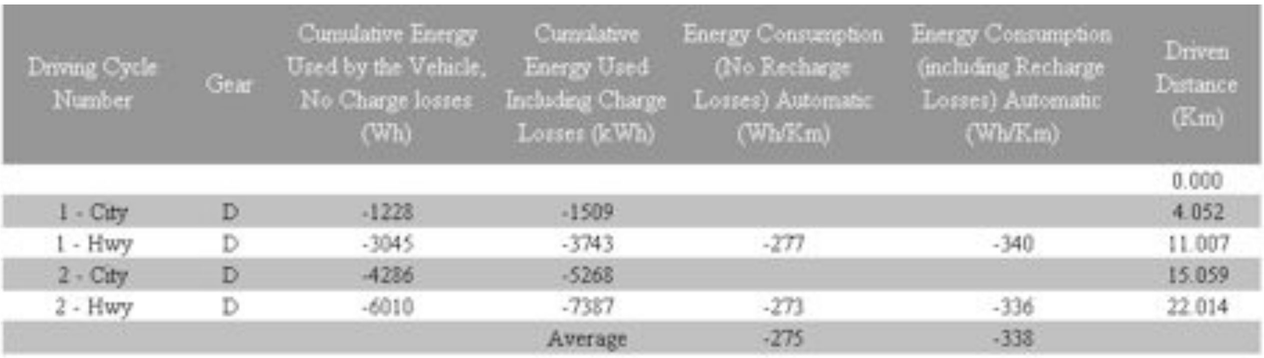
Table 7: The discharge capacity (Ah) over two NEDC drive cycles driving the Ford Focus automatic



Driving Cycle Number	Gear	Discharge Capacities During Individual Cycles (Ah)
1 - City	D	-8.4
1 - Hwy	D	-13.0
2 - City	D	-8.0
2 - Hwy	D	-13.0

For the Ford Focus automatic the energy consumption in Wh/Km was calculated the same way as with the Ford Focus manual discussed in section 4.1.1. Table 8 shows the calculated energy consumptions without recharge losses for the Focus automatic, reported as 275 Wh/Km. As expected, including the recharge system losses into the vehicle's energy consumptions increases the calculated energy consumption significantly, now reaching 338W h/km.

Table 8: The calculated energy consumption from Ford Focus automatic



Driving Cycle Number	Gear	Cumulative Energy Used by the Vehicle, No Charge losses (Wh)	Cumulative Energy Used Including Charge Losses (kWh)	Energy Consumption (No Recharge Losses) Automatic (Wh/Km)	Energy Consumption (including Recharge Losses) Automatic (Wh/Km)	Driven Distance (Km)
						0.000
1 - City	D	-1228	-1509			4.052
1 - Hwy	D	-3045	-3743	-277	-340	11.007
2 - City	D	-4286	-5268			15.059
2 - Hwy	D	-6010	-7387	-273	-336	22.014
			Average	-275	-338	

4.2.2. Range Test and Energy Consumption

Table 17 in the Appendix shows the individual energy consumptions and the maximum vehicle's range driving in gear D. The very low energy consumption of just – 2Ah during the last Hwy cycle, marked with an asterisk (*), was because the vehicle was not able to cover the whole distance due the exhausted battery. Over the 4 h and 45 minutes of driving, the vehicle achieved a distance of 94.1 Km. As during the experiments with the Ford Focus manual the experiment provided the opportunity to record the individual energy consumptions for each drive cycle. Figure 20 shows the individual discharge capacity over the whole range test until the battery was exhausted. As during the previous experiments the discharge capacity of the first drive cycles where slightly higher. Towards the end of the range test the Ah readings increased.

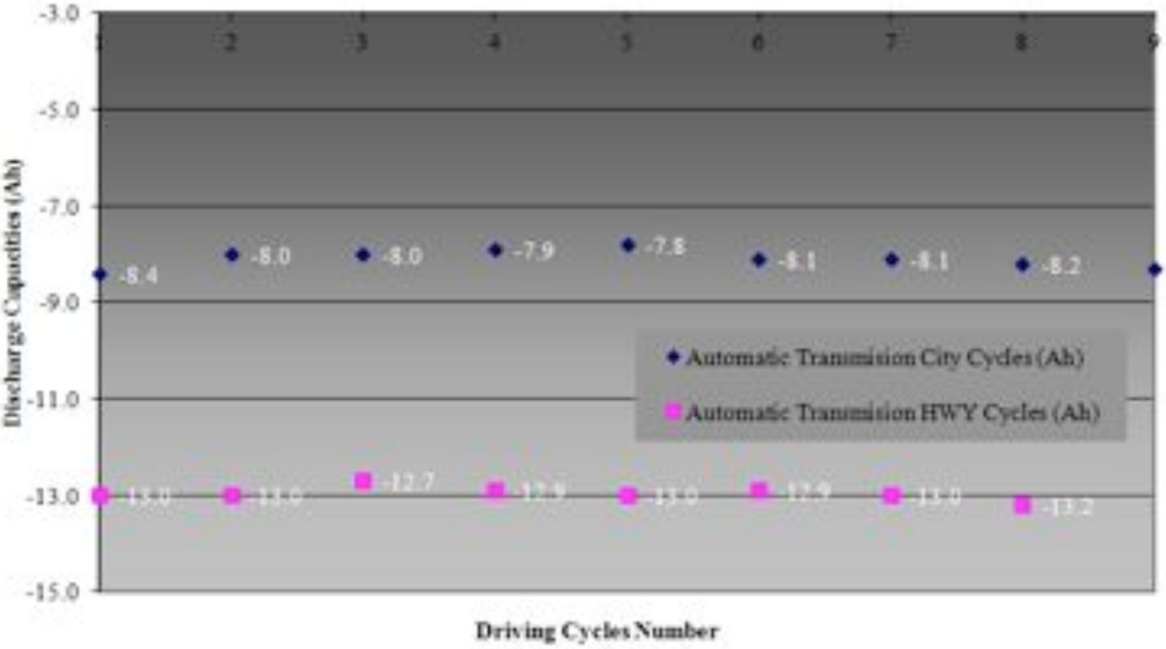


Figure 20: The individual discharge capacity for each drive cycles driving in automatic gear selection D until the battery was exhausted

4.3. Mitsubishi MiEV RBS Performance Testing and Energy Consumption

This experiment investigated the RBS performance and theoretical efficiency of the Mitsubishi MiEV by comparing the energy consumption driving different RBS settings and different drive cycles.

4.3.1. NEDC Drive cycle in RBS Mode C, D and B

To investigate the RBS performance, the first experiment involved driving according to the NEDC driving standard. Figure 21 shows the recorded speed and current profiles of driving in C, D and B-Mode. The potential energy from the moving vehicle is directly proportional to the speed and therefore the reproducibility of the vehicle speed over the three individual experiments was of great importance. Figure 21 shows how the speed profiles of the three experiments agree with each other within the maximum permitted deviation of +/- 2kmh as required by the standards. As expected, during acceleration the current increases and during the vehicles deceleration some of the kinetic energy was recovered and converted into electricity and used to recharge the battery, indicated by the current trace on the negative scale. The softest RBS setting (C-Mode) indicates the least energy generation during the deceleration of the vehicle, while the strongest setting in B-Mode shows the highest current flowing back into the vehicle's battery. As expected, the medium settings (D-mode) provided current levels between C and B mode. The trend of the regenerating performance from driving the three different RBS settings agree with the expectations from the vehicles user manual [32].

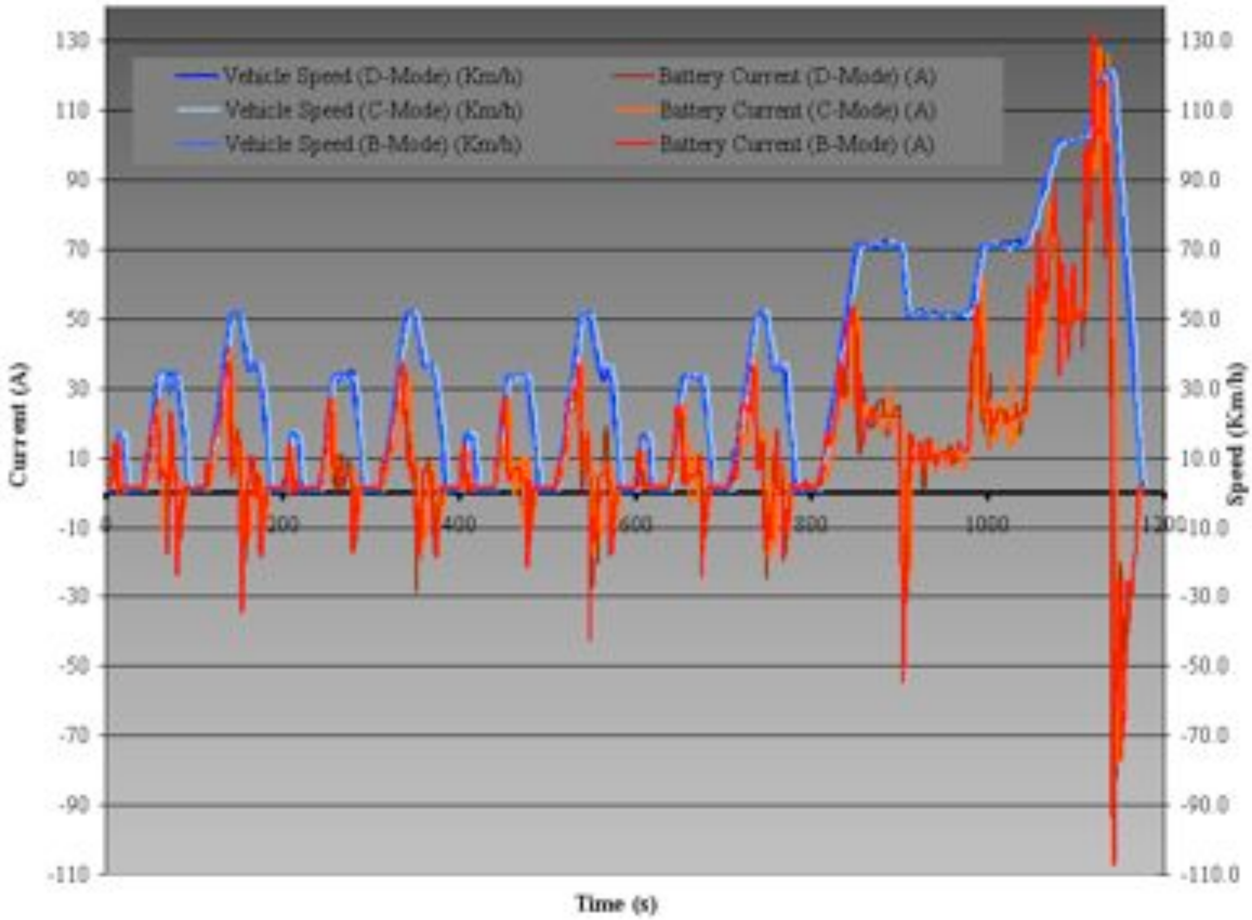


Figure 21: The speed and current profile driving three NEDC drive cycles for different driving modes.

The battery voltage, required to calculate the energy consumption in Wh/km, was not directly available from driving the first NEDC drive cycle as it was not possible to record voltage and current simultaneously. By connecting a shielded current clamp, connected to ground, together with the National Instrument logging device to the main battery for measuring voltages, the Mitsubishi MiEV internal computerized circuit monitoring system detected a battery earth leak to ground and triggered a fault which switched the car in to “limp mode”. This was indicated by the symbol of a turtle on the dashboard, as shown in Figure 22. In “limp mode” the maximum speed was 25 Km/h and testing under these conditions was not possible.

Figure 22: The MiEV dashboard informing about system errors and the limp mode indicated by the symbol of the turtle (inside the red circle)

Therefore, for an approximation of the energy consumption in Wh/Km, the battery voltage was logged every second on a separate NEDC drive cycle and averaged over the duration of the city and Hwy cycle. Therefore the test results assumed similar battery voltages as logged on separate, individual drive cycles. For the calculation of the energy consumption C in Wh/km, the consumed energy *E* used by the vehicle and generated energy by the RBS, the vehicle current was logged every second, multiplied by the averaged battery voltage and the negative and positive currents individually integrated over the time of the whole drive cycle. The electric energy consumption *C* was then calculated by the equation (2)

Table 9 shows the energy consumptions (without charge losses) and the energy consumption improved by the RBS in Wh/km and percentage. As expected the C mode generated the least amount of energy (16 Wh/Km) while driving in B mode generated the most energy (21

Wh/Km) and D mode 19 Wh/Km during the slow downs. Due to the higher energy consumption when driving in D and B mode the overall energy consumption showed no significant improvements compared to the C-Mode.

Table 9: Comparing RBS performance and energy consumptions driving NEDC drive cycle under different settings

	NEDC MiEV C Mode	NEDC MiEV D Mode	NEDC MiEV B Mode
Wh/Km without RBS	136	138	142
Wh/Km with RBS	120	119	121
Improvement (Wh/km)	16	19	21
Improvement (%)	12	14	15

4.3.2. FTB75 Drive cycle in RBS Mode C, D and B

This experiment involved driving FTB75 drive cycles under the same RBS settings as before. As with previous test driving, it was important to repeat the speed profile within the maximum deviation of +/- 2 Km/h as required by the test standards. The three traces (blue) on the speed profiles on Figure 23 show how the drive cycles agree with each other. As expected the highest currents were generated by the RBS by driving in B-mode indicated by the red trace. Driving in B-mode also drew relatively high currents indicated by the red traces on the positive scale. Table 10 provides an overview of the calculated energy consumption (without charge losses) assuming similar battery voltages and the energy generated by the RBS over all drive cycles in each mode. Although B-Mode generated the highest RBS currents it also used the highest currents. As a result, the overall energy consumption was better by driving in D-Mode or C-Mode.

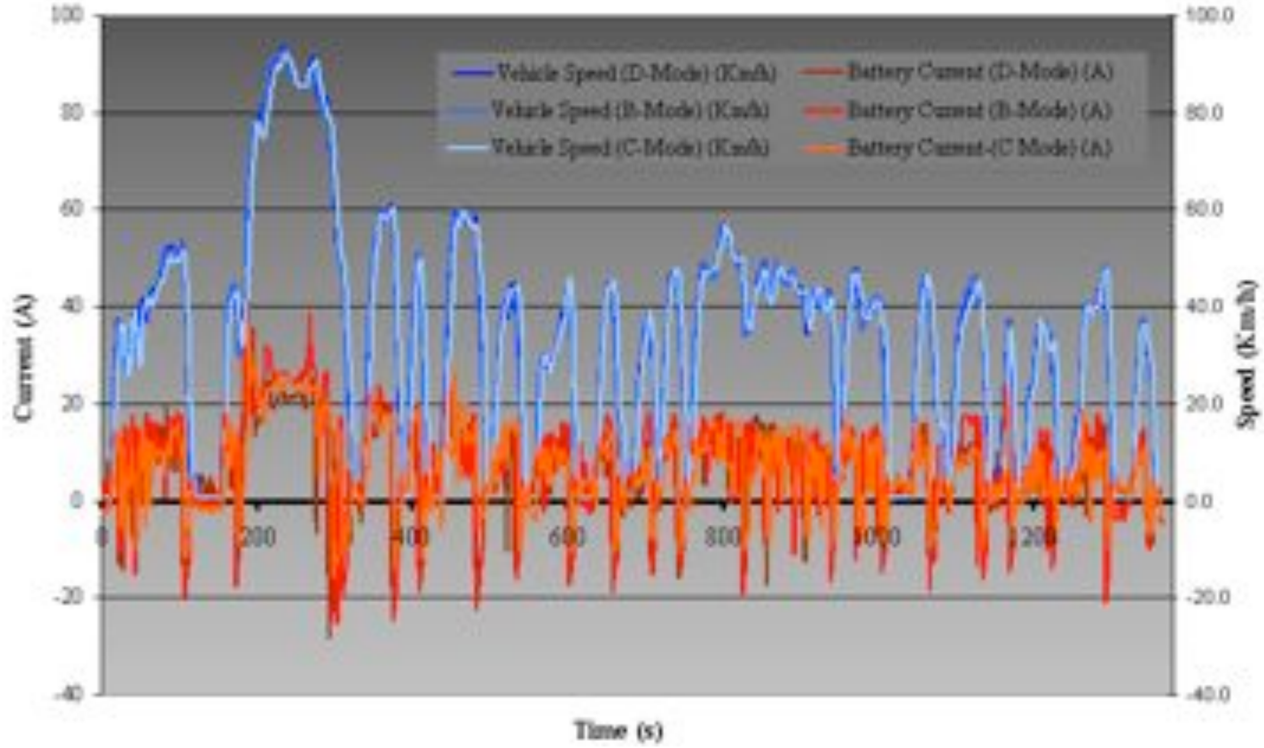
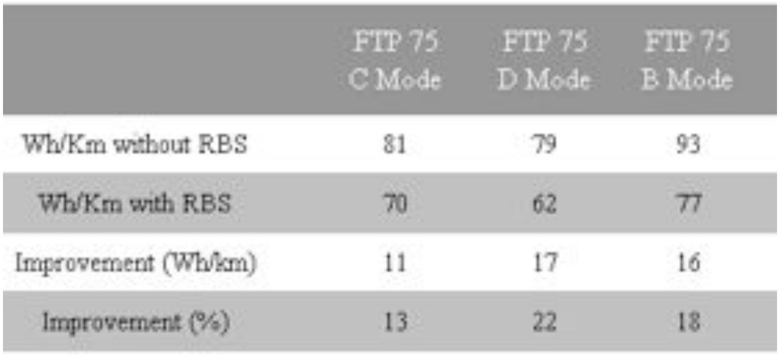


Figure 23: The speed and current profile driving three FTP75 drive cycles for different driving modes.

Table 10: Comparing RBS performance and energy consumptions driving an FTP 75 drive cycle under different settings



	FTP 75 C Mode	FTP 75 D Mode	FTP 75 B Mode
Wh/Km without RBS	81	79	93
Wh/Km with RBS	70	62	77
Improvement (Wh/km)	11	17	16
Improvement (%)	13	22	18

4.3.3. US Federal HWY Drive cycle in RBS Mode D and B

Figure 24 shows the speed, current and brake light profile from driving an US Federal Hwy drive cycle. Despite the relative continuous high speed and no "stop and go" driving pattern some kinetic energy was recovered. A noticeable difference was in the time of use of the brake light. In B mode the brake light was switched on later than in D-mode. Hence in B-

Mode the friction brake was in operation less than in D mode. Table 11 shows the energy consumption and RBS performance for D and B Mode. On a Hwy drive cycle there is not much braking required. During such a driving pattern an RBS operation time is relative short and hence cannot generate a lot of energy compared to a city drive cycle. Driving in D mode improved the energy consumption by only 5 Wh/km and in B mode by only 3 Wh/km respectively. Figure 24 shows a difference in current levels between D and B-Mode driving. This difference was caused due a required battery recharge for the test in B-Mode. Due the lower battery voltage on the first test (D-Mode) the motor required more current to provide the same power as compared to the second test (B-Mode).

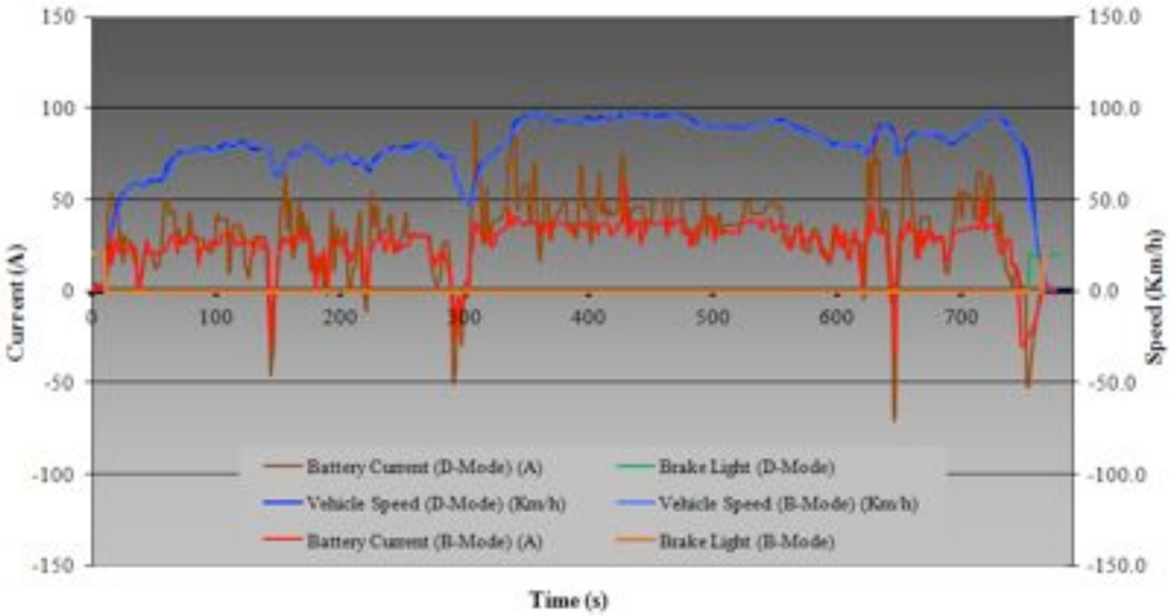
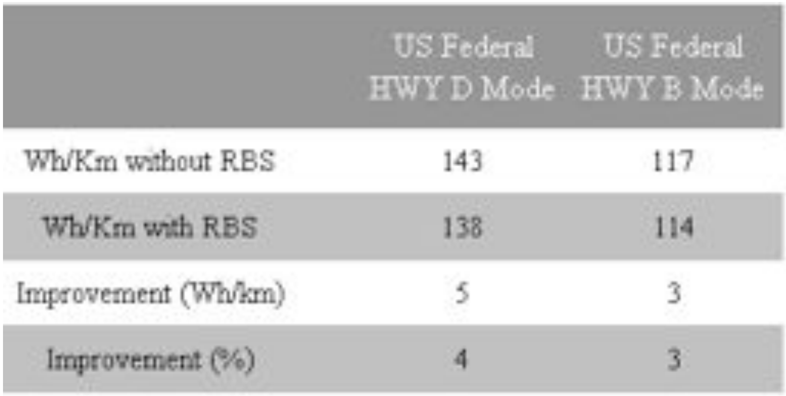


Figure 24: The speed, current and brake light operation profile driving an US Federal Hwy drive cycle in D- and B mode

Table 11: Comparing RBS performance and energy consumptions driving an US Federal HWY drive cycle in D and B mode



	US Federal HWY D Mode	US Federal HWY B Mode
Wh/Km without RBS	143	117
Wh/Km with RBS	138	114
Improvement (Wh/km)	5	3
Improvement (%)	4	3

4.3.4. Theoretical RBS efficiency

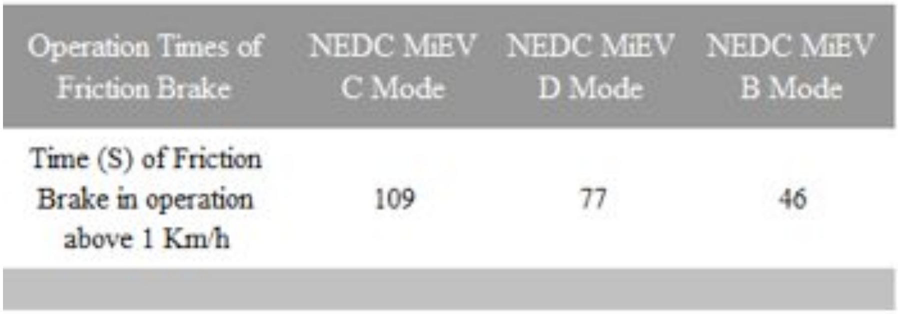
Section 1.2 outlined the theoretical kinetic energy of 625 x 10^3Ws (0.174 kWh) available from the Mitsubishi MiEV travelling at a speed of 120 km/h. This section investigates how much of the theoretical kinetic energy can be recovered by the RBS system. On the last NEDC drive cycle the vehicle was required to be accelerated to 120 km/h and then slowed down to a full stop. At the point where the vehicle was to be required to slow down the energy generated by the RBS was integrated over the time until the vehicle stoped. The Total generated energy from slowing down from 120 km/h was 378 x 10^3Ws (0.105 kWh).

4.3.5. Brake Pedal Pressure and Duty Cycle of Friction Brake

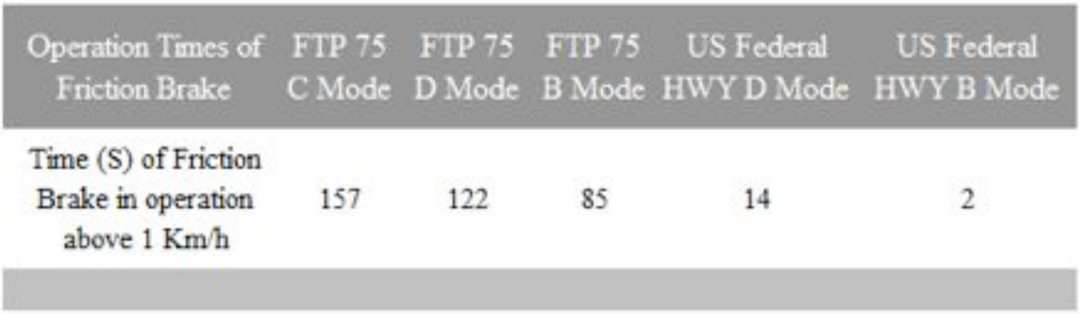
For all the experiments with the Mitsubishi MiEV, the brake pedal pressure had no influence on the RBS performance. The RBS performance setting was manually selected by the driver for D, C or B mode. During the driving the level of applied RBS braking force was controlled not as expected by the brake pedal but controlled by the acceleration pedal. Releasing the pedal activated the RBS system continuously until full level and therefore the friction brake pedal did not influence the applied RBS braking level.

Beside the pedal pressure the operation of the brake light was logged over the drive cycles. Table 12 show the operation time in seconds when the pedal was pressed and the friction brake in use. Between the C and B mode there was a significant difference in the duration where the friction brake was in use. This time difference was caused due to the different strength of RBS settings. RBS setting B mode supports the friction brake much more than in setting D or C mode.

Table 12: The operation time in seconds of the friction brake



Operation Times of Friction Brake	NEDC MiEV C Mode	NEDC MiEV D Mode	NEDC MiEV B Mode
Time (S) of Friction Brake in operation above 1 Km/h	109	77	46



Operation Times of Friction Brake	FTP 75 C Mode	FTP 75 D Mode	FTP 75 B Mode	US Federal HWY D Mode	US Federal HWY B Mode
Time (S) of Friction Brake in operation above 1 Km/h	157	122	85	14	2

4.4. Lotus Elise RBS Performance Testing and Energy Consumption

4.4.1. NEDC and FTP75 Drive cycle

The experiments involved driving an NEDC and a FTP75 drive cycle and recording the vehicle RBS and energy consumption performance data. Figure 25 shows the currents and speed profiles driving the two different drive cycles.

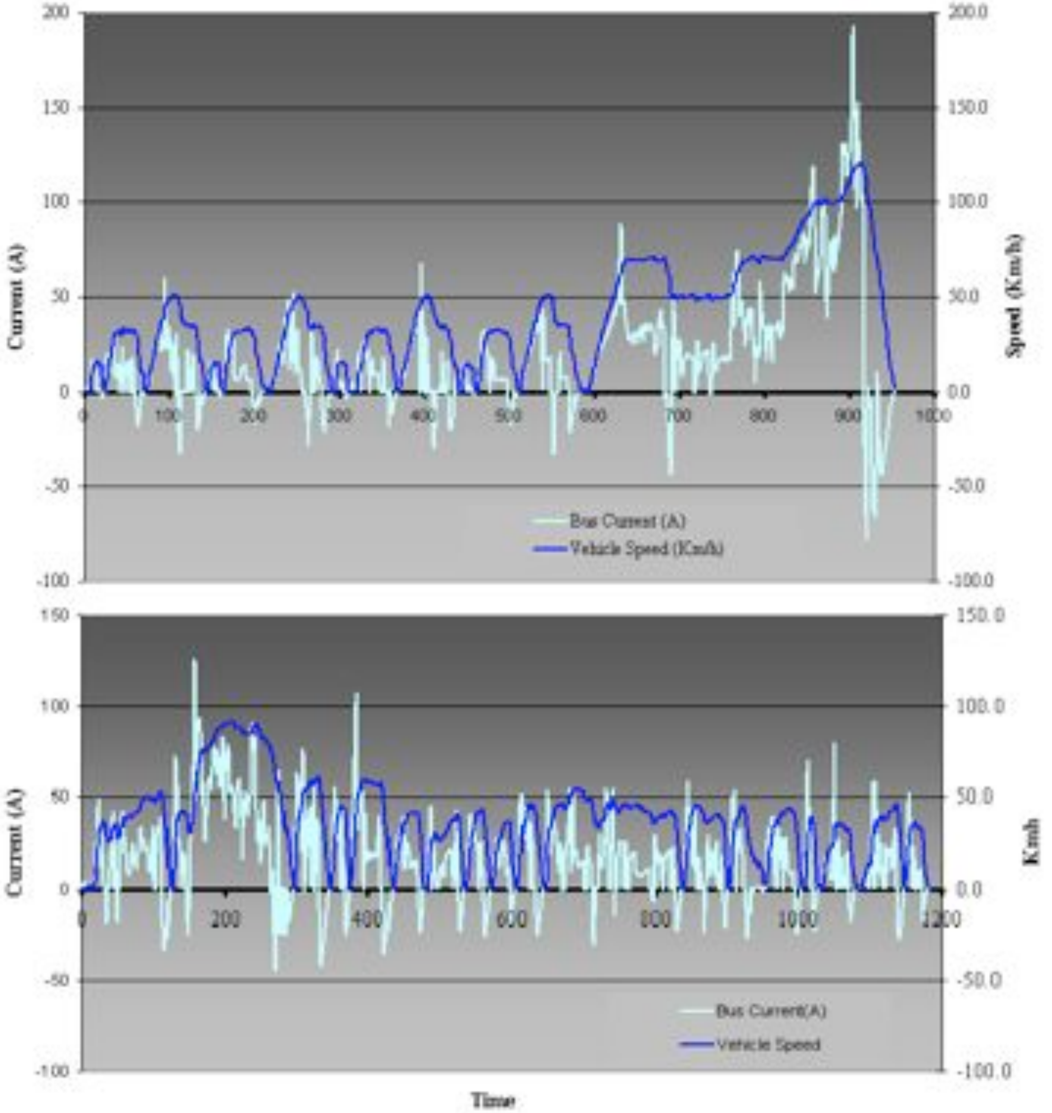
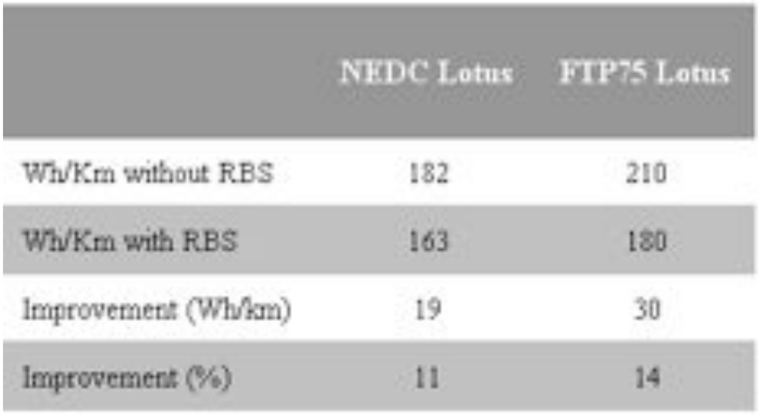


Figure 25: The speed and current profile from driving an NEDC and FTP75 drive cycle.

To calculate the energy consumption in Ws the logged voltage and current levels were multiplied and integrated over the whole driving time. The Ws were converted to Wh and the energy consumption (without charge losses) in Wh/km calculated using equation 2.

Table 13 shows that driving the Lotus on the NEDC with RBS improved the energy consumption by 10.7%. Driving the Lotus with the same RBS settings on the FTP75 drive cycle improved the energy consumption by 14%.

Table 13: Energy consumption and RBS energy efficiency improvement

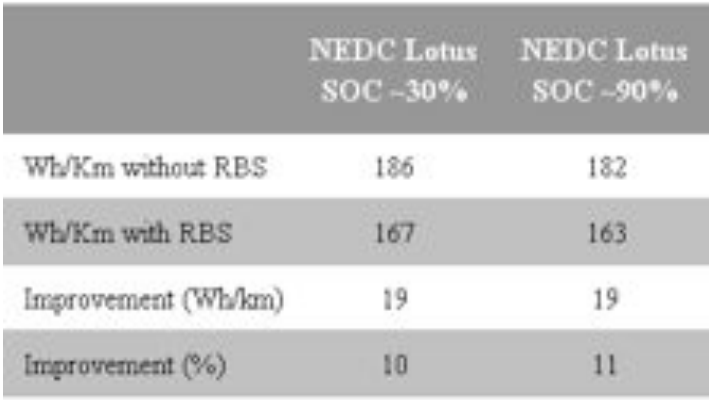


	NEDC Lotus	FTP75 Lotus
Wh/Km without RBS	182	210
Wh/Km with RBS	163	180
Improvement (Wh/km)	19	30
Improvement (%)	11	14

4.4.2. RBS Performance and Different Levels of SOC

The first Lotus NEDC drive cycle was conducted with an estimated initial SOC level of 30%. The second NEDC drive cycle was repeated the next day with a charged battery and an estimated SOC level of 90%. Table 14 shows an energy consumption improvement of 10% for a nearly exhausted battery and an improvement of 10.7% for driving with a near fully charged battery.

Table 14: RBS performance driving under different battery SOC level



	NEDC Lotus SOC ~30%	NEDC Lotus SOC ~90%
Wh/Km without RBS	186	182
Wh/Km with RBS	167	163
Improvement (Wh/km)	19	19
Improvement (%)	10	11

4.4.3. Brake Pedal Pressure

For all experiments on the Lotus the brake pedal pressure did not influence the level of RBS applied. The triggering of the RBS operation was controlled by the stop light switch. As soon as the pedal was pressed the RBS system was activated. The performance curve was pre-programmed in the RBS controller module. After programming the performance profile into the RBS system it was not possible for the driver to manually change the RBS settings.

5. Discussion

The first aim of the two independent experiments was to find the energy consumption and the drivable range of the two different EV Ford Focus models driving in different gears on chassis dynamometer. The aim of collecting data from the Ford Focus was to answer the question whether different gearing on an EV has an impact on the energy consumption. The aim of the second part of the experiment was to investigate the RBS performance of the Mitsubishi MiEV and the Lotus Elise. The aim for the results from the second experiments was to answer the questions how the performance of the RBS is affected by driving under different settings speed profiles and different SOC. The results from these experiments will help to decide if it is worth to implement an RBS system in an EV.

5.1. Energy Consumption

The energy consumption test showed noticeably higher energy consumption on the first two NEDC drive cycles. This was assumed to be due to the higher friction of the cold vehicle drive train. Because the standard for measuring energy consumption requires just two drive cycles, the measured energy consumption is overestimated and in fact lower on the following cycles, once the vehicles achieved operation temperature. Due to the limited time and available test equipment the vehicles energy consumption was measured by the internal energy meter on the vehicles battery. This meant that no charge losses were measured directly as required by the standards. To overcome the issue the levels of charge losses were assumed and factored in the measured energy consumption, as required by the standards. Further sources of potential errors include the allowable speed deviation of +/- 2km/h. If for example during a NECD city cycle the required speed was 15km/h then for a valid test one car could have been driven 13km/h and other car 17km/h. Such a relative large range might induce deviations in energy consumptions. In addition, the averaged voltage for the calculation of the energy consumption in Wh/km can cause some inaccuracies. Figure 26 shows the differences between the energy consumptions of the two different cars and driving in different gear ratios. Driving in gear 2 and 4 required 242 Wh/km and driving in 3 and 4 240 Wh/km. This small deviation of 1% could have been caused by the inaccuracy of the instruments as discussed further in the report. Therefore it is not possible to say if it is slightly more efficient to drive in gear 2 and 4 or gear 3 and 4. The Ford Focus manual and automatic have identical motors, batteries and controllers, and the difference in energy consumption was significant. The Focus in gear 2 and 4 used 242Wh/km while the Focus automatic used 338Wh/km. This is equivalent to an increased energy consumption of 28.5%. The main reason for this energy loss was because it was not possible for the EV converter to interface the computer controlled automatic gearbox [42]. The result was that the gearbox did not change gear appropriately and a lot of energy was lost in heat at the torque converter of the automatic gearbox.

Figure 26: The different energy consumptions with and without charge losses and driving in different gear ratios

The experiments have shown a significant difference in energy consumptions of the two cars. But it has also shown that strictly following a test standard on how to measure energy can lead to errors. If the cars charged energy were measure as recommended by the standard and in this case over night without supervision, the moment of the batteries full charge could have been missed. Therefore the investigation about the battery charger strategy was important to prevent false results. After consultation with the EV converter, the charge strategies of the charger were investigated and the battery chargers reconfigured [39].

5.2. Range Tests

Figure 27 shows the vehicle maximum driving ranges. As expected from the results of the energy consumptions there was no significant range difference driving in gear 2 and 4 and 3 and 4. Both experiment shown similar vehicle ranges of 143 km and 141 km respectively. The much higher energy consumption from the Focus automatic resulted in a significant reduction of the drivable range to just 94 km. Errors of the measured maximum driving distance was limited to the maximum allowable speed deviation of +/- 2km/h and the chassis dynamometer instrumentation accuracy of 0.5 %. A small drivable range is a main disadvantage of an EV. These experiments have shown that correct gearing of an EV is an important factor for its efficiency and hence it’s maximum drivable range.

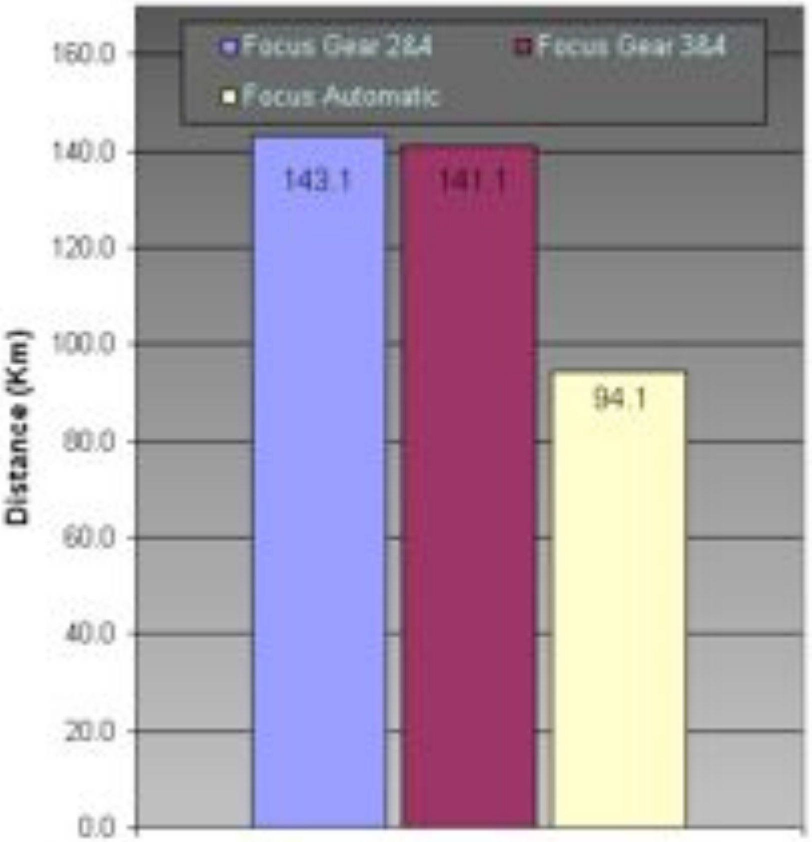


Figure 27: The maximum drivable distance for the Ford Focus manual and automatic

5.3. RBS Performance

5.3.1. RBS Performance Mitsubishi MiEV

The theoretical kinetic energy available from the Mitsubishi MiEV discussed in section 1.2, travelling at a speed of 120 km/h was 625 x 10^3 Ws. The experiment showed that the RBS of the MiEV was able to generate 392.13 x 10^3 Ws of electricity. This is 63% of the available kinetic energy at the speed of 120 km/h. As a reference this result is in the order of the achieved RBS recovery rates between 66 % and 76 % from an experiment conducted on a hybrid city bus [13]. It is assumed that due the higher vehicle weight and the resulting higher surface pressure and the bigger wheels of the bus more energy can be transmitted and converted in electricity than on the smaller and lighter Mitsubishi MiEV.

Driving the Mitsubishi under different drive cycles and RBS settings has shown a wide range of RBS performances. The RBS from the MiEV improved the energy consumption between 3% (US Federal Hwy cycle in B-Mode) and 22% (FTP 75 in D-Mode). Such a large range shows how significant the RBS performance depends on driving pattern and RBS configurations. Despite the US Federal HWY cycle not being a typical stop and go pattern, an improved energy consumption of 3% and 4% was measured by driving in B and D mode respectively.

It is also important that the RBS settings agree with the load to prevent a load mismatch. A fully applied RBS does not necessary provide the best performance on that particular driving pattern. Driving the MiEV on the FTP75 for example showed that the strongest RBS settings did not generate the most energy per km. Although the higher electricity generation in D-mode compared to B-mode was not significant, it is assumed that driving the FTP75 in D-Mode matched the load better than the B mode and hence more energy was recovered by driving in D mode.

5.3.2. RBS Performance Lotus

Although the Lotus RBS does not operate in conjunction with an ABS system and the RBS was not finetuned on a chassis dynamometer it was possible to improve the efficiency by 11% on the NEDC and 14% on the FTP75 drive cycle. As a comparison, the much higher efficiency improvement by the Mitsubishi MiEV is assumed to be due the Mitsubishi factory tuned RBS performance and ABS system allowing to get closer to the point where the wheels can lock up and would cause dangerous driving conditions. The optimum RBS calibration cannot be easily found by a simple aftermarket electric conversion. The immense effort to interface and optimize an RBS with an ABS was outlined by a research project conducted by D.Peng [19] discussed in the literature review. The different vehicle weight, batteries, motors and controllers of these two vehicles might also have an impact on the RBS efficiencies but was not investigated during this project.

Driving two identical drive cycles with the Lotus under different SOC did not show any significant differences in energy consumption and RBS performance. Measuring the RBS under different SOC showed just a 1% difference in efficiency. A slightly larger difference between different SOC of 4.1% was seen on an experiment conducted on a hybrid electric city bus RBS and charge system [13]. One of the reasons for the lower RBS charge efficiencies driving under different SOC on the Lotus might be the calibration of the RBS. As mentioned above the performance and therefore the level of charging capacity is not fully utilized on the Lotus.

5.4. How Much Energy Can Be Recovered?

The maximum generated energy by an RBS during the experiments was only 30 Wh/km driving the Lotus on a FTP75 drive cycle. This might raise the question: Is it financially worthwhile to implement a costly RBS system? Ignoring recharge losses and assuming an electricity price of 25 c/kWh the cost savings from the RBS would be a mere 0.75c per km. Assuming an extra cost of AUD 2000.- for an RBS system, the vehicle must travel a distance of 267’000km to offset the extra cost. Even if the electricity price would raise to $1.- per kWh the vehicle still needs to be driven 66’667 Km to offset the cost. This “back of the envelope” calculation of the simple payback time shows that financially it is not worth to implement an RBS in an EV. There are, however, other reasons why major car manufacturer implement RBS systems in new factory cars [43], [44]. An RBS system not just saves energy and improves efficiency but it also increases the vehicles range. This can help to reduce certain customers “range anxiety” a term used to describe the psychological state of mind of a driver unsure if they can reach their destination before the battery goes flat [45]. An increased vehicle range can be a beneficial sales argument for a car manufacturer. Another benefit of an RBS is the reduced stress and operation time of the mechanical friction brake. Driving the Mitsubishi MiEV on the FTP75 in B-mode compared to the C-Mode reduced the operation of the friction brake from 157 seconds to 85 seconds. It is assumed that such an improvement will have a significant impact on maintenance and down time costs of an EV. Road tests by the author prior to the experiments have shown that driving an EV with RBS also improves the drivability of an electric vehicle. During deceleration the driver can experience the braking effect of an RBS similar to a braking effect of standard combustion engine car. Such a benefit might also be a strong sales argument for a new factory electric car.

5.5. Can appropriate gearing save more energy than an RBS?

From all the experiments during this project the best efficiency improvement by an RBS was 22% whereas the worst case difference between the Fords gearing was 28.5%. Comparing the RBS results with the efficiency improvements on the Fords have shown, that between the investigated cars an appropriate EV gearing can save more energy than a RBS. As discussed above, however, there are other benefits from an RBS system than just energy savings.

5.6. Instrumentation Errors

Measuring the RBS performance was a difficult and complex task. Driving strategy and data from several instruments and computers interlink with each other and provided the potential for accumulating errors. The following provides an overview of possible errors.

Errors and potential errors for the MiEV:

- Exposure of inductive current clamp to electromagnetic noise from the chassis dynamometer motors and EV motor controllers. “Zero-Trim” of current clamp was very sensitive and difficult to adjust, due the required large range of current.
- Due technical issues battery voltage and battery current was logged on identical but separate drive cycles.
- Potential error of logging time intervals due the a Windows PC which is not running a real time operation system
- Dynamometer instrumentation accuracy of 0.5%
- +/- 2km/h allowable vehicle speed tolerance
- No vehicle specific coast down data available for chassis dynamometer load profile

Errors and potential errors for the Lotus:

- No calibration of the motor controller’s internal instrumentation system. Data relay on manufacturer calibration and tolerances
- +/- 2km/h allowable vehicle speed tolerance
- Dynamometer instrumentation accuracy of 0.5%
- No vehicle specific coast down data available for chassis dynamometer

Due the potential of some sources of errors difficult to quantify in the instrumentation chain the measured energy consumption data were compared with the car manufacturer and the literature. Mitsubishi claims an energy consumption for the MiEV of 135 Wh/km [32] and an experiment on an MiEV conducted by the University of Sheffield [11] resulted in 140 Wh/km driving two consecutive NEDC cycles also testing under R101 standard. The average energy consumption of the MiEV on the NEDC drive cycle measured on this project was 120 Wh/km (without charge losses). Allowing for a charge efficiency of 0.89 % this agrees well with the energy consumption stated by Mitsubishi.

6. Conclusion & Recommendations

The project involved the driving of 4 different pure-EV‘s on a chassis dynamometer. The objective was to measure and compare electricity consumption and maximum drivable range of two electric driven Fords under different gearing. In addition the project investigated the efficiency improvement of electric cars driving them under different RBS configurations and driving pattern. This was achieved by measuring, calculating and comparing energy consumptions of the EVs.

- The comparison of the energy consumption on the manual cars by driving in different gearing gears such as gear 2 and 4 and 3 and 4 did not show a significant difference in the energy consumption and drivable vehicle range
- The comparison of the energy consumption and drivable range under different designed gearing of the Ford Focus manual and automatic shown a significant difference in electricity consumptions. This has highlighted the importance of the careful gearbox selection, design and potential control strategies of automatic gearboxes for an aftermarket EV conversion project.
- The experiments also demonstrated that following EV test standards requires technical understanding and strictly following a standard can lead to measuring errors.
- Measuring energy consumption on just two consecutive drive cycles, as required by the R101, might overestimate the energy consumption of EVs due a higher friction on a cold drive train.
- The configuration of the battery charger can also have a significant impact on the efficient operation of an EV. The charge energy consumption of the Fords after fully recharging the main batteries was relative high. After a full charge the battery charger was not automatically disconnected and used standby energy for itself and for standby power of the car.
- Under certain conditions, an appropriate gearing can operate an EV more efficiently than the support of an RBS. For the RBS to operate at its maximum efficiency, it must be fine-tuned to match the load and should be interfaced with an ABS.
- Driving a car with RBS under different SOC did not show a significant difference in RBS recharge efficiencies.
- Analysis of the results from the chassis dynamometer testing showed that an RBS does not save enough energy to offset its cost of implementation.

- Other benefits such as extending the EVs range, drivability and stress reduction on the friction brake can be surmised to be the main drivers for the implementation of an RBS.
- The experiments demonstrated that the precise and accurate use of instrumentation of an EV on a chassis dynamometer is not an easy task. Interaction of instrumentation, electrical interferences, and several different computers has the potential to induce errors difficult to quantify.
- Although chassis dynamometer testing provides a stable test environment it does not represent real world driving conditions. Different cities or areas provide different topographical properties and traffic conditions. A real road test driving under every day conditions might help to answer the question of how efficient an RBS performs for example under Perth W.A. driving conditions.
- Determining the energy consumption over just two NECD drive cycles has shown variation in the energy consumptions between the two cycles due to reduced friction on the driving train. Further investigations for driving more than just two drive cycles might improve the accuracy of the actual energy consumption of EVs.
- Further investigations might include how micro charging by an RBS impacts the battery life cycle of the EV's costly main battery.
- Chassis dynamometer testing requires a large and expensive test environment and is time consuming. Therefore characterizing and modelling EV chassis dynamometer driving in software might help to investigate EV efficiencies more cost and time effective.
- On the Lotus it might be interesting how much more energy can be recovered by interfacing the RBS with an ABS and optimize the calibration of the Lotus on a chassis dynamometer.

References

[1] U.S.-Department-of-Energy. (2009, 11.11.). *Annual Energy Review 2009*. Available: http://www.eia.gov/totalenergy/data/annual/index.cfm

[2] International-Energy-Agency, "Transport Energy and CO2," October 2009 2009.

[3] S. H. B. Yim, Steven R. H., "Public Health Impacts of Combustion Emissions in the United Kingdom," *Environmental Science & Technology,* vol. 46, pp. 4291-4296, 2012/04/17 2012.

[4] University-Of-Western-Australia. (n.d., 19.11.). *Fast-Charging Network Trial* Available: http://therevproject.com/trials/charging-trial.php

[5] M. Dale, *Know All About Hybrid Vehicles*. Delhi: The English Press, 2012.

[6] CNN. (2012, 18.11.). *Year of the electric car blows a fuse*. Available: http://money.cnn.com/2012/10/19/autos/electric-car/index.html

[7] AEVA. (2012, 18.11.12). *About us*. Available: http://www.aeva.asn.au/about

[8] EV-Works. (2012, 18.11.). *Welcome to EV Works, Australia's electric vehicle specialist!* Available: http://www.evworks.com.au/index.php

[9] Perth-Electric-Vehicle. (n.d., 18.11.). *Electric Vehicle Conversions and Hybrid Vehicle Servicing*. Available: http://www.perthelectricvehicle.com.au/

[10] U. S. Departement-of-Energy, "One Million Electric Vehicles By 2015 " February 2011 2011.

[11] C. Walsh, "Electric Drive Vehicle Deployment in the UK," University of Sheffield2009.

[12] A. E.Fuhs, *Hybrid Vehicles and the Future of Personal Transport*. Boca Raton: CRC Press, 2009.

[13] Z. Junzhi*, et al.*, "Regenerative Braking System for Series Hybrid Electric City Bus," *The World Electric Vehicle Journal,* vol. Vol 2, pp. 128-134, 2008.

[14] U.S.-Department-of-Energy. (2011, 18.11.). *Advanced Vehicle Testing Activity*. Available: http://www1.eere.energy.gov/vehiclesandfuels/avta/index.html

[15] S. M. DeMers, "Mechanical and regenerative braking integration for a hybrid electric vehicle," M.A.Sc. MR43632, University of Waterloo (Canada), Canada, 2008.

[16] Green-Car-Congress. (2012, Volvo Car Corporation developing flywheel kinetic energy recovery system; considering broad application Available: http://www.greencarcongress.com/2011/05/vcc-20110526.html

[17] F. Wicks*, et al.*, "Analysis of compressed air regenerative braking and a thermally enhanced option," in *Energy Conversion Engineering Conference, 2002. IECEC '02. 2002 37th Intersociety*, 2002, pp. 406-411.

[18] Department-of-Mechanical-Engineering
"Elastic Regenerative Braking System based on Superelastic Shape Memory Material, " August 2008 2008.

[19] D. Peng*, et al.*, "Combined Control Of A Regenerative Braking And Anti-Lock Braking System For Hybrid Electric Vehicles," *International Journal of Automotive Technology,* vol. Vol. 9, , p. pp. 749−757.

[20] Battery-University. (2012, 02.04.). Charging Lithium-ion. Available: http://batteryuniversity.com/learn/article/charging_lithium_ion_batteries

[21] E. Nam, "Drive Cycle Development and Realworld data in the United States," presented at the GRPE Informal Group on WLTP, Geneva, Switzerland, 2009.

[22] Delphi. (2010, *World Wide Emissions Standards*. Available: http://www.delphi.com/pdf/emissions/Delphi_PC.pdf

[23] Diesel-Net. (2012, 18.11.). *Emission Test Cycles*. Available: http://www.dieselnet.com/standards/cycles/

[24] United-Nations. (2005, 02.02.). *Regulation No. 101* Available: http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/r101r2e.pdf

[25] J. E. Francfort*, et al.*, "Plug-in Hybrid Electric Vehicle Fuel Use Reporting Methods and Results " 2009.

[26] C. Walsh*, et al.*, "Electric Vehicle Driving Style and Duty Variation Performance Study," University of Sheffield2010.

[27] Australian-Government. (2008, 19.11.). *Fuel consumption label*. Available: http://www.environment.gov.au/settlements/transport/fuelguide/label.html

[28] J. Oakley, "Evaluating Electric Vehicles," Honours Thesis Bachelor of Engineering, Electrical and Electronic Engineering, University of Western Australia, Perth, 2011.

[29] TBS-Electronics. (2012, 18.06.). *Battery Monitor*. Available: http://www.tbs-electronics.com/products_expertpro_features.htm

[30] University-of-Western-Australia. (n.d., 18.11.). *Electric Ford Focus*. Available: http://therevproject.com/vehicles/electric-ford-focus.php

[31] University-of-Western-Australia (n.d., 18.11.). *Automotive Lab* Available: http://robotics.ee.uwa.edu.au/rev/rev-racer.html

[32] Mitsubishi-Motors. (n.d., 04.06.). *Plug in to the future today with i-MiEV*. Available: http://www.mitsubishi-motors.com.au/vehicles/cars/i-miev

[33] EV-Works. (2010, 20.04.). *EV Works chosen for WA EV trial*. Available: http://www.evworks.com.au/index.php

[34] University-of-Western-Australia. (2011, *Electric Ford Focus*. Available: http://therevproject.com/vehicles/electric-ford-focus.php

[35] University-of-Western-Australia. (2009, *Welcome to the REV Project*. Available: http://therevproject.com/

[36] UQM-Technologies. (n.d., 04.04.). *Passenger Vehicle Full Electric Propulsion Systems*. Available: http://www.uqm.com/powerphase%20select%2075.html

[37] EPA. (2012, 18.11.12). *Importing Vehicles and Engines into the U.S*. Available: http://www.epa.gov/oms/imports/glossary.htm#curb

[38] University-of-Western-Australia. (2012, *Welcome to the REV Project, Charging Stations*. Available: http://therevproject.com/

[39] R. M. EV-Works, "Ford Focus Charger," ed. Perth W.A. Landsdale 6065, 2012.

[40] First-Power. (n.d., 19.11.12). *Characteristics of Power LiFePO4 battery*. Available: http://www.efirstpower.com/li.html).

[41] EV-Works. (2010, 20.04.). *Switched Mode Battery Charger*. Available: http://www.evworks.com.au/index.php?product=CHG-KP7220KL

[42] R. M. EV-Works, "Interfacing Automatic Gear Box," ed. Perth W.A. Landsdale 6065, 2012.

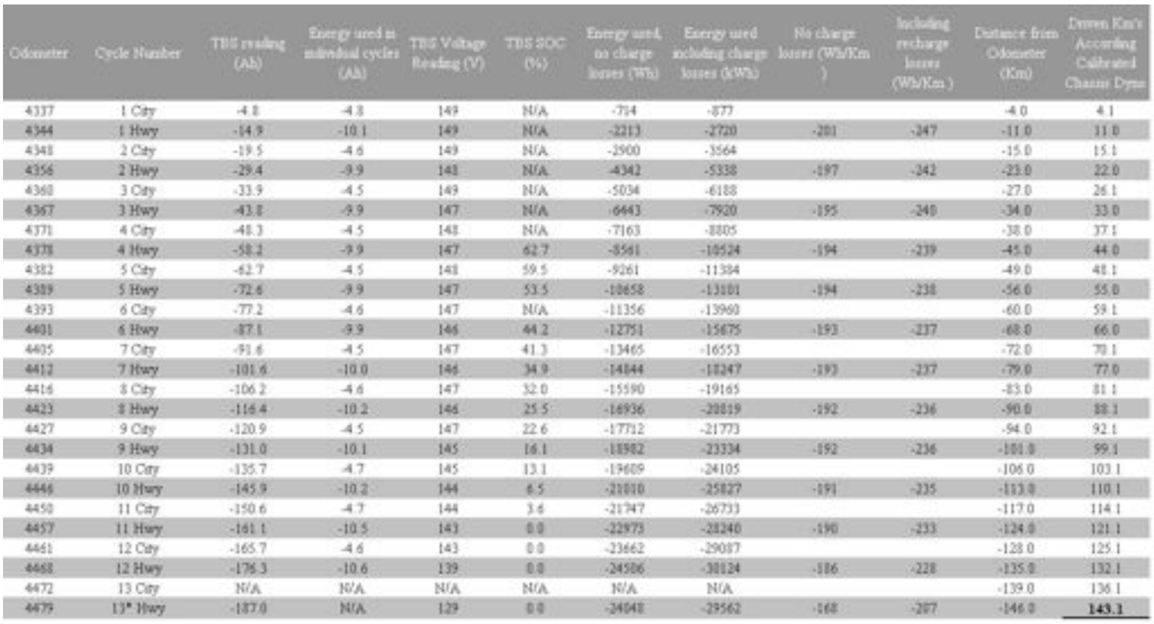
[43] Holden. (2012, 01.08.). *Holden Volt Specifications Confirmed*. Available: http://holdenhq.com.au/holden-volt-specifications/

[44] Nissan. (2012, 01.08.). *Power Management*. Available: http://www.nissanusa.com/leaf-electric-car/key-features

[45] National-Geographics. (2012, 19.11.). *Range Anxiety: Fact or Fiction?* Available: http://news.nationalgeographic.com.au/news/energy/2011/03/110310-electric-car-range-anxiety/)

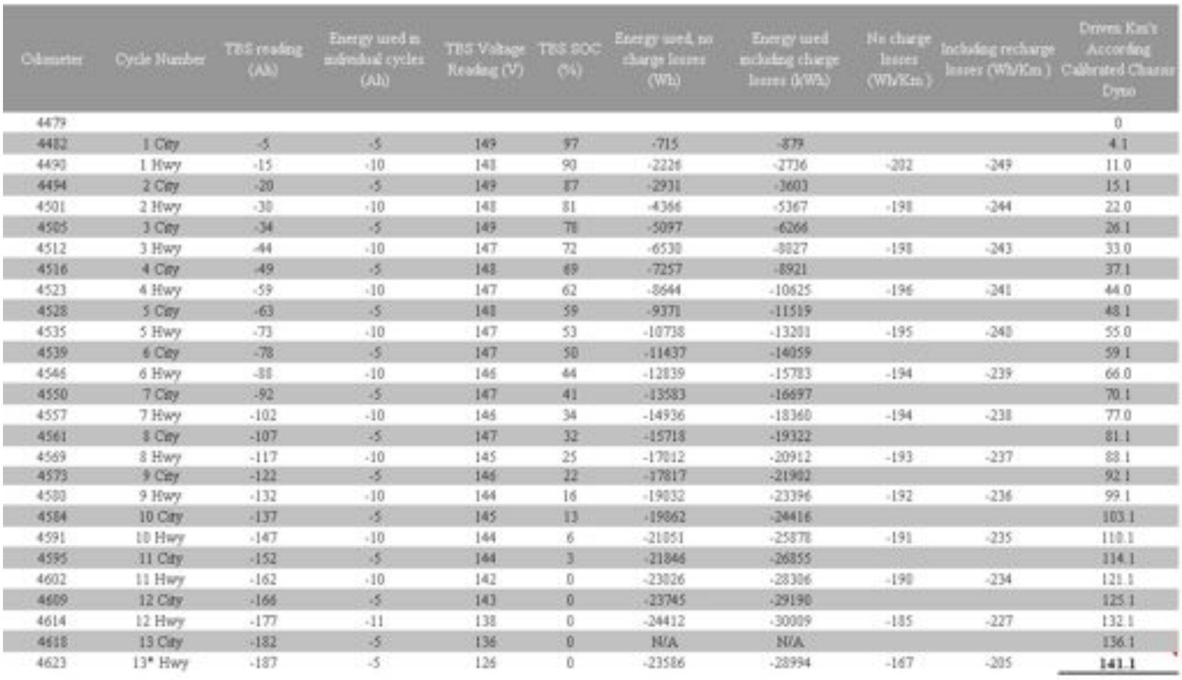
Appendix

Table 15: The maximum range of 143 Km and the individual energy consumptions over the whole range test driving in gear 2 and 4



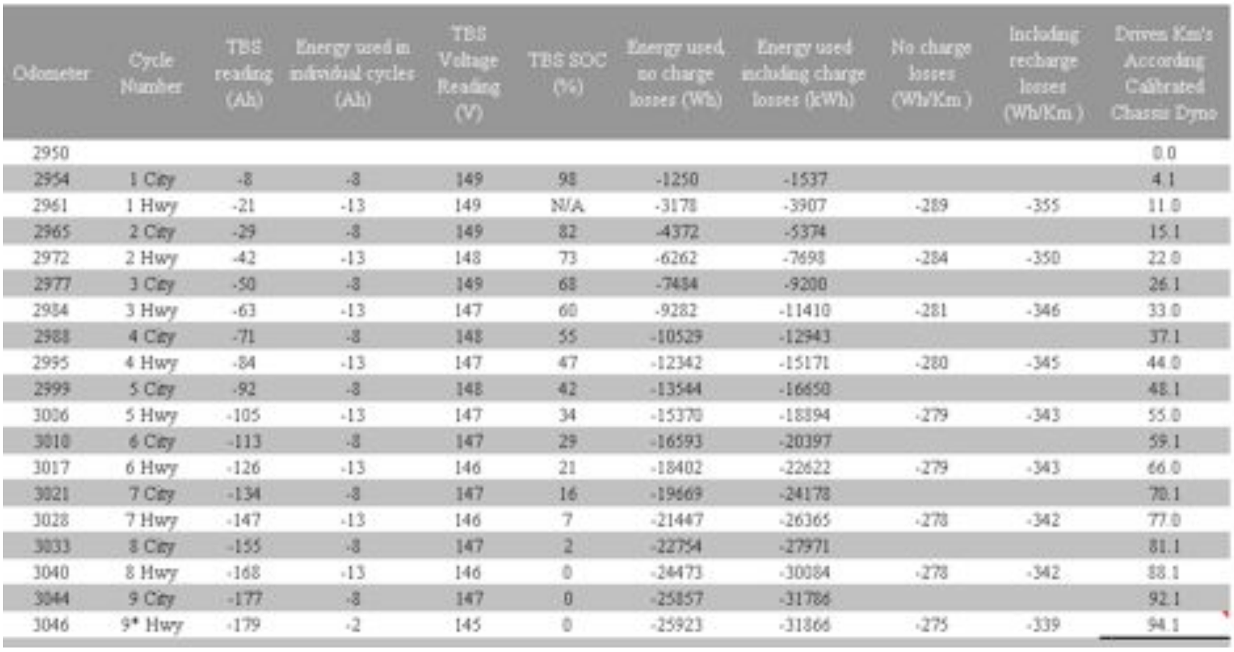
Odometer	Cycle Number	TBS reading (Ah)	Energy used in individual cycles (Ah)	TBS Voltage Reading (V)	TBS SOC (%)	Energy used, no charge losses (Wh)	Energy used including charge losses (kWh)	No charge losses (Wh/Km)	Including recharge losses (Wh/Km)	Distance from Odometer (Km)	Driven Km's According Calibrated Chassis Dyn
4337	1 City	-4.8	-4.8	149	N/A	-714	-877			-4.0	4.1
4344	1 Hwy	-14.9	-10.1	149	N/A	-2213	-2720	-201	-247	-11.0	11.0
4348	2 City	-19.5	-4.6	149	N/A	-2900	-3564			-15.0	15.1
4356	2 Hwy	-29.4	-9.9	148	N/A	-4342	-5338	-197	-242	-23.0	22.0
4360	3 City	-33.9	-4.5	149	N/A	-5034	-6188			-27.0	26.1
4367	3 Hwy	-43.8	-9.9	147	N/A	-6443	-7920	-195	-240	-34.0	33.0
4371	4 City	-48.3	-4.5	148	N/A	-7163	-8805			-38.0	37.1
4378	4 Hwy	-58.2	-9.9	147	62.7	-8561	-10524	-194	-239	-45.0	44.0
4382	5 City	-62.7	-4.5	148	59.5	-9261	-11384			-49.0	48.1
4389	5 Hwy	-72.6	-9.9	147	53.5	-10658	-13101	-194	-238	-56.0	55.0
4393	6 City	-77.2	-4.6	147	N/A	-11356	-13960			-60.0	59.1
4401	6 Hwy	-87.1	-9.9	146	44.2	-12751	-15675	-193	-237	-68.0	66.0
4405	7 City	-91.6	-4.5	147	41.3	-13465	-16553			-72.0	70.1
4412	7 Hwy	-101.6	-10.0	146	34.9	-14844	-18247	-193	-237	-79.0	77.0
4416	8 City	-106.2	-4.6	147	32.0	-15590	-19165			-83.0	81.1
4423	8 Hwy	-116.4	-10.2	146	25.5	-16936	-20819	-192	-236	-90.0	88.1
4427	9 City	-120.9	-4.5	147	22.6	-17712	-21773			-94.0	92.1
4434	9 Hwy	-131.0	-10.1	145	16.1	-18982	-23334	-192	-236	-101.0	99.1
4439	10 City	-135.7	-4.7	145	13.1	-19609	-24105			-106.0	103.1
4446	10 Hwy	-145.9	-10.2	144	6.5	-21010	-25827	-191	-235	-113.0	110.1
4450	11 City	-150.6	-4.7	144	3.6	-21747	-26733			-117.0	114.1
4457	11 Hwy	-161.1	-10.5	143	0.0	-22973	-28240	-190	-233	-124.0	121.1
4461	12 City	-165.7	-4.6	143	0.0	-23662	-29087			-128.0	125.1
4468	12 Hwy	-176.3	-10.6	139	0.0	-24506	-30124	-186	-228	-135.0	132.1
4472	13 City	N/A	N/A	N/A	N/A	N/A	N/A			-139.0	136.1
4479	13* Hwy	-187.0	N/A	129	0.0	-24048	-29562	-168	-207	-146.0	**143.1**

Table 16: The maximum range of 141 Km and the individual energy consumptions over the whole range test driving in gear 3 and 4



Odometer	Cycle Number	TBS reading (Ah)	Energy used in individual cycles (Ah)	TBS Voltage Reading (V)	TBS SOC (%)	Energy used, no charge losses (Wh)	Energy used including charge losses (kWh)	No charge losses (Wh/Km)	Including recharge losses (Wh/Km)	Driven Km's According Calibrated Chassis Dyno
4479										0
4482	1 City	-5	-5	149	97	-715	-879			4.1
4490	1 Hwy	-15	-10	148	90	-2226	-2736	-202	-249	11.0
4494	2 City	-20	-5	149	87	-2931	-3603			15.1
4501	2 Hwy	-30	-10	148	81	-4366	-5367	-198	-244	22.0
4505	3 City	-34	-5	149	78	-5097	-6266			26.1
4512	3 Hwy	-44	-10	147	72	-6530	-8027	-198	-243	33.0
4516	4 City	-49	-5	148	69	-7257	-8921			37.1
4523	4 Hwy	-59	-10	147	62	-8644	-10625	-196	-241	44.0
4528	5 City	-63	-5	148	59	-9371	-11519			48.1
4535	5 Hwy	-73	-10	147	53	-10738	-13201	-195	-240	55.0
4539	6 City	-78	-5	147	50	-11437	-14059			59.1
4546	6 Hwy	-88	-10	146	44	-12839	-15783	-194	-239	66.0
4550	7 City	-92	-5	147	41	-13583	-16697			70.1
4557	7 Hwy	-102	-10	146	34	-14936	-18360	-194	-238	77.0
4561	8 City	-107	-5	147	32	-15718	-19322			81.1
4569	8 Hwy	-117	-10	145	25	-17012	-20912	-193	-237	88.1
4573	9 City	-122	-5	146	22	-17817	-21902			92.1
4580	9 Hwy	-132	-10	144	16	-19032	-23396	-192	-236	99.1
4584	10 City	-137	-5	145	13	-19862	-24416			103.1
4591	10 Hwy	-147	-10	144	6	-21051	-25878	-191	-235	110.1
4595	11 City	-152	-5	144	3	-21846	-26855			114.1
4602	11 Hwy	-162	-10	142	0	-23026	-28306	-190	-234	121.1
4609	12 City	-166	-5	143	0	-23745	-29190			125.1
4614	12 Hwy	-177	-11	138	0	-24412	-30009	-185	-227	132.1
4618	13 City	-182	-5	136	0	N/A	N/A			136.1
4623	13* Hwy	-187	-5	126	0	-23586	-28994	-167	-205	**141.1**

Table 17: The maximum range of 94.1 Km and the individual energy consumptions over the whole range test driving the Ford Automatic



Odometer	Cycle Number	TBS reading (Ah)	Energy used in individual cycles (Ah)	TBS Voltage Reading (V)	TBS SOC (%)	Energy used, no charge losses (Wh)	Energy used including charge losses (kWh)	No charge losses (Wh/Km)	Including recharge losses (Wh/Km)	Driven Km's According Calibrated Chassis Dyno
2950										0.0
2954	1 City	-8	-8	149	98	-1250	-1537			4.1
2961	1 Hwy	-21	-13	149	N/A	-3178	-3907	-289	-355	11.0
2965	2 City	-29	-8	149	82	-4372	-5374			15.1
2972	2 Hwy	-42	-13	148	73	-6262	-7698	-284	-350	22.0
2977	3 City	-50	-8	149	68	-7484	-9200			26.1
2984	3 Hwy	-63	-13	147	60	-9282	-11410	-281	-346	33.0
2988	4 City	-71	-8	148	55	-10529	-12943			37.1
2995	4 Hwy	-84	-13	147	47	-12342	-15171	-280	-345	44.0
2999	5 City	-92	-8	148	42	-13544	-16650			48.1
3006	5 Hwy	-105	-13	147	34	-15370	-18894	-279	-343	55.0
3010	6 City	-113	-8	147	29	-16593	-20397			59.1
3017	6 Hwy	-126	-13	146	21	-18402	-22622	-279	-343	66.0
3021	7 City	-134	-8	147	16	-19669	-24178			70.1
3028	7 Hwy	-147	-13	146	7	-21447	-26365	-278	-342	77.0
3033	8 City	-155	-8	147	2	-22754	-27971			81.1
3040	8 Hwy	-168	-13	146	0	-24473	-30084	-278	-342	88.1
3044	9 City	-177	-8	147	0	-25857	-31786			92.1
3046	9* Hwy	-179	-2	145	0	-25923	-31866	-275	-339	94.1