Wager, G., McHenry, M.P., Whale, J. and Bräunl, T. (2013) Testing energy efficiency and driving range of electric vehicles in relation to gear selection. Renewable Energy, 62 . pp. 303-312.

Testing energy efficiency and driving range of electric vehicles in relation to gear selection

Revised submission to Renewable Energy

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Abstract

Electric vehicles (EVs) have the potential to be operated using a clean, renewable energy source. However, a major limitation is their relatively short vehicle driving range and the associated driver 'range anxiety'. This research investigates the effect of gearing on energy consumption and driving range efficiency on an EV-converted Ford Focus using a chassis dynamometer in a controlled test environment in accordance with international standards. Two designs of the Ford Focus were used in the tests; one with an automatic gear drive, and the other with a manual gear drive. The electricity consumption of the two cars driving under different gearing configurations was measured under identical drive cycles. The vehicle range tests showed that measuring energy consumption on just two consecutive drive cycles on a calibrated chassis dynamometer will lead to a small overestimation of the energy consumption due to a ‘cold’ drive train. The results also suggest greater attention needs to be paid to EV battery charger efficiency, particularly in terms of standby energy consumption, which can increase the total energy required for EV owners markedly.

Keywords: Electric vehicle; drive cycle; range; efficiency; gearing; dynamometer; NEDC.

1. Introduction

The International Energy Agency (IEA) states that transport accounts for about 25% of the total global CO_2 production [1]. Electric vehicles (EVs) are a viable alternative to internal combustion engine (ICE) vehicles and can contribute to reduction of energy security and supply risks, and mitigate carbon emissions and air pollution, provided the energy to run EVs is supplied from local renewable energy sources and is well-integrated with the electricity system [2-10]. Health issues and increased mortality from ICE vehicle air pollution is a consequence of increased exposure to exhaust gas emissions and particulates [2, 5]. As a single example, an air quality study by Yim and Barret [11] found about 19,000 premature deaths in the UK per year due to combustion emissions generated in the UK and mainland Europe. This number far exceeds the annual road fatalities in the UK (1,901 fatalities and 23,122 serious injuries in year 2011 [12]) or the estimated 7,500 premature deaths from transport in general [11]. New and potentially cleaner transport technologies such as EVs, however, are not yet mainstream and their wider adoption has been hindered by several issues including high purchase costs, short vehicle driving ranges, limited recharging/refuelling stations, time-consuming recharging of batteries, vehicle safety, specialist vehicle applicability, and concerns of electricity infrastructure inadequacy in many regions [2, 3, 9, 10, 13-20].

The idea of the EV is not new; they first appeared in the mid-19th century when ICE vehicles required hand cranking to start [3]. Yet, after the invention of the electric starter motor for combustion engine vehicles, many EVs disappeared from the market and the ICE became the dominant vehicle propulsion technology. In 1997 Toyota developed the Prius, the first mainstream hybrid EV [21], primarily developed for improving fuel economy and more efficient urban driving [14]. Toyota reached a cumulative sale of two million Prius vehicles in 2010, making it the world's best-selling hybrid car, and in 2012 CNN claimed that by the end of that year most major car manufacturers will have a plug-in car available for sale [22]. Further trends towards large-scale manufacturing of EVs has become a political imperative, with President Obama's goal of one million EVs in the US by 2015, representing a milestone in the reduction of the dependency on foreign oil imports [23]. However, there is sparse refilling infrastructure available for EVs and they cannot be refuelled within a comparable time to liquid or gas ICEs [10, 14]. The options for recharging EVs at present are limited to homes, some workplaces and a few official charging stations. Therefore, it is imperative that EV driving ranges are optimised, the cars are efficiently designed and the car is driven in an energy-efficient manner [24]. Nonetheless, many EV enthusiasts have not waited for buy-in from major car manufactures or widely available charging infrastructure [3]. In Australia, for example, an Electric Vehicle Organisation was founded in 1973 [25] and is still operational today, providing forums for social and technical communication to support the local car conversion industry, such as EV-Works in Landsdale, Perth, Western Australia [26], or Electric Vehicle Conversions in Balcatta, also in Perth, Western Australia [27]. These companies offer the conversion of a standard car into an EV. Figure 1 shows one of the two Ford Focus vehicles tested for this study, both of which were standard factory motor vehicles that were converted by EV-Works into pure EVs [28]. Both vehicles had identical electric main drive motors, controllers and batteries (lithium-ion), with the only difference being the gearing.

[Insert Figure 1 approximately here].

2. EV Testing and Drive Cycles

Measuring the performance and efficiency of EVs is a complex task when considering the effects of variable environmental factors, such as wind speed and direction, temperature, and ascending and descending slopes. All of these provide testing challenges and may significantly influence a vehicles' energy consumption and driving range testing results [4]. Many of these problems can be overcome by using a chassis dynamometer, a device capable of measuring forces on a car's wheels or engine. Some advanced chassis dynamometers are computer controlled and are capable of simulating driving under real road conditions.

Drive cycle testing was developed in the late 1960s for uniform emission testing on passenger cars with combustion engines [29, 30]. A drive cycle represents a common driving pattern of motor vehicle users, and testing is usually performed on a calibrated chassis dynamometer to provide a stable, climate controlled and traffic-free environment. Drive cycles use predefined speed and acceleration profiles, and for a specific vehicle test, the (often human) test driver of the motor vehicle is required to follow the profile. To maintain the required profiles, a computerised driving aid supports the driver by indicating the rate of acceleration and deceleration of the vehicle, and vehicle operating conditions, to produce a valid test drive. Meeting these operating conditions is critical as the rate of acceleration, deceleration and vehicle speed influence vehicle emissions, energy consumption, etc., and heavily influence test results. Figure 2 shows a typical computer driving aid used for this research and in industry for vehicle testing.

There are several international standards for chassis dynamometer drive cycle testing for combustion engine vehicles for different countries, and they all exhibit somewhat different drive cycle profiles and properties. The New European Driving Cycle (NEDC), introduced in 2000 [31], contains the European Union Urban Driving Cycle (UDC or ECE-

15) and the Extra Urban Driving Cycle (EUDC), which is applied for Euro 3 standards and onwards emission testing. The first section represents the European Union Urban Driving Cycle from the Economic Commission for Europe (ECE) with a slow suburban test for 780 seconds. The second section represents a highway driving speed pattern for an additional 400 seconds at high speed with no stopping. In contrast, the US Federal city driving pattern for vehicle testing, which is also known as the FTP 75 (Federal Test Procedure) developed by the U.S. Environmental Protection Agency, exhibits a more 'aggressive' urban/city drive cycle than the ECE. The second section (highway driving) represents driving on a freeway with no stopping and little deceleration. The high dynamic variation in the FTP 75 city cycle is likely to represent a more 'real world' driving scenario than the ECE urban cycle with its 'flatter' shaped profile representing consistent and slow driving conditions. These drive cycle standards are also used for EV testing [32]. From an EV testing perspective, drive cycles provide a uniform testing procedure for range and energy consumption, and also for other performance testing including the evaluation of regenerative braking systems (RBS) and anti-lock braking systems (ABS). This research focusses on demonstrating efficiency and range characteristics using only gearing configurations without the benefits of RBS, which can vary considerably depending on vehicle and driving conditions, and exhibit strong dependencies on optimisation and calibration to match loads.

Although the predefined drive cycles provide a stable test procedure for vehicle comparisons, they will not always reflect actual road conditions, and how vehicles will perform in practice. Variables such as hills, air resistance, temperatures, road surfaces, various traffic conditions and driving patterns will all influence performance, efficiency and energy consumption of a vehicle [24, 33, 34]. A study conducted by the University of Sheffield [35] investigated EV energy consumption and range tests on a laboratory chassis dynamometer and compared results with equivalent road tests, all repeated for various driving patterns. The range for the EV (a Smart Fortwo electric drive) in the chassis dynamometer range tests was between 105.66 km and 114.68 km for all selected driving patterns, demonstrating how different drive cycles can influence the range of the vehicle. The road tests showed an even larger variation in vehicle range, with the maximum range recorded between 61.2 km and 74.0 km [36]. Further investigations of test driving an EV on real roads with a pool of 25 different drivers found larger variations in the maximum range of between 56 km and 107 km [35]. This study highlighted the significant differences in driver behaviour on road tests, and resulting range and energy consumption variations, emphasising the importance of chassis dynamometer testing for benchmarking results.

[Insert Figure 2 approximately here].

3. Materials and Method

Two Ford Focus EVs were tested on a computer-controlled chassis dynamometer at the Orbital Corporation facility in Balcatta in Perth, Western Australia. Car 1 had a manual factory gearbox whereas Car 2 had a factory automatic gearbox installed. Neither vehicle employed a regenerative braking system. Table 1 provides an overview of the two different EV vehicles and their configurations for testing.

Table 1: An overview of the Ford Focus EV gearing, battery, motor and configurations.

Model	**Gearbox**	**Battery**	**Motor**	**RBS**	**Factory EV**
1. Ford Focus [37]	Manual	144V, 23kWh	80kW	No	No
2. Ford Focus [37]	Automatic	144V, 23kWh	80kW	No	No

Figure 3 shows the Ford Focus on an energy consumption test on the chassis dynamometer. The custom-made instrumentation system was used to measure the electric current from/to, and voltage of, the battery bank, and the distance driven during the experiment. Orbital's calibrated test equipment and instrumentation included a capability for road load simulation.

The test facility fulfils the requirements for the testing of motor vehicles according to international standards. The facility was adapted to be suitable for EV testing by installing additional equipment as described below. The existing chassis dynamometer instrumentation logged the ambient temperature, vehicle speed, and dynamometer force parameters during the drive cycle tests. The computer of the chassis dynamometer contained pre-programmed drive cycles that met the requirements of the United Nations ECE Regulations R101 standard [32].

[Insert Figure 3 approximately here].

3.1. Vehicle Instrumentation

In addition to the dynamometer instrumentation systems, a custom-designed, constructed and programmed data acquisition system was installed and calibrated to log the following data: date and time; vehicle main battery voltage (V); main battery charge current (-A); main battery discharge current (+A); motor controller temperature (°C); brake light status information (on/off), and brake pedal foot pressure (kg). The core of the system was a National Instruments data acquisition unit, together with hardware and a graphical user interface that were designed for measuring, displaying and logging vehicle test data. An open source application programmed using LabVIEW™ software provided the option to modify the system during the project if required. The data sampling rate was 500 Hz, with data averaged and stored in a text file every second, such that testing to the NEDC produced a text file with 1,180 averaged data points. In addition to the custom-built instrumentation the two electric Fords were equipped with an installed energy meter from TBS Electronics BV [38]. The meter measured the main battery voltage (V), instantaneous current (A), cumulative ampere hours (Ah), and battery state of charge (SOC) in percentage (%), through a multi-functional display. The TBS energy meter was required in order to provide information to meet the standard R101 [32], which states that all vehicle recharge electricity is measured on the wall socket. Due to the impractically of this arrangement in the facility, the TBS energy meter provided this data. The unit of specific energy consumption required by the R101 standard is Wh/km, and to approximate the vehicle energy consumption in Wh, the main battery voltage was logged over two drive cycles, averaged and multiplied by the recorded Ah displayed by the TBS energy meter. This technique was assumed to be within an acceptable accuracy as the typical voltage discharge curve of a lithium-ion cell or lithium polymer cell is relatively stable to a discharge capacity percentage of about 80%. After testing, the vehicle was required to be recharged and the charge energy E measured as described above. The electric energy consumption c (expressed in Wh/km and rounded to the nearest whole number), is defined as $c = E / D_{test}$, where D_{test} is the distance (km) covered during the test [32]. The charge energy E was divided by an assumed charging system efficiency of 0.86. The charging system efficiency was derived from the assumed battery charging efficiency of 0.88 [39], 0.99 for the battery recharge efficiency [40], and 0.99 for the wiring system. The total cumulative energy was then divided by the km measured to obtain energy consumption in Wh/km. All data was analysed using a spreadsheet and a graphical interface.

The electric Ford Focus uses 45 lithium-ion-phosphate battery cells of 160Ah each, so a total of 23kWh, from supplier Winston Batteries, China. This battery cell type has a nominal voltage of 3.2V and an almost linear discharge curve down to 2.8V at 90% discharge at room temperature when applying the maximum recommended constant discharge rate of 3C (equivalent to 480A). Our measurements, shown in Figure 4, highlight the fluctuating battery voltage level during the much more realistic discharge of two consecutive drive cycles. The drop in battery voltage is proportional to load, especially during acceleration phases and when maintaining the higher vehicle speeds of the extra-urban cycle. However, during the brief break between drive cycles, the voltage level recovers to a level close to the initial voltage.

[Insert Figure 4 approximately here].

3.2. The R101 Standards and Vehicle Testing Procedures

The testing procedures for the energy consumption and range tests were conducted as close as practicable to the United Nations ECE Regulations R101 standard (for the EV testing procedure with regards to energy consumption and range see Annex 7 and Annex 9 of the standard, respectively, [32]). The R101 is a United Nations regulation from the year 2005 [41], that allows comparable emission/fuel/energy consumption measurements of motor vehicles under idealised road conditions using a chassis dynamometer. Regulations such as R101 were developed for uniform testing of passenger cars powered by ICEs only, or powered by a hybrid electric power train. Measured are CO_2 emissions and fuel consumption for ICE cars, as well as electric energy consumption and electric range for hybrid and battery-electric cars. For the EV energy consumption test, the standard requires the vehicles and the battery to be preconditioned prior to testing to provide uniform testing conditions for all types of vehicles and batteries. (Figure 5). The key requirement includes the main battery to be in operation for at least seven days, to have undergone driving of a minimum of 300 km, and to be fully discharged and then fully charged prior to performance testing. In addition, the vehicles were required to remain at a temperature between 20°C to 30°C, with vehicle tyres inflated to pressures specified by the vehicle manufacturer. All drive cycles were required to be completed with all auxiliary devices such as the heater and air-conditioner switched off. The test drive required two consecutive NEDC drive cycles with a maximum tolerance of +/- 2 km/h in the speed profile, and +/- 1s in time. The end of the range test, as defined by the R101 standard, occurs when the vehicle cannot maintain 50 km/h, or there is an indication from the car informing the driver that the vehicle must be stopped due to a low battery level [32]. The vehicle was required to drive continuous NEDC drive cycles until the battery was discharged. (Figure 6). Prior to the experiments, however, the test vehicles' main batteries could not be fully discharged and recharged due to the time restriction for other ongoing projects and test drives conducted at Orbital's facility. Therefore, the two electric Fords' pre-test battery conditioning was limited to a full charge overnight prior to testing in a dedicated charging area. Test procedures such as those used in the Advanced Vehicle Testing Activity (AVTA), were outside the scope of the research [42].

[Insert Figures 5 and 6 approximately here].

4. Results and Discussion

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

The Ford Focus manual EV (Car 1) was tested using NEDC drive cycles according to the R101 standard with the aim of measuring the energy consumption and the maximum vehicle driving range under different gear selections. The vehicle energy consumption test required two consecutive NEDC drive cycles in gears 2 and 4, where the city cycle and the highway cycle were driven in second and fourth gear, respectively. After fully recharging the batteries overnight, the vehicle was driven again for the same pattern in gears 3 and 4. Vehicle energy consumption results were manually recorded from the TBS energy meter for each individual drive cycle. The TBS energy meter recorded discharge capacities during two consecutive NEDC drive cycles in second and fourth gear. The first drive cycle recorded a discharge of 5.1 Ah for the city driving part of the cycle and a discharge of 10.2 Ah for the highway driving part of the cycle. In the second cycle, the TBS energy meter recorded slightly lower discharge capacities of 4.7 Ah and 10 Ah for both city and highway driving, respectively. This was assumed to be due to reduced friction within the driving train, including the gearbox, bearings and tyres subsequent to the completion of the first drive cycles. The TBS energy meter recorded slightly lower discharge rates in all second drive cycles for all of the Ford Focus manual EV experiments. For example, the discharge from two consecutive NEDC cycles in gears 3 and 4 for the first cycle was 4.8 Ah for the city driving part of the cycle and 10.0 Ah for the subsequent highway driving part of the cycle. In the second cycle lower discharges of 4.7 Ah and 9.9 Ah were recorded for city and highway driving, respectively. The calculated energy consumption from the two consecutive drive cycles in gears 2 and 4 without charge losses was 195 Wh/km (see Table 2). However, after charging system efficiency loss calculations were included, the total energy consumption results were 226 Wh/km. Similarly Table 3 shows the calculated energy consumption in gears 3 and 4 of 195 Wh/km without recharge losses. When including the recharge losses the calculated vehicle's total energy consumption increases to 226 Wh/km. These differences demonstrate the importance of measuring both the energy used by the EV and the total energy required to recharge the EV.

Table 2: The calculated energy consumption in Wh/km of the Ford Focus manual EV driving in gears 2 and 4.

Driving cycle no.	**Gear**	**Cumulative consumption w/out losses (Wh)**	**Cumulative consumption inc. losses (Wh)**	**Energy consumption w/out losses (Wh/km)**	**Energy consumption inc. losses (Wh/km)**	**Distance driven (km)**
1- City	2	751.9	871.8	-	-	4.052
1- Highway	4	2,193.2	2,542.9	199	231	11.007
2- City	2	2,930.4	3,397.6	-	-	15.059
2- Highway	4	4,289.8	4,973.8	190	221	22.014
Average				195	226	

Table 3: The calculated energy consumption in Wh/km of the Ford Focus manual EV driving in gears 3 and 4.

Driving cycle no.	**Gear**	**Cumulative consumption w/out losses (Wh)**	**Cumulative consumption inc. losses (Wh)**	**Energy consumption w/out losses (Wh/km)**	**Energy consumption inc. losses (Wh/km)**	**Distance driven (km)**
1- City	3	710.	873	-	-	4.052
1- Highway	4	2,156	2,500	196	227	11.007
2- City	3	2,891	3,352	-	-	15.059
2- Highway	4	4,291	4,975	194	225	22.014
Average				195	226	

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 gears 2 and 4 until the battery was exhausted in order to obtain the vehicle's maximum range. After an overnight full battery charge the range test was repeated in gears 3 and 4.

Over a total of 5 hours and 15 minutes of driving, the range test provided data on the maximum vehicle range and the individual discharge capacities for each drive cycle during continuous driving. Table 4 shows the individual discharge capacity and energy consumptions over the whole range test driving in gears 2 and 4, and the maximum achieved distance of 143 km until the battery was exhausted. The car was not able to complete the highway part of the last cycle — marked with an asterisk (*) in Table 4. The significantly higher current recorded during the last drive cycle was due to a very low battery voltage from a low SOC and was unable to maintain the maximum required speed of 120 km/h. During acceleration to the required speed of 120 km/h, the battery was unable to provide sufficient energy, and the manufacturer's warning signal light indicated to the driver to slow down the vehicle and stop. The energy consumption of city and highway driving in the first drive cycle were slightly higher than subsequent cycles, which again is likely to be due to decreasing drive train losses. Nonetheless, the table shows that during the range test the energy consumption was stable. Table 5 shows the equivalent EV maximum range test results using gears 3 and 4. Over a total of 5 hours and 30 minutes of repeated drive cycles the maximum vehicle range achieved was 141 km. As during the previous experiment in gears 2 and 4, the discharge capacities in the first drive cycle were slightly higher than latter cycles, with Ah recordings increasing with decreased battery voltages when meeting the drive cycle specifications.

Table 4: The recorded parameters during the range test up to 143 km, including individual drive cycle energy consumption, for the Ford Focus manual EV in gears 2 and 4.

Cycle no.	TBS (Ah)	TBS cycle (Ah)	TBS voltage (V)	TBS SOC (%)	Energy use w/out	Energy use without	W/out losses (Wh/km)	With losses (Wh/km)	Km travelled (Dyno.)

					losses (Wh)	**losses (Wh)**			
1- City	4.8	4.8	149	N/A	714	828			4.1
1- Highway	14.9	10.1	149	N/A	2,213	2,565	201	233	11.0
2- City	19.5	4.6	149	N/A	2,900	3,362			15.1
2- Highway	29.4	9.9	148	N/A	4,342	5,035	193	224	22.0
3- City	33.9	4.5	149	N/A	5,034	5,837			26.1
3- Highway	43.8	9.9	147	N/A	6,443	7,470	191	221	33.0
4- City	48.3	4.5	148	N/A	7,163	8,305			37.1
4- Highway	58.2	9.9	147	62.7	8,5,61	9,926	192	223	44.0
5- City	62.7	4.5	148	59.5	9,261	10,737			48.1
5- Highway	72.6	9.9	147	53.5	10,658	12,357	190	221	55.0
6- City	77.2	4.6	147	N/A	11,356	13,167			59.1
6- Highway	87.1	9.9	146	44.2	12,751	14,784	190	221	66.0
7- City	91.6	4.5	147	41.3	13,465	15,612			70.1
7- Highway	101.6	10.0	146	34.9	14,844	17,210	190	220	77.0
8- City	106.2	4.6	147	32.0	15,590	18,076			81.1
8- Highway	116.4	10.2	146	25.5	16,936	19,636	190	220	88.1
9- City	120.9	4.5	147	22.6	17,712	20,536			92.1
9- Highway	131.0	10.1	145	16.1	18,982	22,008	186	215	99.1
10- City	135.7	4.7	145	13.1	19,609	22,735			103.1
10- Highway	145.9	10.2	144	6.5	21,010	24,359	184	214	110.1
11- City	150.6	4.7	144	3.6	21,747	25,214			114.1
11- Highway	161.1	10.5	143	0.0	22,973	26,636	178	207	121.1
12- City	165.7	4.6	143	0.0	23,662	27,435			125.1
12- Highway	176.3	10.6	139	0.0	24,506	28,413	139	161	132.1
13- City	N/A	N/A	N/A	N/A	N/A	N/A			136.1
13- Highway*	187.0	N/A	129	0.0	24,048	27,882	42	48	**143.1**

Table 5: The recorded parameters during the range test up to 141 km, including individual drive cycle energy consumption, for the Ford Focus manual EV in gears 3 and 4.

Cycle no.	TBS (Ah)	TBS cycle (Ah)	TBS voltage (V)	TBS SOC (%)	Energy use w/out losses (Wh)	Energy use without losses (Wh)	W/out losses (Wh/km)	With losses (Wh/km)	Km travelled (Dyno.)
1- City	5	5	149	97	715	829			4.1
1- Highway	15	10	148	90	2,226	2,581	202	234	11.0
2- City	20	5	149	87	2,931	3,399			15.1
2- Highway	30	10	148	81	4,366	5,062	194	225	22.0
3- City	34	5	149	78	5,097	5,910			26.1
3- Highway	44	10	147	72	6,530	7,571	197	228	33.0
4- City	49	5	148	69	7,257	8,414			37.1
4- Highway	59	10	147	62	8,644	10,022	192	223	44.0
5- City	63	5	148	59	9,371	10,865			48.1
5- Highway	73	10	147	53	10,738	12,451	190	221	55.0
6- City	78	5	147	50	11,437	13,260			59.1
6- Highway	88	10	146	44	12,839	14,886	191	221	66.0
7- City	92	5	147	41	13,583	15,748			70.1
7- Highway	102	10	146	34	14,936	17,317	190	221	77.0
8- City	107	5	147	32	15,718	18,224			81.1
8- Highway	117	10	145	25	17,012	19,724	189	219	88.1
9- City	122	5	146	22	17,817	20,658			92.1
9- Highway	132	10	144	16	19,032	22,066	184	213	99.1
10- City	137	5	145	13	19,862	23,028			103.1
10- Highway	147	10	144	6	21,051	24,408	183	213	110.1
11- City	152	5	144	3	21,846	25,329			114.1
11- Highway	162	10	142	0	23,026	26,697	179	208	121.1
12- City	166	5	143	0	23,745	27,531			125.1
12- Highway	177	11	138	0	24,412	28,304	126	146	132.1
13- City	182	5	136	0	N/A	N/A			136.1
13- Highway*	187	5	126	0	23,586	27,347	91	106	**141.1**

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

Experiment 2 investigated the energy consumption and the vehicle driving range of the automatic Ford Focus EV (Car 2). The vehicle was driven for two consecutive NEDC drive cycles in automatic gear mode D. After the completion of the energy consumption test the vehicle was fully recharged overnight before the range test, which involved driving continuous NEDC drive cycles until the battery was exhausted. Table 6 shows the discharge (Ah) recorded from the TBS energy meter during the driving of two consecutive NEDC drive cycles, and contrasts the results with the Ford Focus EV manual NEDC drive cycles in gears 2 and 4, and 3 and 4. In the first cycle, the battery discharge recording for the city driving part of the cycle was 8.4 Ah, and the discharge for the following highway driving part of the cycle was 13.0 Ah. In the second NEDC cycle, the battery discharge differed for city driving (8.0 Ah) with the discharge for highway driving remaining the same as in the first cycle (8.4 Ah). When comparing the automatic EV versus the manual EV battery discharge recording over identical NEDC drive cycles, the automatic clearly discharged the battery to a greater extent than either of the manual gearing tests. The calculated automatic Ford Focus EV energy consumption without recharge losses was 273 Wh/km, and the calculated total energy consumption (including losses) was 317 Wh/km (Table 7).

Table 6: A comparison of the battery discharge, over two NEDC drive cycles, of the Ford Focus automatic EV, and the Ford Focus manual EV. .

	Automatic		**Manual**		**Manual**	
Driving cycle no.	**Gear**	**Discharge during cycle (Ah)**	**Gear**	**Discharge during cycle (Ah)**	**Gear**	**Discharge during cycle (Ah)**
1- City	D	8.4	2	5.1	3	5.14.8
1- Highway	D	13.0	4	10.2	4	10.2
2- City	D	8.0	2	4.7	3	4.7
2- Highway	D	13.0	4	9.9	4	10.0

Table 7: The calculated energy consumption in Wh/km of the Ford Focus automatic EV driving in gear D.

Driving cycle no.	**Gear**	**Cumulative consumption w/out losses (Wh)**	**Cumulative consumption inc. losses (Wh)**	**Energy consumption w/out losses (Wh/km)**	**Energy consumption inc. losses (Wh/km)**	**Distance driven (km)**
1- City	D	1,228	1,424	-	-	4.052
1- Highway	D	3,045	3,530	277	321	11.007
2- City	D	4,286	4,969	-	-	15.059
2- Highway	D	6,010	7,968	269	312	22.014
Average				273	317	

Table 8 shows the individual drive cycle energy consumptions and the maximum vehicle range for the Ford Focus automatic EV driving in gear D. The last NEDC highway drive cycle, marked with an asterisk (*), was incomplete due the exhausted battery. After the four hours and 45 minutes of driving the vehicle achieved a distance of 94.1 km. Figure 7 compares the maximum driving ranges of the two EVs with all tested gearing configurations. The figure shows similar vehicle ranges of 143 km and 141 km for the two Ford Focus manual EV gearing cases. However, the much higher energy consumption from the Ford Focus automatic EV resulted in a significant reduction of the drivable range to just 94 km. Errors of the measured maximum driving distance were limited to the maximum allowable speed deviation of +/- 2 km/h and the chassis dynamometer instrumentation accuracy of 0.5%. These experiments demonstrate that appropriate automatic EV gearing is a fundamental factor in maximising energy efficiency and drivable range. Figure 8 shows the individual battery discharge capacities for each drive cycle in all range tests, showing a generally decreasing and then increasing profile of the Ah recordings, consistent with the manual and automatic gearing test data. As discussed previously, initial decreasing energy consumption after the first drive cycle is likely to be due to reducing friction within the drive train. During the last cycles of the range tests, the low battery SOC meant that the vehicle was not able to match the speed required by the NEDC, particularly on the highway driving part of the cycle. On the last cycles of the test the vehicle was thus much slower than on previous cycles and hence the energy consumption was lower.

Figure 9 shows the negligible difference between the energy consumptions of the two Ford Focus EV gearing experiments in gears 2 and 4, and gears 3 and 4, both recording 226 Wh/km. With the uncertainty of the instruments it is not possible to determine which gearing was most efficient. However, these results combined with the range tests suggest very little difference in performance. In terms of comparing the Ford Focus manual EV with the automatic EV, the difference in energy consumption was significant despite identical motors, batteries and controllers. The Ford Focus automatic EV consumed 317 Wh/km in the range test, an increase of around 40% relative to the manual range tests. The primary reason for this increased consumption is the inability for the EV converter to interface with the computer controlled automatic gearbox, resulting in sub-optimal gear changes [43].

[Insert Figures 7, 8, and 9 approximately here].

Table 8: The recorded parameters during the range test up to 94 km, including individual drive cycle energy consumption, for the Ford Focus automatic EV in gear D.

Cycle no.	TBS (Ah)	TBS cycle (Ah)	TBS voltage (V)	TBS SOC (%)	Energy use w/out losses (Wh)	Energy use without losses (Wh)	W/out losses (Wh/km)	With losses (Wh/km)	Km travelled (Dyno.)
1- City	8	8	149	98	1,250	1,449			4.1
1- Highway	21	13	149	N/A	3,178	3,685	289	335	11.0
2- City	29	8	149	82	4,372	5,069			15.1
2- Highway	42	13	148	73	6,262	7,261	280	325	22.0
3- City	50	8	149	68	7,484	8,678			26.1
3- Highway	63	13	147	60	9,282	10,762	274	318	33.0
4- City	71	8	148	55	10,529	12,208			37.1
4- Highway	84	13	147	47	12,342	14,309	278	322	44.0
5- City	92	8	148	42	13,544	15,704			48.1
5- Highway	105	13	147	34	15,370	17,820	275	319	55.0
6- City	113	8	147	29	16,593	19,238			59.1
6- Highway	126	13	146	21	18,402	21,337	276	319	66.0
7- City	134	8	147	16	19,669	22,804			70.1
7- Highway	147	13	146	7	21,447	24,867	277	321	77.0
8- City	155	8	147	2	22,754	26,382			81.1
8- Highway	168	13	146	0	24,473	28,375	275	319	88.1
9- City	177	8	147	0	25,857	29,980			92.1
9- Highway*	179	2	145	0	25,923	30,056	240	278	**94.1**

The results must be viewed in the light of the sources of uncertainty associated with these experiments. The vehicle energy consumption was measured by the internal energy meter on the vehicle battery, resulting in an inability to measure the charge losses as required by the R101 standard. However, the total energy consumption including losses was assumed and approximated, as described in Section 3.1. The capacity and equipment to monitor the total EV energy consumption required to recharge the battery was unavailable for the experiments, as required by the R101 standard. This was fundamentally due to the restricted time available on Orbital's chassis dynamometer facility, resulting in additional charging to meet the battery charger's standby mode and vehicle's standby power when fully charged overnight, rather than fully-charging the vehicle and then undertaking testing as per the R101 standard. Battery charger self-consumption and residual battery charging can be a significant electricity consumer for EVs when not in use [44]. Results from the UWA Renewable Energy Vehicle Project (REV) found the cumulative energy used to 'top up' charge a vehicle battery was 7.4 kW, after which an additional 7.7 kW was consumed over a three-day interval by standby 'trickle' charging regimes by both the batteries and the charger [45]. Further sources of potential uncertainty include the allowable speed deviation of +/- 2 km/h from the NEDC drive cycle tests. Such relatively large uncertainties would influence the accuracy of energy consumption measurement and associated calculations over the experiment. In addition, the averaged voltages and the total system efficiency assumptions also introduce uncertainties in the EV energy consumption results.

5. Conclusions

Within the context of the limitations of this study, the difference in energy consumption and drivable range between the manual and automatic converted Ford Focus EVs was significant. This highlights the importance of careful gearbox selection, design and control strategies for automatic gearboxes for an aftermarket EV conversion that can extend range even without RBS. In contrast, the energy consumption between the manual EV drive cycle tests using different gears were not significant and did not influence the range of the vehicle. The energy consumption over just two NEDC drive cycles was shown to vary due to reduced friction on the driving train. The range tests showed that measuring energy consumption on just two consecutive drive cycles on the chassis dynamometer, as required by the R101standard, might overestimate the energy consumption of EVs due to a higher friction on a ‘cold’ drive train. The experiments also indicated that the configuration of the battery charger can have a significant impact on the total energy consumption of EVs. In addition, a battery charger may not automatically disconnect and power down, which will consume significant amounts of energy in standby mode.

The experimental demands demonstrated that the precise and accurate use of instrumentation of an EV on a chassis dynamometer is challenging. The interaction between instrumentation, electrical interferences and several different computers has the potential to induce errors that can be difficult to quantify. Furthermore, chassis dynamometer testing requires a large and expensive test environment and is time consuming. The authors recommend that the collation of characterised and modelled EV chassis dynamometer test results can be used to develop and validate software programs that might enable more cost-effective and time-efficient drive cycle investigations. The experiments also demonstrated that following EV test standards requires specialised technical expertise and attention to detail in meeting drive cycle parameters.

Acknowledgements

The authors would like to thank Orbital Corporation for the provision of test equipment, tools and test space. Also special thanks to Orbital’s Director Dr. Geoff Cathcart, Operation Manager Geoff Armstrong, Vehicle Control Engineer Alun Morgan, Team Leader Patrick O'Sullivan, Test-Engineer Nick Serginson and all Orbital staff members in supporting this research.

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Figures

Figure 1: The licenced Ford Focus converted to an EV that was used in the research. Source: [37].

Figure 2: Computerised driving aid for a human test driver to follow a predefined drive cycle used during the testing at Orbital's facility. 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, and the crosshair is the present speed. The uncertainty of the results can be inferred by the difference between the speed reading on the dashboard (51 km/h), and the crosshair (~49 km/h).

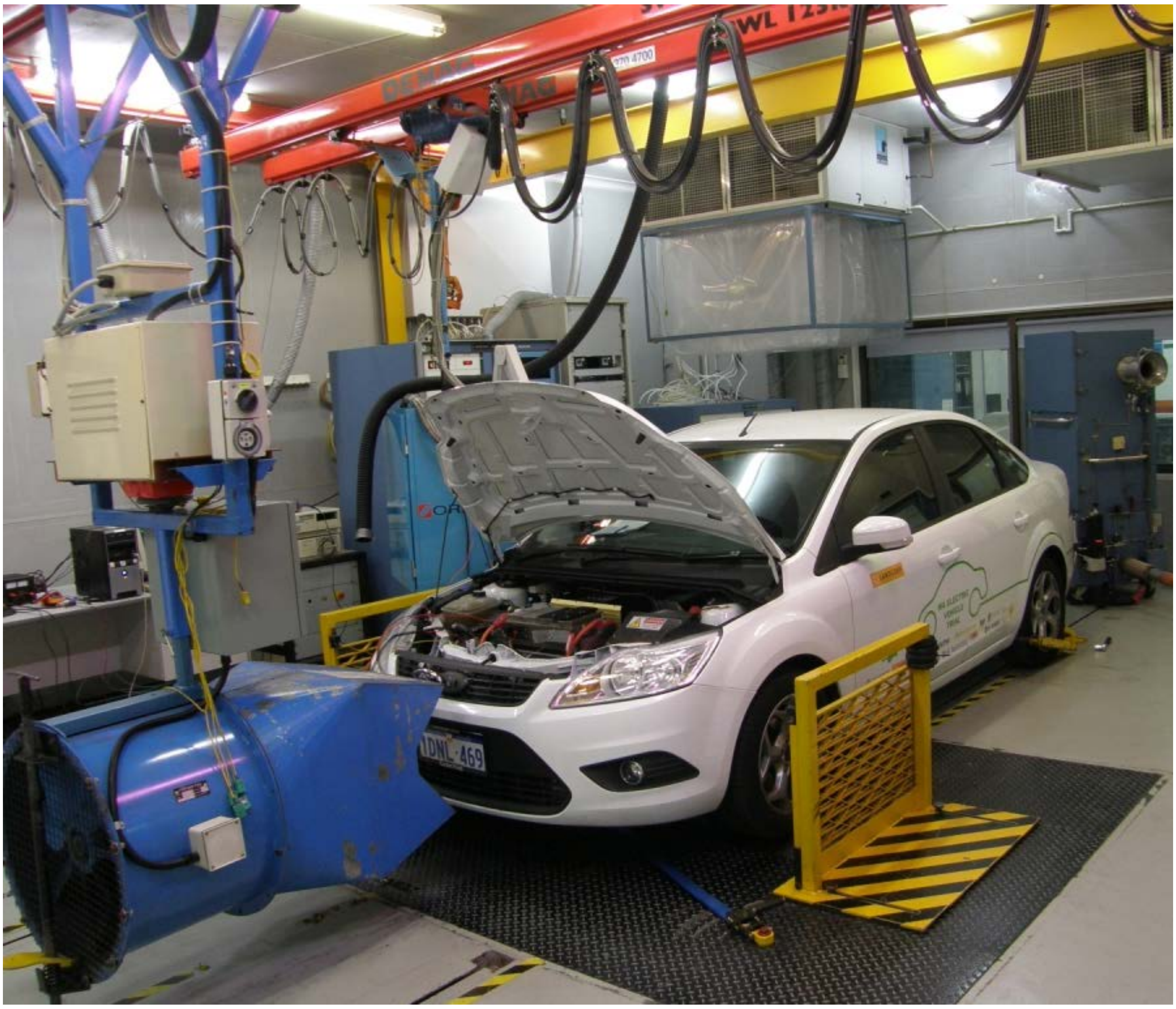

Figure 3: The Ford Focus EV on a chassis dynamometer under test conditions at Orbital's test facility.

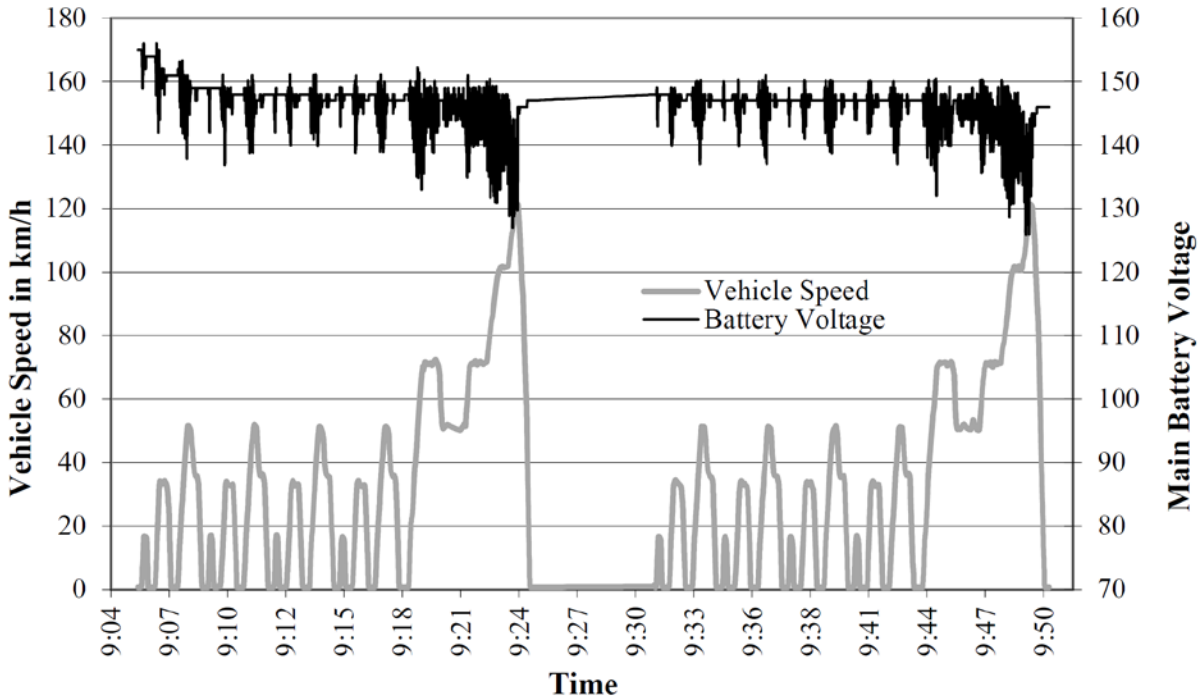

Figure 4: Vehicle speed and battery voltage during two consecutive drive cycles.

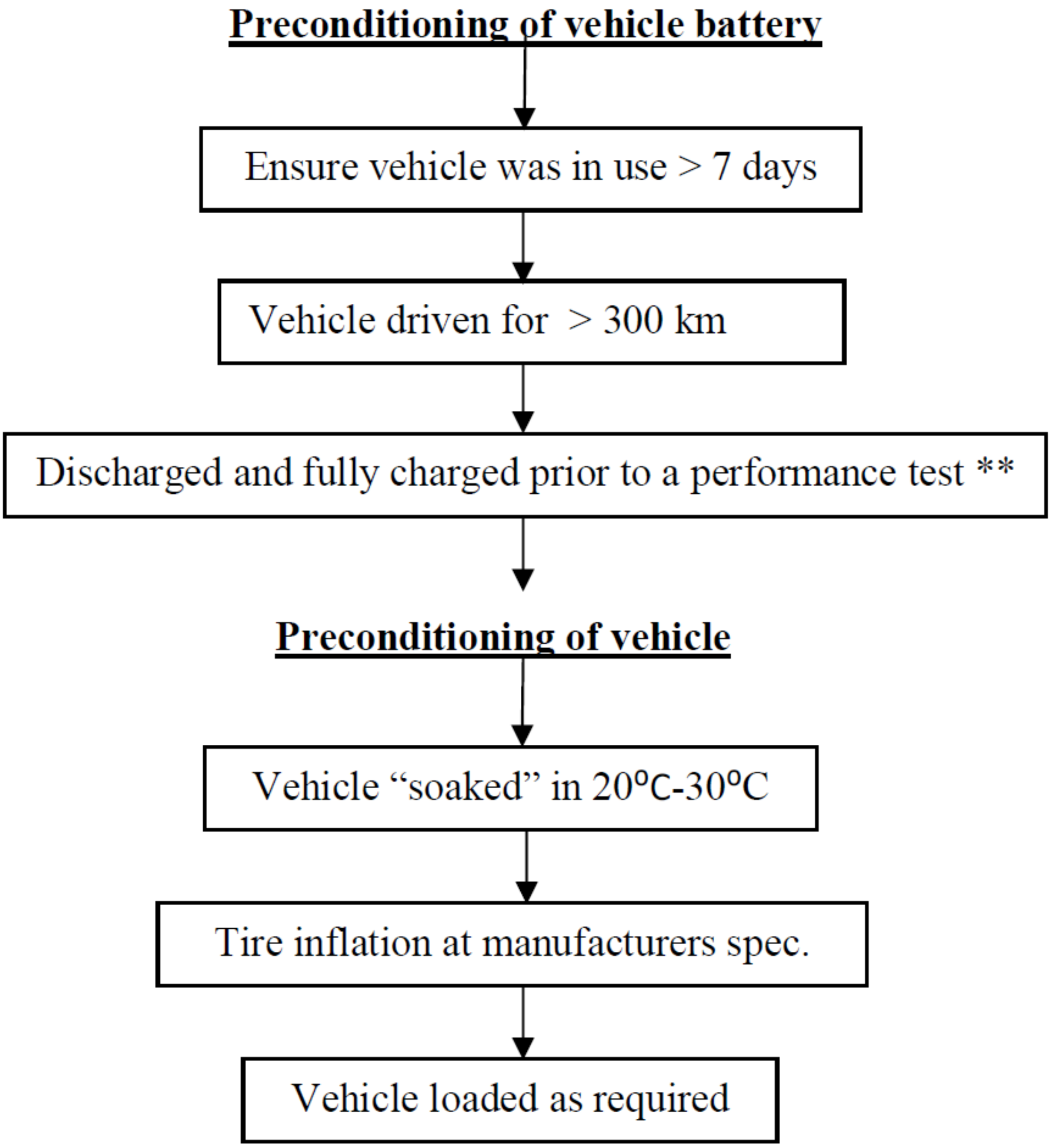

Figure 5: Preconditioning procedures for battery and vehicle following regulation R101.

** Due to time restriction on the chassis dynamometer, only a full charge was conducted.

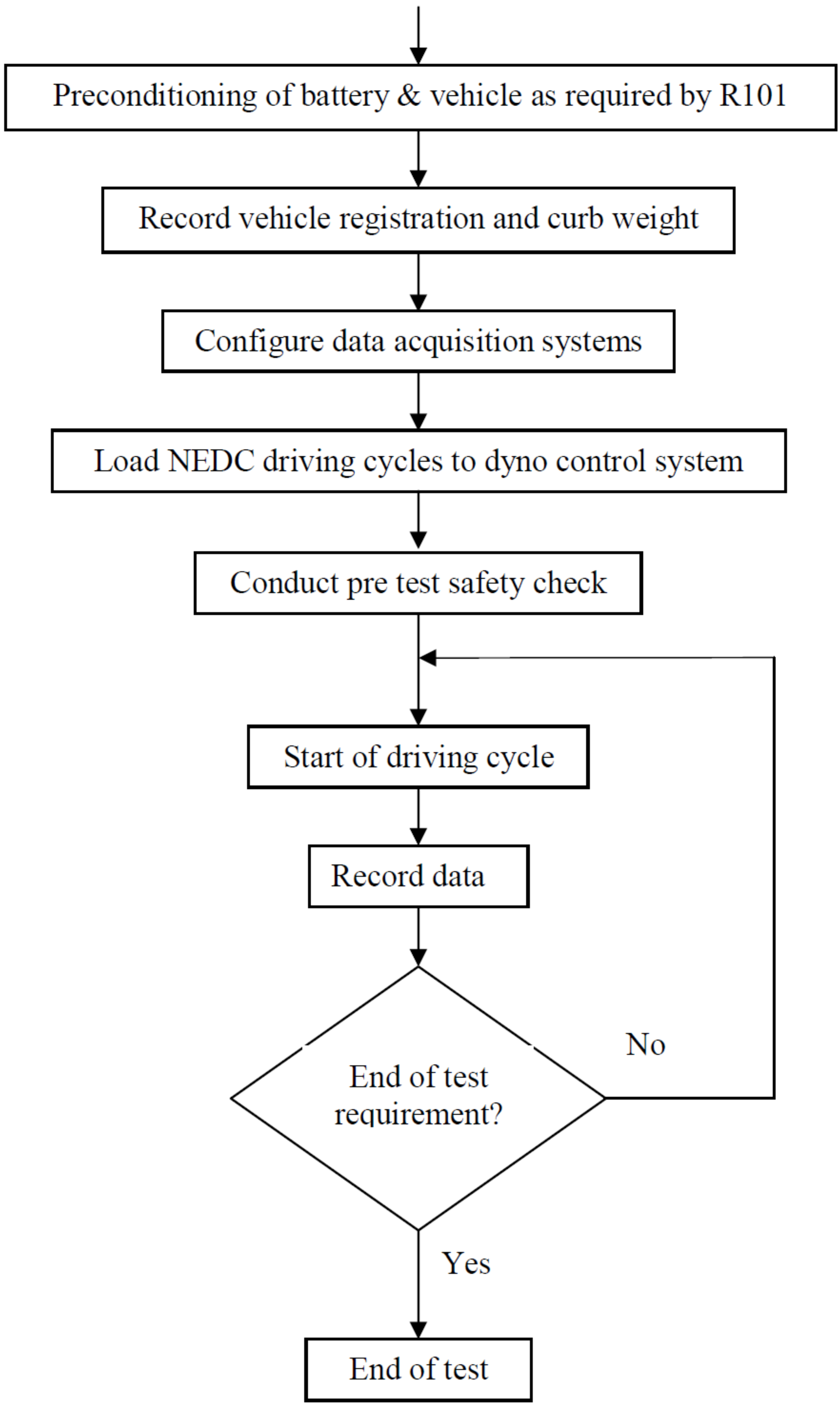

Figure 6: Testing procedure following regulation R101 preconditioning procedures.

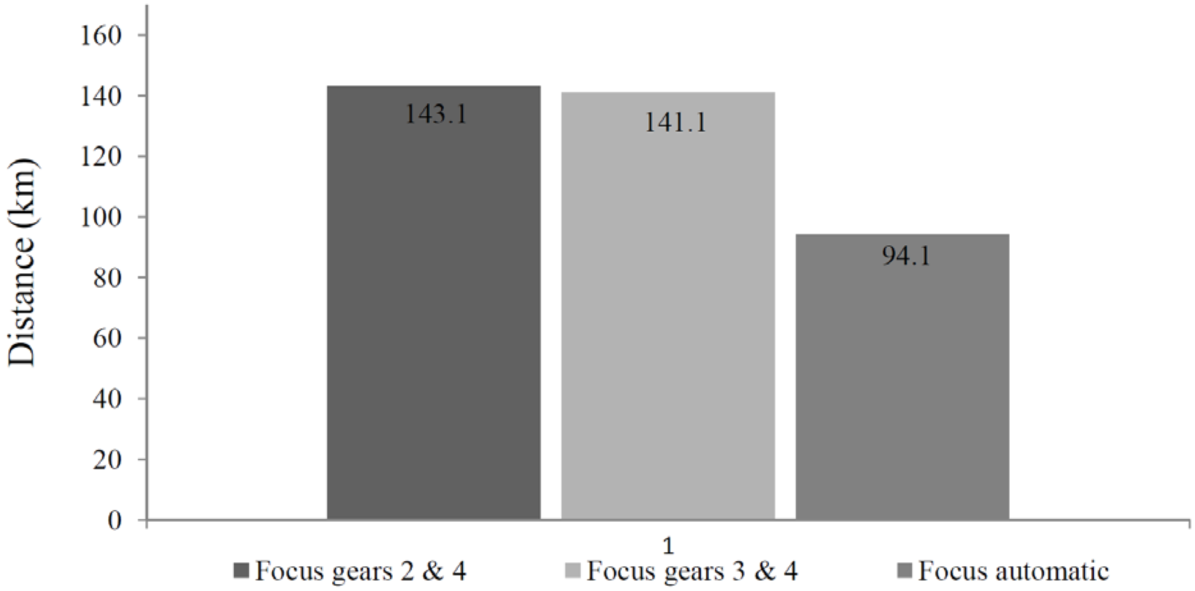

Figure 7: The maximum range for the two Ford Focus EVs tested under different gearing configurations.

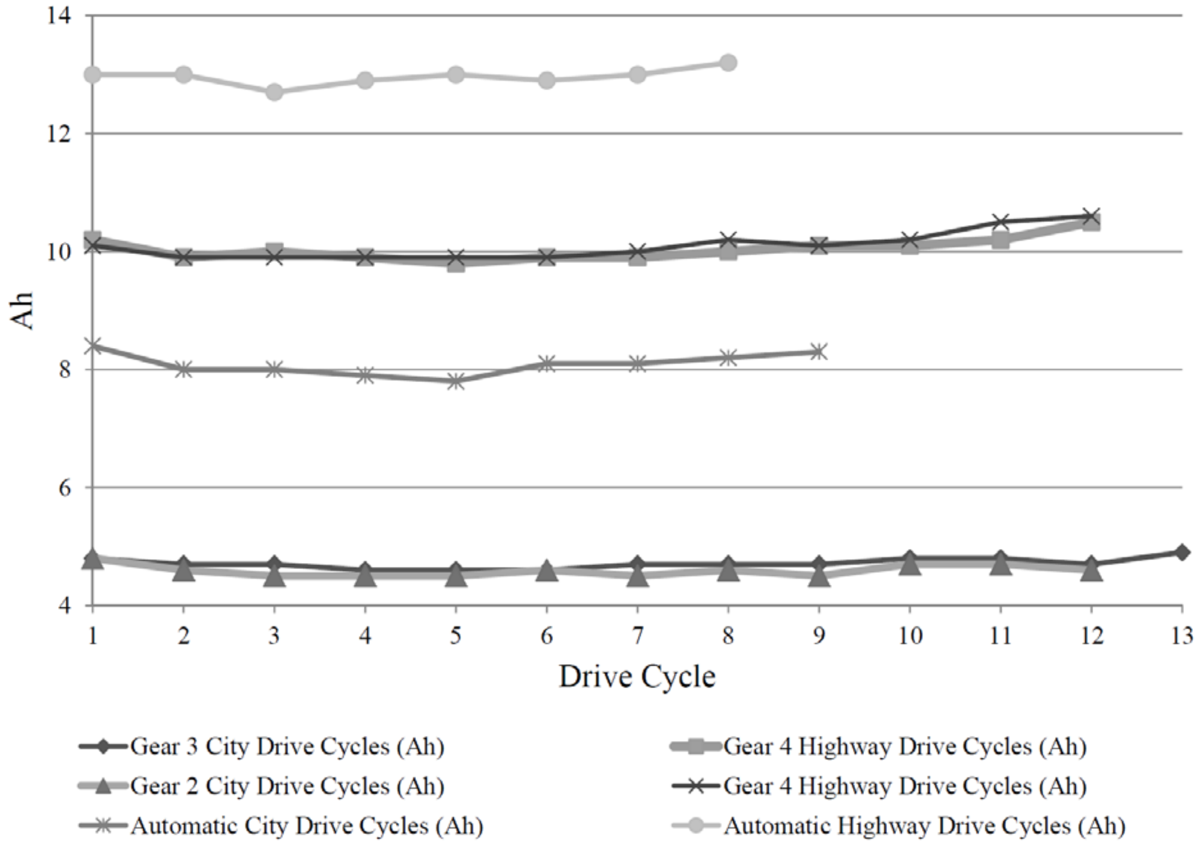

Figure 8: Battery discharge capacities for each city and highway part of repeated drive cycles for both the manual and automatic Ford Focus EVs.

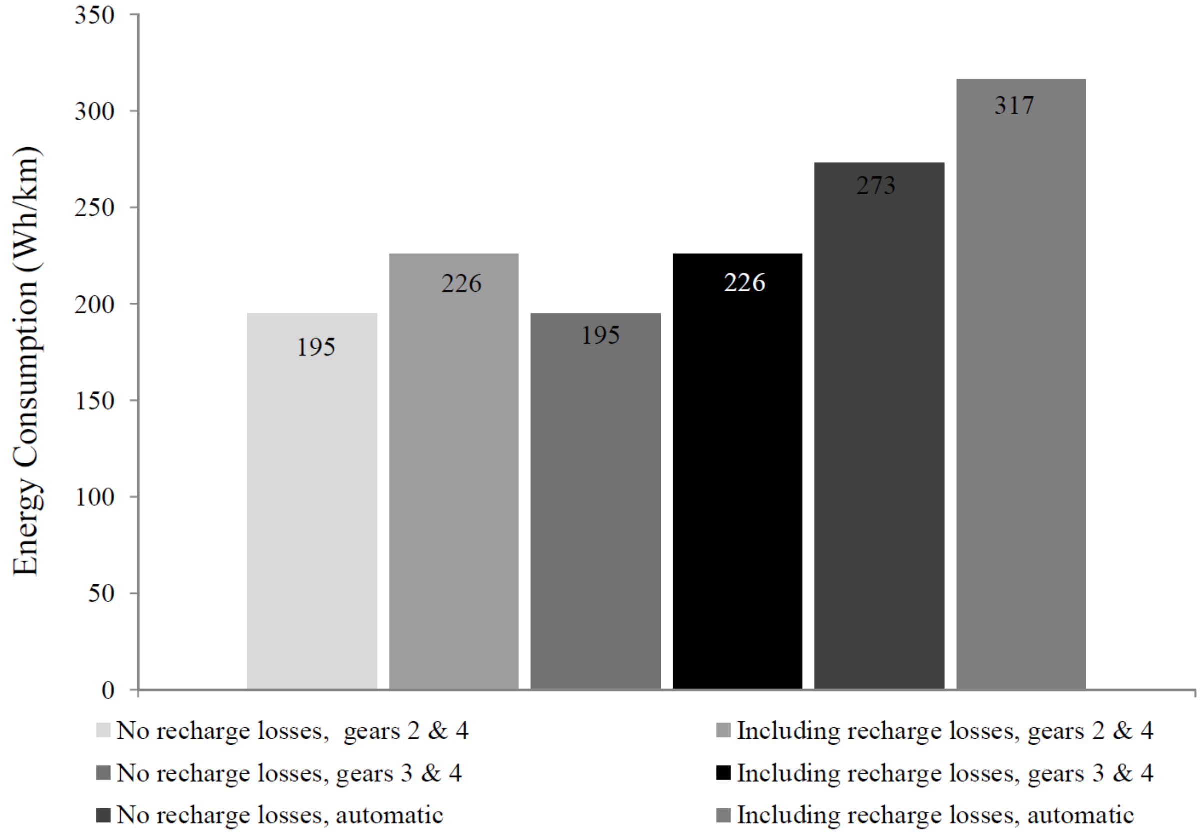

Figure 9: The total energy consumption including recharge losses for the two Ford Focus EVs tested under different gearing configurations.