Limitations of testing standards for battery electric vehicles: accessories, energy usage, and range

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Abstract: Issues with hydrocarbon fuel supply security, price volatility, alongside environmental and health concerns of conventional internal combustion engine ICE) transport technologies have raised interest in electric vehicle (EV) alternatives. However, the methods of EV testing for performance and range are inadequate adaptations from ICE testing standards designed to measure liquid fuel economy and emissions under largely unrealistic conditions. This research assesses the performance of a battery EV (BEV) by conducting a number of real-world driving tests under varying conditions, including the impact of vehicle accessory usage (lights, air-conditioning, stereo, heater etc.), and additional passengers. Our results demonstrate that large increases of energy consumption from accessory usage and additional passengers do occur in BEVs, which remain outside of most published EV/BEV and ICE vehicle standard test results, which themselves have recently come under scrutiny for other reasons. Due to the relatively small battery in modern BEVs this additional loss in efficiency and range under real world on-road conditions may severely compromise the nascent BEV industry; particularly in areas with limited charging infrastructure.

Acronyms:

ADR	Australian Design Rule
BEV	Battery Electric Vehicle
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
NEDC	New European Driving Cycle
PHEV	Plug-in Hybrid Electric Vehicle
RBS	Regenerative Braking System
UDC	Urban Driving Cycle

1. Introduction and Research Objectives

The term *Electric Vehicle* (EV) applies to all means of transportation where a proportion of propulsion is provided by electric motors. This research focuses on purely battery-electric vehicles (BEV). First generation hybrid electric vehicles (HEV) such as the Toyota Prius and the Honda Insight were largely conventional vehicles. For example the Prius only had a 1.3kWh nickel metal hydride battery [1], and was able to drive on the battery for only 90 seconds/1.5km. More recent plug-in HEVs have come to the market with larger batteries (but are still small compared to BEVs), such as the 2012 Toyota Prius Plug-in Hybrid at 4.4kWh for 18km in mixed electric/petrol mode [2], or the Chevrolet Volt at 16kWh for 56km pure electric drive [3]. Several manufacturers are now releasing fully-electric BEV vehicles as a fossil fuel emission-free means of transport. However, vehicle testing consistently suggests that standard tests do not give an accurate measure of actual vehicle fuel consumption or emissions when used on the road [4, 5]. While standardised tests have been designed to be comparable and repeatable to enable consumers to make informed decisions based on the rated economy and emissions, the standards may leave BEV drivers particularly vulnerable to differences between published vehicle efficiencies and performances to standards and actual driving conditions. For example, Mitsubishi's published range for the iMiEV BEV is 160km [6], based on dynamometer testing to standards – yet this is not realistically achievable on the road. When BEVs have battery technologies that engender a smaller range in comparison to conventional ICE vehicles, it is more important that BEV testing produces an accurate measure of performance and range for a consumer. Unless this is addressed, the emergence of the nascent BEV industry may be severely compromised by an overstatement of range and performance - adding to existing scepticism about their performance and practicality [7]. Compounding the issue are a large number of vehicle testing standards in use in different countries and regions, creating some confusion for the numerous published values for performance and range the same vehicle in different jurisdictions [8, 9]. The primary objectives of this study were to document the influence of driving factors, such as peak/off-peak city driving and the usage of accessories such as air-conditioning (AC), heater, etc., and additional passengers on the energy consumption of a BEV, as well as to investigate the relationship between standard testing methods and real-world driving.

1.1 Vehicle Testing Standards

All standard tests consist of following a predefined speed profile (drive cycle) on an indoor calibrated chassis dynamometer in a climate controlled and traffic-free environment where the vehicle sits on the rollers of a dynamometer which spins a mass to simulate the acceleration forces experienced on the road [10]. An additional braking system is used on this mass to simulate the rolling and wind resistances. Drive cycle testing was developed in the late 1960s for uniform emission testing of ICE passenger vehicles [11, 12]. There are several co-existing national standards for chassis dynamometer drive cycle testing for ICE vehicles from different countries, all exhibiting somewhat different drive cycle profiles. For example, the New European Driving Cycle (NEDC), introduced in 2000 [13], contains the European Union Urban Driving Cycle (UDC or ECE-15), which is applied for 'Euro 3' standards. In contrast, the US Federal city driving pattern for vehicle testing (also known as the Federal Test Procedure 75, or FTP 75) exhibits a more 'aggressive' urban/city drive cycle than the ECE, more likely to represent a more 'real world' driving scenario. Fig. 1 shows the artificial nature of the speed profile from the NEDC which is comprised of drive cycles that were meant to represent low speed city driving followed by motorway driving. From these measurements a city, highway and combined fuel consumption figure are generated. The NEDC test procedure is identical to the Australian Design Rules (ADR) 81/02 used for the labelling of all new cars sold in Australia, with EV economy values displayed in kWh/km [10]. However, the NEDC test procedure developed with European driving data may not be appropriate or accurately reflect Australian driving conditions. As with other standards, the ADR 81/02 was developed for ICE vehicles and was adapted for BEVs [14]. The adaptation means the BEV range is calculated by dividing the stated capacity of the battery by the energy consumption value determined in the speed profile test [10]. This is likely to underestimate actual BEV energy consumption due to the combination of unrealistic energy consumption from the drive cycle tests and an oversimplification of a consistent battery capacity over time when it is known that Li-ion cells lose capacity with time and use [15-18]. In recognition of the increasingly large differences between the NEDC cycles and real world values, the EU is planning to introduce the new Worldwide Harmonized Light Vehicles Test Procedure (WLTP) in 2017 [19]. However, even if Australia remains with the ADR 81/02 procedures derived from the NEDC or the new WLTP, this article describes the many limitations of all existing approaches that do not cater specifically for BEVs.

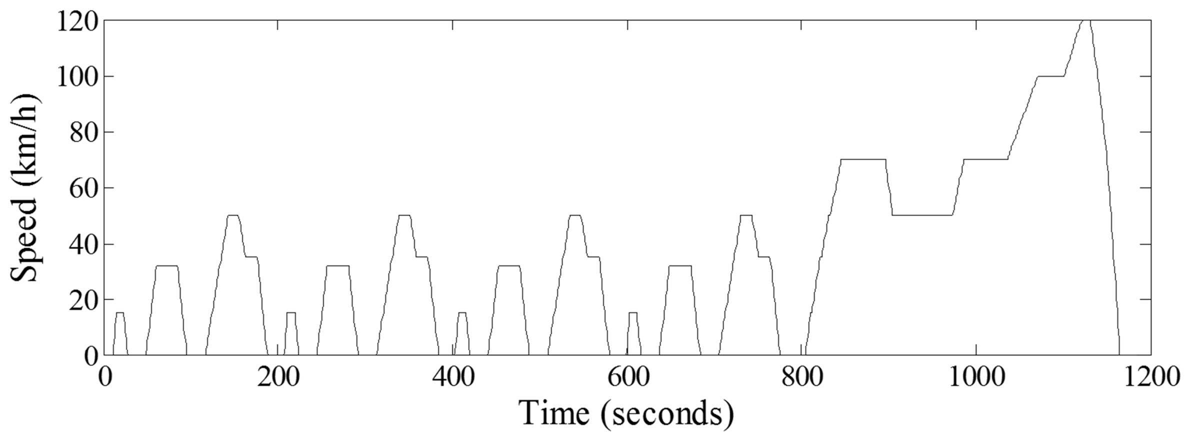

Fig. 1. *New European Drive Cycle speed profile* [20]

1.2 Actual Vehicle Performance Vagaries on the Road

Road testing of BEVs is notoriously challenging to determine actual performance and efficiency due to a range of environmental (wind, rain, temperature, topography, geography) and driver influences (style, time of use, number of passengers, accessory use, etc.) [21-27]. Additionally, when batteries in BEVs provide both propulsion and auxiliary power (operating brake booster vacuum pumps, power steering, navigation, computers, stereos, and in particular A/C and heating systems) this may contribute to considerable additional energy consumption and a corresponding reduction in driving range [21, 23, 24, 26-33]. As thermal comfort is a subjective individual concept dependent on external and internal vehicular environmental conditions on the whole body and individual body parts, and metabolic heat fluctuations [34], it is challenging to include into testing in a detailed manner. Vehicular comfort modelling procedures include the use of thermal manikins, surface sensors simulating human bodies in seats, physiological and psychological comfort models, [35, 36], and many are based on a variety of parameters (hypothalamus temperature, mean skin temperature, mean radiant temperature, air velocity, humidity ratio, etc.) to determine the degree of general comfort [37, 38]. Similar research has been done for passenger comfort in aircraft [39]

The use of AC has a significant effect on energy consumption of a vehicle [34]. This is recognised by the US FTP-75 testing procedure with specific tests to determine changes fuel consumption. However, this is lacking in the ADR 81/02 and the NEDC testing schemes. In conventional vehicles the AC compressor is powered from the engine, and a clutch mechanism engages the compressor when necessary. In BEVs the AC usually comprises of a separate small electric motor and fans to drive the AC system that are battery-powered. Heating systems in conventional vehicles do not have a noticeable effect on energy consumption as ICEs produce large quantities of heat and are cooled using water and radiator systems which is directed to a heater core through which air is passed. The only additional energy consumption arises from the electric fan used to generate airflow in the cabin. In contrast BEVs must contain electric heating elements which can represent a substantial electrical load in colder climates that may significantly impact efficiency and range. Lights and other electrical accessories (such as stereo sound systems, and mobile devices) will also influence energy consumption, although these loads are relatively small. While modern EVs with regenerative braking systems (RBS) exhibit additional energy efficiency and range, this analysis focussed only on quantifying additional accessory consumption when driving in urban areas in off-peak traffic conditions, with peak traffic conditions included as a comparison.

2. Methods

The vehicle tested was the ‘REV Eco’, a BEV conversion of a 2008 model Hyundai Getz small passenger vehicle (Fig. 2). The BEV features a 28 kW DC electric motor without energy recuperation and 13 kWh of Li-ion-phosphate batteries with an approximate 80km driving range. All original accessories were operational including AC, fans, stereo, lights, and power steering, although the heat for the BEV was generated using an electric positive temperature coefficient element. Also, as the BEV drive motor does not move when the vehicle is stationary, a separate electric motor was installed to drive the compressor, and a contactor used to switch the DC motor on. Multiple devices were used during testing, including headlights and stereo. All drive tests were conducted at an average outside ambient temperature of 20 degrees Celsius. BEV energy consumption readings (in Ah) were taken using a wired-in TBS electronics E-Xpert pro high-precision battery monitor [41]. This system measures voltage as well as current via a shunt resistor and is therefore capable of recording energy flows in both directions. The monitor has an accuracy of +/- 0.4% for current and voltage measurements with a refresh rate of 1Hz. Tests recorded Ah readings and calculated kWh values using the nominal voltage of the battery pack. In addition, a conventional ICE (petrol) Getz of the same model was tested under the same conditions to compare the test against the BEV conversion and also to the published figures for fuel consumption from the ADR 81/02 testing procedure.

The parameters varied for road testing were:

a. Peak traffic vs. off-peak traffic
b. Driver only vs. driver with two passengers (150kg total)
c. Electric air-conditioning on/off
d. Electric heater on/off
e. Headlights and stereo on/off

These variations were captured in road tests measuring the energy consumption of the BEV driving under the following conditions:

1. Off-peak traffic, driver only, no accessories running ;
2. Off-peak traffic, driver only, with electric AC running (only);
3. Off-peak traffic, driver only, with electric heater running (only)
4. Off-peak traffic, driver only, with headlights and stereo running (only),
5. Off-peak traffic, driver with two passengers, no accessories running,
6. Peak traffic, driver only, no accessories running.

All trials have been conducted at roughly the same temperature of about 20°C. Fig. 3 shows the route selected to represent city driving which features traffic lights, hills, and variable traffic. The particular route was chosen as a good representation of a daily commuter drive in most cities, including mostly arterial roads with traffic lights as well as some smaller suburban roads. The route leaves a suburb before entering an arterial road between Perth and Fremantle at maximum speeds between 50 and 60 km/h. The round trip distance is around 27 km with start/stop at The University of Western Australia. Since there will be some variations when driving the same path even at identical weather and traffic conditions, the driving experiment for each setting has been repeated five times. This will give us consumption and range measurement which will be much more relevant to the typical driver's use than artificial drive cycle data from a dynamometer.

Only a single fixed power setting was implemented and tested for both heating and AC, so they can be considered as on/off accessories. The weight of the two adult passengers was 75kg, each. Charging efficiency of the BEV was determined by measuring both the energy use recorded at the mains general power outlet at the metre, and the on-board battery charger. This was achieved using a residential electricity meter to give energy readings in kWh. The battery was charged over several hours with voltage and current values recorded every five minutes and the instantaneous power was calculated. The ratio between this value and the reading from the power meter gives the efficiency value. Five trials were completed to find the average energy consumption for each trial. BEV position and speed was logged using a USB GPS mouse connected to a laptop, as well as an on-board vehicle information system 'EyeBot' recording at 10Hz sampling frequency [42]. The GPS data recorded BEV position and speed to verify the influence of peak and off-peak traffic conditions. Peak traffic conditions results in higher fuel consumption in ICE vehicles, with fuel consumption the highest when traffic is transitioning between free-flowing and congested [31]. All trials were completed on non-holiday weekdays during school periods at off-peak traffic periods, and one trial at peak conditions for comparison. The peak traffic conditions were from 7am to 10am and also from 3pm to 6pm, and the off-peak period was 10am to 3pm.

Fig. 2. *The 'REV Eco', a BEV conversion of Hyundai Getz completed at the University of Western Australia*

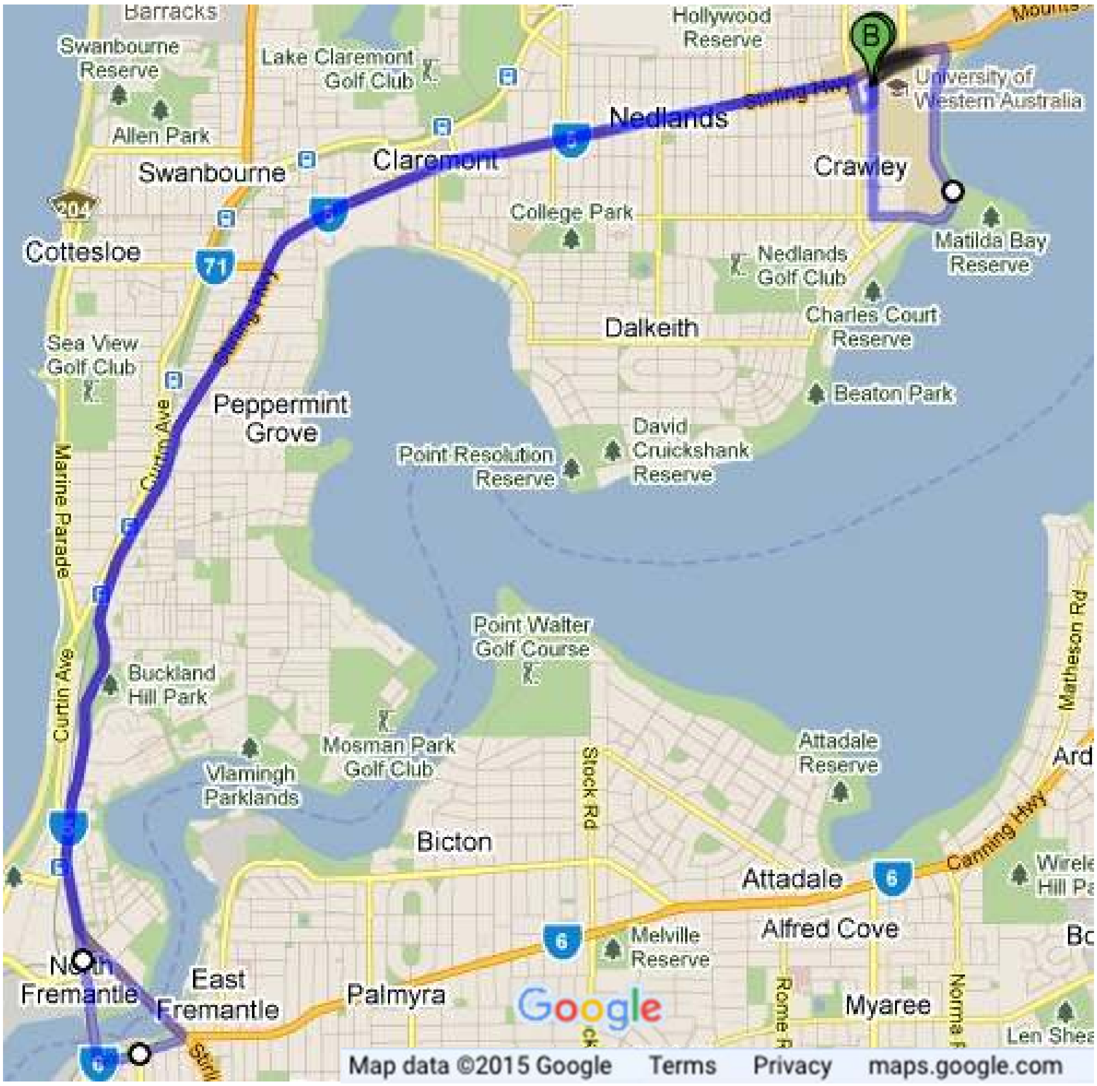

Fig. 3. *Test route of 26.6km round trip (using Google Maps)*

3. Results

3.1. BEV Performance on Road

Fig. 4 shows the average energy consumption recorded for each test condition over five trials. Fig. 5 shows the average speed for the five trials for each test condition. As the trials for accessory usage were completed during off-peak times, the average speed values are similar for those conditions. Energy consumption tests found the difference between peak and off-peak traffic decreased energy consumption and increased average speed by 14.8% and 25.5%, respectively. This indicates that acceleration events have a large impact on energy consumption (particularly without the inclusion of a RBS). The use of accessories had a large impact on energy consumption. The AC and heating used a large amount of energy, increasing energy consumption over the baseline of 29.6% and 32.6% respectively. Note that the effects of both AC and heater can be significantly higher in very hot or very cold conditions. Two additional passengers increased power consumption by 21.3%. Combined driving lights and stereo usage caused a relatively small 5.2% increase over the baseline. For comparison a conventional ICE (petrol, automatic) Getz was test driven during off-peak urban conditions for a total distance of 79.1km (three loops of the BEV test route). The conventional Getz consumed 5.37L of petrol, resulting in a fuel consumption figure of 6.79 L/100km (as calculated in Equation 1). Table 1 shows the published fuel consumption values from standard testing according to ADR 81/02 procedures. The authors note the difference between the ADR 81/02 drive cycle and the urban driving test is likely to be the primary factor in the lower fuel consumption for the drive test relative to the urban drive cycle used for ADR 81/02.

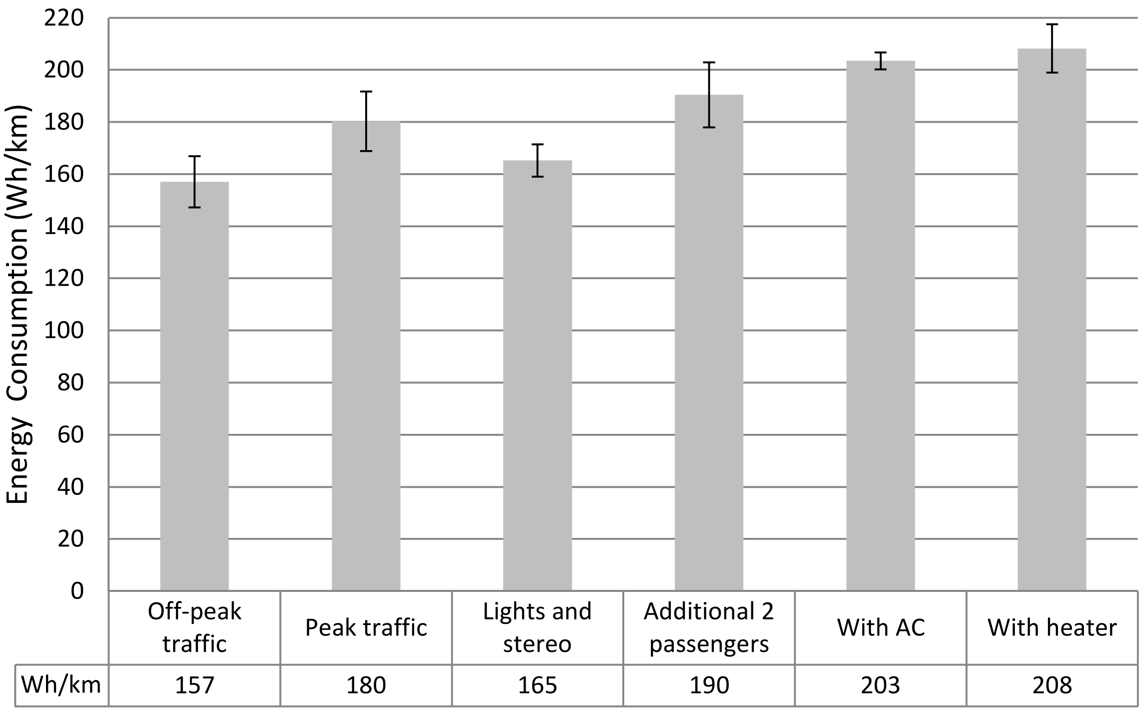

Fig. 4. *REV Getz average energy consumption with standard deviation error bars*

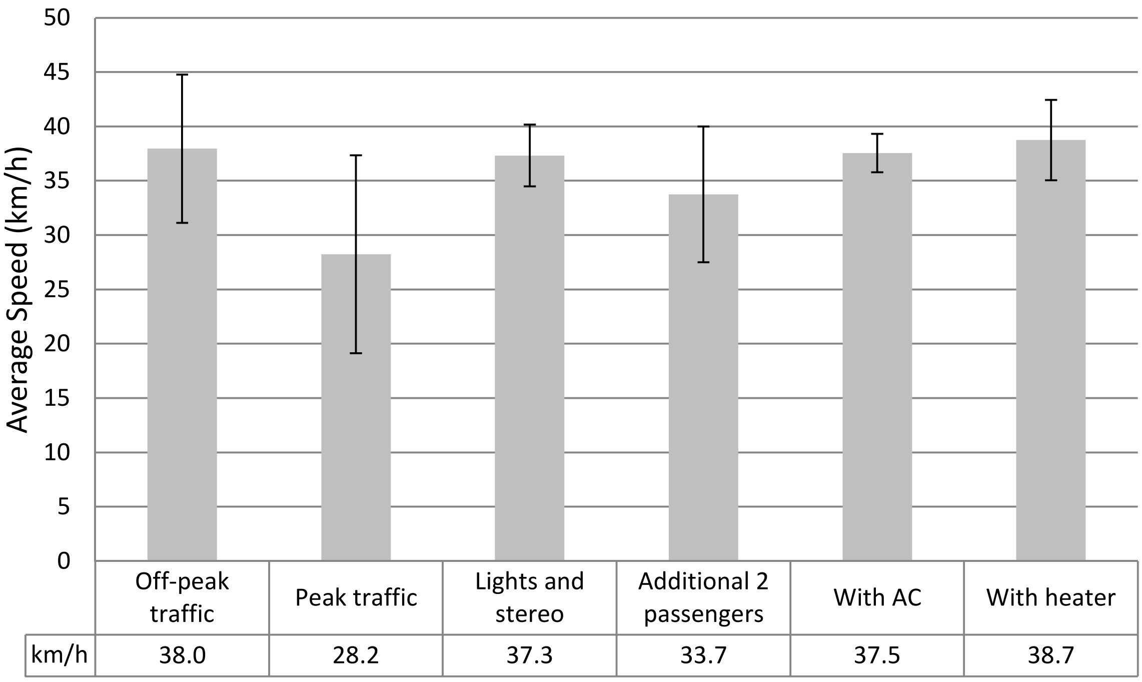

Fig. 5. *REV Getz average speed with standard deviation error bars*

$$\text{Fuel Consumption} = \frac{\text{Fuel Used}}{\text{Distance Traveled}} \times 100 = \frac{5.37\text{L}}{79.1\text{km}} \times 100 \approx 6.79\ \text{L/100km} \quad (1)$$

Table 1 Automatic ICE Getz ADR 81/02 fuel consumption test.

Vehicle\Test Cycle	Urban	Extra Urban	Combined
Hyundai Getz	9.5 L/100km	5.4 L/100km	6.9 L/100km

3.2. Charging

Charging efficiency tests determined losses in the charging system. The REV Eco BEV was driven until the TBS battery monitor charge reading was 30.0%, and then the vehicle was charged to 99.1%. Fig. 6 shows charging the battery versus time with battery current, voltage, and energy supplied recorded at 5-minute intervals, with power being the product of the voltage and current as per Equation 2. Fig. 7 shows the cumulative energy supplied to the charging system over time. The charging efficiency was determined by integrating numerically the values in Fig. 6 using the trapezoidal rule described in Equation 3, and was calculated using Equation 4 from the energy readings.

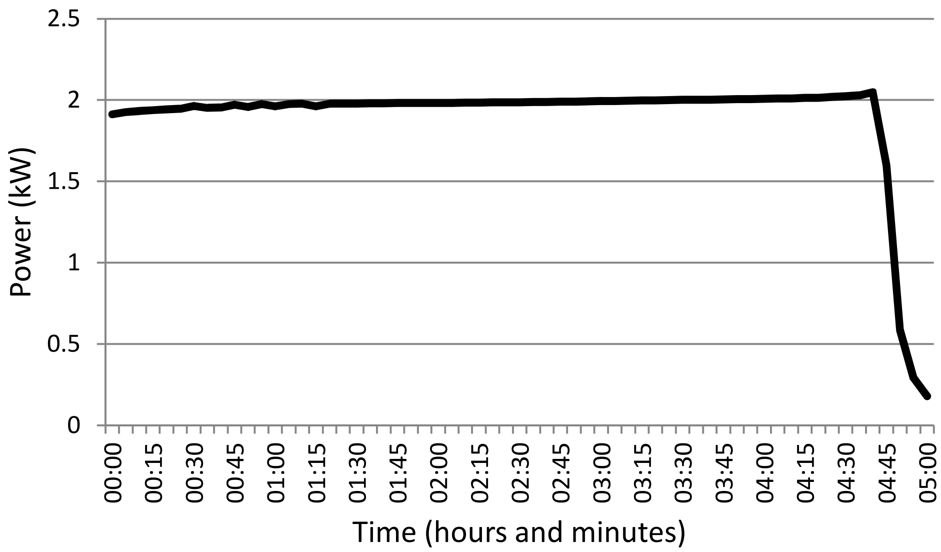

Fig. 6. *REV Getz power supplied to the battery versus time*

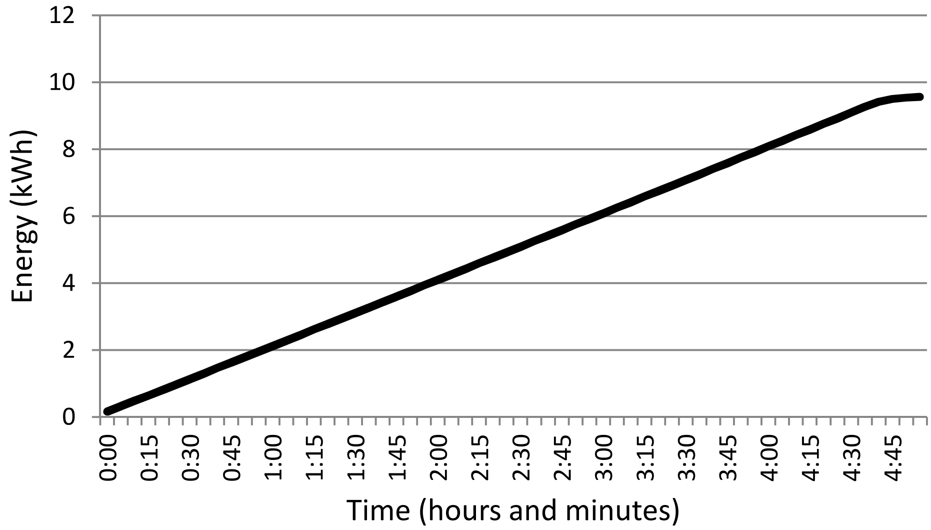

Fig. 7. *REV Getz accumulated energy supplied to the charging system*

$$P = I \times V \tag{2}$$

$$\int_{i}^{i+1} f(t)dt \approx \big((i+1) - i\big)\frac{f(i)+f(i+1)}{2} \tag{3}$$

$$\text{Efficiency} = \frac{\text{Useful power ouput}}{\text{Total power input}} = \frac{9.55\ \text{kWh}}{10.95\ \text{kWh}} = \eta \approx 0.87 \tag{4}$$

4. Analysis and Discussion

4.1. BEV Performance on Road

Road tests demonstrated that accessory usage has a significant impact on energy consumption, which is particularly evident with climate control. The road tests showed the AC increased the BEV energy consumption by around 30% (Fig. 8). Similarly the heating system increased energy consumption by 33%. These findings are also supported by tests conducted on air-conditioning systems in ICE vehicles in [43, 44]. For most countries with warm or moderate climate and winter temperatures above about –10°C, heating of ICE vehicles does not require additional energy, as the excess heat from relatively inefficient fuel combustion heats the cabin. No standard test procedures consider the impact of heating systems in vehicle testing, and in colder climates/regions/periods, this may greatly overstate a BEVs efficiency and range. In BEVs with a Li-ion battery, real world testing has demonstrated the high sensitivity to traffic, device use, driver preferences, and weather conditions with higher ambient temperatures increasing the rate of capacity loss over time, although lower ambient temperatures reduce the effective capacity at the time of use [45, 46, 47]. The effective capacity is also reduced by higher current draws, and the effect of cooler ambient temperatures and higher BEV current draws from heater use can compound to reduce the vehicle range under these conditions. The combined load from the driving lights and stereo was about 200W, resulting in a 5% increase in energy used by the BEV. For conventional ICE vehicles Kassakian et al. [40] calculated a 200W electrical load can lead to a 0.4 L/100km increase in fuel consumption. Therefore, vehicle designers need to be vigilant of the significant impact that all electrical loads have on range for all vehicles, and testing standards should enable consumers to be able to discriminate between these undisclosed energy consuming accessories. Finally, loading the vehicle with two additional passengers (at 150kg total weight) increased the power consumption by 21%. This is a significant increase in energy consumption for an individual vehicle. The effect of additional mass also demonstrates the potential overall energy savings that can be achieved by reducing vehicle mass, e.g. through the use of new materials such as carbon fiber.

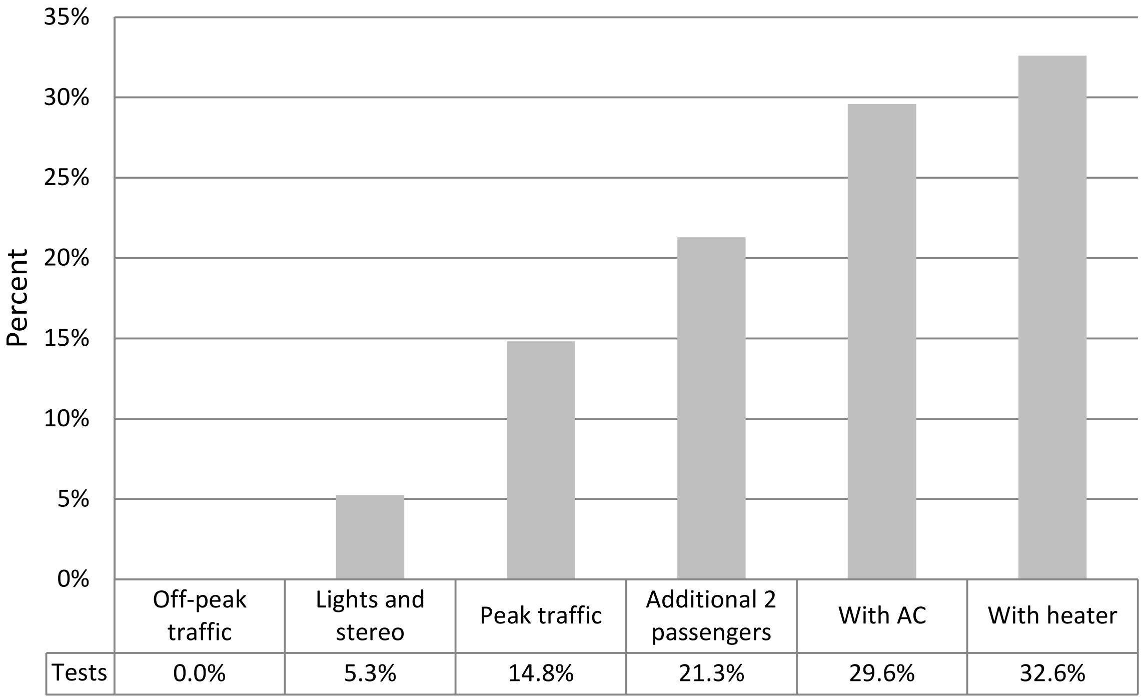

Fig. 8. *REV Eco BEV driving test energy consumption comparison.*

4.2. Charging

The charging efficiency results for the BEV of 87% validated the figures released by the battery charger manufacturer of greater than 85% [48]. The consistently high charging efficiency measured at each five minute interval shows that only around 13% of the energy at the residential mains general power is consumed by charging the BEV. In addition to BEV driving performance and efficiency comparisons, the conversion losses from the home electricity outlet to batteries is an important element of BEV efficiency to be disclosed to consumers.

4.3. *Implications and Recommendations*

The majority of the standard testing procedures do not take into account accessory usage, despite modern cars including increasing amounts of electrical equipment. The lowest energy usage was recorded on the city route during off-peak times, which was used as the baseline to which other test cases were compared. The road test completed with the conventional ICE Getz recorded fuel consumption comparable to the ADR 81/02 combined figure, although in reality the results are heavily dependent on traffic conditions at the time. It must be questioned whether the ADR 81/02 urban test profile typifies urban Australian driving. The development of the much more realistic WLTP is a clear indication that the NEDC testing does not approximate actual driving in the EU, and real [19, 49, 50]. The drive test route used in this research had fewer periods of acceleration, higher levels of acceleration, longer periods of constant speed and a higher average speed than the NEDC/ADR profile, and could be argued to be closer to the drive cycle used in the WLTP. While standard test procedures do enable repeatable and comparable testing, the results of existing procedures fail to describe actual driving energy consumption adequately to empower consumers to make informed decisions between conventional vehicles and BEVs.

5. Conclusion

Our real-world testing has demonstrated the drastic differences in energy consumption from different operational conditions, particular those in relation to vehicle accessories and passenger loading. Vehicle accessories significantly impact energy efficiency and range, and this is neglected by vehicle standard testing, particularly in the case for BEVs. Specifically, no standard test procedures consider the impact of heating systems, and in colder locations this may greatly overstate a BEVs efficiency and range. This may result in the publication of overstated vehicle performance and range under non-test conditions when accessories are in use. This research recommends that standards should enable consumers to be able to discriminate between these undisclosed energy consuming accessories and impact of additional passengers. Furthermore, standards adapted to test BEVs where range is calculated by simply dividing the stated capacity of the battery (even when Li-ion cells lose capacity with time and use) by the energy consumption values achieved in the drive cycle tests will likely overestimate BEV performance. Finally, this research demonstrated that ‘real world’ driving tests in a given location and time (including traffic conditions) can vary significantly from the drive cycles that the vehicle is tested against, and provides additional impetus to the further evolution of vehicle testing standards underway. The inclusion of drive cycles that approximate off-peak and peak urban driving, in addition to peak and off-peak extra urban driving is also recommended where practical. While these limitations of present standards may not be a major issue for vehicles with an on-board ICE, modern BEVs with relatively small batteries may compromise market trust and acceptability of the nascent technology if consumers are unaware of the sensitivity of the BEV to various operating conditions, and also of the limitations of the adaptations of conventional testing procedures for BEVs.

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