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Driving Electric Vehicles at Highway Speeds

The effect of higher driving speeds on energy consumption and driving range for electric vehicles in Australia

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Guido Wager [a]*, Jonathan Whale [b], Thomas Braunl [a]

[a]The University of Western Australia, School of Electrical Electronic and Computer Engineering

Address:
School of Electrical, Electronic and Computer Engineering
The University of Western Australia (M018)
35 Stirling Highway
CRAWLEY Western Australia 6009
Australia

Phone: +61 8 6488 1763
Thomas.Braunl@uwa.edu.au, guido.wager@uwa.edu.au

[b]Murdoch University, School of Engineering and Information Technology, Department of Electrical Engineering, Energy & Physics,

Address:
School of Engineering and Information Technology
Murdoch University
90 South Street
MURDOCH, Western Australia 6150
Australia

J.Whale@murdoch.edu.au

*Corresponding Author

Wager, Guido

E-Mail: guido.wager@uwa.edu.au

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Abstract

Electric vehicles (EVs) have the potential to operate emission free and thus overcome many environmental and health issues associated with cars run on fossil fuels. Recharging time and driving range are amongst the biggest hurdles for the mainstream acceptance and implementation of EV technology. Fast-DC charging significantly reduces the recharging time and can be used to make longer EV trips possible, e.g. on highways between cities. Although some EV and hybrid car studies have been conducted that address separately issues such as limited drivable ranges, charge stations, impact from auxiliary loads on vehicle energy consumption and emissions, there is currently limited research on the impact on drivable range from the combination of driving EVs at highway speeds, using auxiliary loads such as heating or air conditioning (AC), and reduced charge capacity from fast-DC charging and discharge safety margins. In this study we investigate these parameters and their impact on energy consumption and drivable range of EVs. Our results show a significantly reduced range under conditions relevant for highway driving and significant deviation from driving ranges published by EV manufacturers. The results and outcomes of this project are critical for the efficient design and implementation of so-called ‘Electric Highways’. To prevent stranded cars and a possible negative perception of EVs, drivers and charging infrastructure planners need be aware of how EV energy and recharging demands can significantly change under different loads and driving patterns.

Nomenclature

N	Number of samplings (for a sample rate of 1 second) [-]
m	Vehicle mass [kg]
C_{RR}	Tyre rolling resistance coefficient (depends on the specific tyres used) [-]
C_D	Drag coefficient (depends on the vehicle's shape) [-]
AF	Projected frontal area of the vehicle [m^2]
V_i	Vehicle velocity at the current y time increment [m/s]
V_{i-1}	Vehicle velocity at the previous time increment [m/s]
r	Rotational inertia compensation factor [-]
ρ	Density of air [kg/m^3]
g	Physical constant for the gravitational force [m/s^2]

1 Introduction

Although EV sales are increasing globally, even in a large market like the U.S., EVs still make up less than one percent of all new vehicles sold [1]. To date, limited driving range, limited charging infrastructure and long recharging times have hindered EV technology's attempt to become a large-scale feasible alternative to motor vehicles run on fossil fuels. One promising innovation is the relatively new fast-DC charging technology, which reduces recharge time significantly. An EV traction battery can be fast-DC recharged to 80% of its capacity in around 20 minutes and makes long distance travelling with relatively short recharge stops feasible [2]. Innovative entrepreneurs are currently implementing fast-DC charging stations along highways interconnecting major cities [2]. An 'electric highway' is planned for the south west region of rural Western Australia, joining the city of Perth to some of the country towns popular with locals and tourists alike [3, 4].

Apart from recharge time, range is a major factor affecting peoples' willingness to adopt EV technology. The drivable range of an EV is determined by the type of car and the capacity of the batteries as well as the vehicles' efficient design and use. Many factors such as charge level, efficient battery capacity utilisation, driving style, vehicle mass, cross-sectional frontal area, drag coefficient, auxiliary loads, driving pattern, vehicle speed and tyre rolling resistance have the potential to decrease EVs' efficiency. All these factors can be influenced by the EV driver and have a significant impact on energy consumption and hence drivable range.

Manufacturers measure their EVs' energy consumption and range based on data collected during chassis dynamometer testing using a standardised driving pattern such as, for example, the New European Driving Cycle (NEDC). Testing under ideal conditions, with minimum auxiliary loads, and with the aid of the vehicle's regenerative braking system (RBS), EV manufacturers achieve low energy consumption values and long drivable ranges. This idealised testing is very different from the scenario where a vehicle is driven over a long distance at high speeds, such as driving a vehicle between cities across remote areas. The difference between lab conditions and real world conditions impacts much more on the energy consumption and drivable range for EVs than for cars with combustion engines. This is because even small changes in parameters such as the vehicle's weight, auxiliary load (AC and heating) or speed have a large impact on the drivable range on EVs, but not so much in combustion engine cars due to their much bigger and denser energy storage device, the fuel tank.

Thus, using the energy consumption measured under lab conditions is likely to overestimate the drivable range for EVs. Although modern EVs have factory-installed RBS, when driving at steady speed, such as on a highway, the recovered energy from slowing down is minimal compared to a city driving stop-and-go scenario. Therefore, in the absence of an RBS by driving at a steady speed and using large auxiliary loads such as an AC and a heater, the vehicle's energy consumption will be much higher than stated by the manufacturer.

Energy consumption will further increase under continuous high speeds, and with the increased mass and increased cross-frontal area that a roof rack adds to a vehicle. As a consequence the vehicle's range reduces significantly and a further reduction in drivable range can be expected since not all the nominal stored energy from a battery can be accessed and used. To avoid deep discharge and potential permanent damage to battery cells, some energy needs to remain in the battery. For battery protection, factory EVs (e.g. the Nissan Leaf and Mitsubishi i-MiEV) contain a battery control system that monitors the battery charge status and at a critical low battery level switches the vehicles to a 'limp-home mode'. In this mode, the control system reduces the vehicle’s maximum speed significantly to just allow the car to be driven off the road to a safe location before the car comes to a complete stop [5, 6]. In addition, similar to driving a combustion engine car to the next fuel station not all fuel or energy can be used. To prevent being stranded, an extra safety margin in the battery charge needs to be included in the planning of a trip and cannot be used.

The combination of a limited fast-DC charge level of 80% capacity, increased energy consumption at highway speeds, large auxiliary loads such as air conditioning and a battery discharge safety margin would be expected to reduce the vehicle’s drivable range. To address such issues and improve EVs usability and drivability on highways, several studies have been conducted on drive system optimization, charger selection algorithms, the impact from environmental and auxiliary loads on batteries, energy consumption and drivable range [7-11]. Whilst several studies on pure EV energy consumption feature range tests and simulations conducted under laboratory conditions e.g. [12], with new and fully charged batteries [13-20] and for urban driving with a short highway section [21-24], at the time of this study there is little information available on realistic EV use, energy consumption and vehicle range for travel on an electric highway between cities. In particular, there is a gap in the literature on the interaction of the combination of a limited fast-DC charge level of 80% capacity, increased energy consumption at highway speeds, increased loads due to headwinds, increased aerodynamic drag due to roof racks, additional vehicle weight, the absence of energy recovery and a battery discharge safety margin.

The aim of this study is to investigate the drivable range losses of commercial EVs due to the combination of reduced charge levels from fast-DC charging, increased energy consumption from driving at continuous real-road highway speeds and the limited access to the nominal stored energy in the traction battery. Results are compared with estimations of range by EV manufacturers.

2 Methods and Materials

The test cars used in this study were a two year old Nissan Leaf (24,000 km travelled) and a one-year old Mitsubishi i-MiEV (5,100 km travelled), as shown in Figure 1. The Leaf accommodates a 24 kWh battery and the i-MiEV contains a 16 kWh battery. According to published data by Nissan, the Leaf has a range of up to 199 km [25] on full charge, while the Mitsubishi’s range is stated between 150 km [26] and 160 km [27]. Both cars have factory installed RBS systems.

Figure 1: The Mitsubishi i-MiEV and Nissan Leaf test cars used for the experiments

2.1 Road Tests

The vehicles were road tested to determine realistic on-road energy consumptions and to collect data for calculating a realistic drivable range for both vehicles. The driving experiments were conducted on a flat freeway section in Perth, Western Australia at speeds of 60km/h, 70km/h, 80km/h, 90km/h, 100km/h and 110km/h (legal speed limit in Western Australia). To minimise the impact on headwinds, the test drive was conducted in both directions, from north to south and vice versa and the energy consumption values recorded and averaged.

During driving, the onboard speedometer reading was compared to the measurement from a Suunto GPS device on regular intervals and the vehicle speed adjusted accordingly. For the test drives all auxiliary loads such as head lights, heaters and AC were switched off. To determine the available energy from the car's traction batteries the cars were recharged on a 50 kW 'Veefil' fast-DC charging station installed at The University of Western Australia (UWA) as part of the Renewable Energy Vehicle Project (REV). Note that the same type of fast-DC charging stations have been proposed for long distance highway driving, including the electric highway planned for Western Australia [2-4]. To measure the vehicle's energy consumption, the available energy in the batteries and other battery related data is available on the vehicles controller area network (CAN) bus and accessible via the vehicle onboard diagnostic connector (OBD2) as commonly implemented in modern cars [28, 29]. The data from the commercially available OBD2 scan tool was transmitted via a Bluetooth terminal to an android computer system. Since the energy consumption of individual auxiliary loads such as headlights, heater system, AC system and demisters are critical for the overall energy consumption these parameters were measured and logged separately on stationary vehicles.

The calibration and accuracy of all instrumentation used in the experiments was limited to the manufacturer standards of the EVs and the fast-DC charging station.

The drivable range was calculated based on the energy consumption and the available and accessible energy from the traction battery. Vehicle ranges were calculated based on the available energy from an 80% capacity fast-DC charged battery that discharges to a level that leaves a realistic safety margin for the driver to get to the next charging station. In energy terms this safety margin was assumed to be 2 kWh. An additional scenario was modeled in which the range was calculated based on the available energy from an 80% capacity fast-DC charged battery that discharges until the vehicle reduces its power in ‘limp-home mode'.

2.2 Vehicle Mathematical Modelling

The speed limit in Western Australia is 110km/h. To simulate higher speed limits or strong headwinds, or large auxiliary loads, the various components of traction power demand on the cars’ batteries were modelled mathematically and the energy consumption of the cars were calculated to estimate the drivable range at these high speeds and loads. Hayes et al. [30] conducted research on a simplified powertrain model for various new and existing production vehicles. The results showed a strong agreement with published energy consumptions [25, 27]. However, Hayes et al. calculated the range based on a new and fully charged battery with a state of charge (SoC) of 100% and no headwinds or other real-road driving factors influencing the energy consumptions. Furthermore, the battery in an EV will degrade over time resulting in a reduced charge capacity. Real world driving with a degraded battery and fast-DC charging up to just 80% would further negatively impact an EV’s range. In addition, some vehicle-specific parameters such as tyre rolling resistance vary between vehicles and influence energy consumption and range.

In this project the output of the model was compared with results from real-road driving on the two specific vehicles and the parameters calibrated accordingly. The model thus permitted the very accurate estimation of increased energy demands by changes to parameters such as vehicle weight, cross-frontal area due to a roof rack, and strong headwinds.

The traction power demand was calculated using Equation 1 ([31])

$$P_{Tractive} = \sum_{i=1}^{i=N}\left[\mathrm{mgC}_{RR} + \frac{1}{2}\rho\, \mathrm{C_D A}_F \left(\frac{\mathrm{V}_i + \mathrm{V}_{i-1}}{2}\right)^2 + mr\left(\frac{\mathrm{V}_i - \mathrm{V}_{i-1}}{\mathrm{t_{inc}}}\right) + mg(\sin\theta)\right] * \left[\frac{\mathrm{V}_i + \mathrm{V}_{i-1}}{2}\right] \quad (1)$$

The first term in Equation 1 is the power required to maintain a given speed (i.e. the power to overcome rolling resistance) and is given by the gravitational force (g = 9.81 ms^{-2}), vehicle's mass and rolling resistance coefficient of the tires used (C_{RR}). This term will change for the different driving scenarios by altering the vehicle's mass, tyres or tyre pressure. The second term describes the power required to overcome the aerodynamic resistance, which is the drag force that acts on the vehicle as it moves through air. The aerodynamic resistance thus depends on the vehicle's shape and frontal area, captured by the variables C_D and A_F and the density of surrounding air (ρ =1.2 kgm^{-3}). This term increases with increasing vehicle speed as a result of increased friction between air and the vehicle surface. In addition, this term will also be affected by changes in the projected frontal area caused by the addition of a roof rack. The third and fourth terms in Equation 1 are related to the inertial resistance; the first of the inertial terms models power needed to overcome power lost in acceleration while the second inertial term models the power needed to overcome losses due to road gradients. Power lost in rotary power also needs to be considered and this has been taken into consideration by increasing the first inertial term by a compensation factor of 3%. This compensation factor is described as the rotational inertia compensation factor, r. Finally there are drive train losses including battery discharge losses, cabling, inverter, motor and gears. Overall drive train energy losses change with vehicle loads but also between different types of cars and manufacturers. Obtaining these values from manufacturers is difficult [30] and is out of the scope of this project. Therefore these parameters were adjusted (calibrated) until the model agreed with the energy requirements measured on the real-road energy consumption tests. The experiment assumes a flat surface and constant speeds. Hence there are no energy requirements from road gradients, no energy recovery from deceleration and therefore no interaction of RBS or inertia and rotary power compensation factor.

Table 1 shows vehicle specific parameters in Eq. 1 used for the calculations of traction power demand. A powertrain efficiency factor of 0.8 was assumed and multiplied by the calculated traction power demand.

Besides the traction power, the vehicle requires energy for system power such as computer control units, relays and displays. These demands were measured and added to the calculated traction power.

Table 1: vehicle specific parameters used for the calculations [25, 27, 32]

Model	***m***	C_{RR}	C_D	A_F
Leaf	1521kg	0.012-	0.29-	2.27m^2
i-MiEV	1085kg	0.012-	0.33-	2.14m^2

2.3 Modelling of Different Load Scenarios

For both cars the energy consumption and drivable range were modelled for three different driving scenarios. The scenarios were chosen to reflect conditions of overland driving in low-population density areas often encountered for drivers leaving cities for recreation.

1. Scenario 0 is identical to the real-road driving energy consumption test as discussed above. It included a single driver, no ascent or decent, one passenger (80kg) and no headwind. The auxiliary loads were limited to the system loads. There is assumed to be no battery charge safety margin.
2. Scenario 1 is identical to Scenario 0 but with a battery charge safety margin.
3. Scenario 2 included also a battery charge safety margin, no road ascent or decent, two passengers (160kg), baggage of 50kg and no headwind. The auxiliary loads included switching on an AC system with a time-based duty cycle of 50%.
4. Scenario 3 has the same conditions as Scenario 1 and 2 but with an assumed headwind of 20 km/h and the model accounted also for the cars to carry a small roof rack caring a surfboard or Skis (assumed cross sectional area of 0.25m^2). The resulting decline in aerodynamic efficiency from carrying the roof rack was ignored for this study.

Before calculating energy consumption and range for these three scenarios, the model was assessed using a new European drive cycle (NEDC) speed profile. The energy consumption and recovery calculated by the model was compared with EV manufacturers' NEDC energy consumption data. To validate the results from the model, the predicted energy consumptions were compared with data obtained from real-road driving and specific parameters calibrated accordingly.

3 Results and Discussion

The energy consumption for each vehicle was determined using a real-road test consisting of a freeway (highway) section without ascents or descents and driving speeds of 60, 70, 80, 90, 100 and 110km/h. Prior to real-road tests the vehicles were charged on a fast-DC charger to 80% charge capacity. The energy consumptions for auxiliary loads and the battery charge level corresponding to the vehicles switching to 'limp-home mode' were measured on stationary vehicles. To estimate the energy consumption and range under higher speeds and vehicle loads, the available energy in the battery was determined and the vehicles were modeled and their energy demands calculated. The aim was to observe the increased energy consumption under continuous real-road highway speeds and the impact on drivable range under the combination of reduction to 80% capacity due to fast-DC charging, increased energy consumption and the limited access to the nominal stored energy in the traction battery.

Fast-DC charging the Leaf from 'limp-home mode' (SoC 3%) to SoC 80% required 13,544 Wh whilst fast-DC charging the MiEV from 'limp-home mode' (SoC 3%) to SoC 80% required 12,261 Wh. This constitutes an effective capacity of only 56.4% for the Leaf and 76.6% for the i-MiEV. Fast-DC recharging, including a driver's safety margin of 2 kWh in order to not get stranded, reduces the average available charging energy for the Leaf to 11,544 Wh (48%) and of the i-MiEV to 10,261 Wh (64%). Just less than half of the Leaf's full battery weight is not used yet still contributes significantly to the vehicle's weight. To verify the low usable energy of the car's batteries, the Leaf and the i-MiEV were recharged, from the same SoC, eighteen and eight times, respectively. The significant difference between the nominal capacity and the rechargeable (and hence usable) energy is due to a combination of the 80% charge level limit of fast-DC charging, battery aging and battery safety margins.

Auxiliary loads influence the energy consumption of an EV and hence its drivable range. Table 2 shows the major auxiliary loads measured on a stationary i-MiEV and Leaf. On both cars the headlights and rear demister require a continuous supply of 200 W. The heater constitutes the largest auxiliary electrical load and draws 2300 W for the Leaf and 2000 W for the i-MiEV. The second largest auxiliary loads are the AC system with a demand of 1400 W and 1200 W for the Leaf and i-MiEV, respectively.

Table 2: Auxiliary loads measured on a stationary Nissan Leaf and i-MiEV

Type of load	**i-MiEV**	**Leaf**
	Watts (continuous)	Watts (continuous)
Headlights	200	200
Rear demister	200	200
Air conditioner	1200	1400
Heater	2000	2300

Heaters and air-conditioning systems operate on a duty cycle. Depending on the ambient temperature and solar radiation the duty cycles may vary significantly. For the following energy consumption and range estimation in this project an air conditioning time-based duty cycle of 50% was assumed.

3.1 Energy consumption and drivable range for real-road driving

Table 3 shows the measured energy consumptions for the Leaf and i-MiEV for real-road driving under Scenario 1 on a Perth freeway section.

Table 3: The measured energy consumptions at various speeds from Nissan Leaf and i-MiEV

Vehicle Speed (km/h)	***i-MiEV (Wh/km)***	***Leaf (Wh/km)***
60	98	128
70	110	133
80	112	152
90	134	163
100	151	181
110	181	220

Due to the speed limit the real-road testing was limited to 110km/h and thus the energy consumption for driving at speeds above 110 km/h, which occurs in other Australian States and countries, was modelled. The model is based on the underling physics that describes the movement of a vehicle along the road at a given speed (given by Eq 1). As outlined in section 2.2, the equation contains variables that are either specific to the vehicle (such as mass, rolling resistance, drag coefficient and cross frontal area) or depend on the environment under which the experimental data is collected (e.g. temperature and air pressure), making the model semi-empirical. Consequently, these variables need to be calibrated for a given application. This was achieved by using our experimental data from Table 1 and adjusting the model input parameters (such as mechanical and electrical drive train losses, roll resistance and density of air) such that the model output described by Eq. 1 agreed with the measured energy consumption. Thus the specific model used in this study is predictive only for the two vehicles used in this study. However, this model is easily transferable to other vehicles and can become predictive for any given vehicle and/or road condition simply by recalibrating the model.

The model was assessed by comparing the energy consumption for an NEDC driving test calculated by the model to the manufacturer's published data. Overall, the results of measured energy consumption and drivable range from the model showed good agreement with the published NEDC data. For the Nissan Leaf NEDC, the model predicted an energy consumption of 165 Wh/km, 10% greater than the published value of

150 Wh/km [25]. For the iMiEV, the model predicted an energy consumption of 125 Wh/km, which was exactly the same as the published value from the manufacturer. The modelling revealed that the final energy demand is very sensitive to the input parameters in Eq. 1 and the exact energy consumption of 150 Wh/km published by Nissan [25] can easily be reproduced by adjusting the values of these parameters. For example, using different tyre resistance values with a range given by tyre manufacturers (0.006 to 0.0013 [33]) results in final NEDC energy demands ranging from 121 Wh/km to 157 Wh/km for the Nissan Leaf. However the aim of the modelling was not to achieve the exact energy consumption published by a manufacturer but to calculate trends in energy consumption for driving at higher speeds, increased vehicle weight or larger auxiliary loads as expected for the conditions in the three different scenarios. Thus, rather than setting the parameters for tyre resistance and other parameters to values that reproduce the exact energy consumption published by Nissan or Mitsubishi, the parameters were calibrated using the data from real-road testing from the vehicle used in the experiment.

Figure 2 shows the measured energy consumptions obtained from the OBD2 scan tool (black markers) for the vehicle speeds listed in Table 3. and the calculated (dotted lines) energy consumption values after model calibration versus speed for the Leaf and i-MiEV. The mean unsigned error between the measured and calculated values over the six measured speeds of Figure 2 was 3.2% for the Leaf and 3.4% for the i-MiEV. This agreement is expected since the model was calibrated until a high level of agreement was achieved between the model output and the measured energy consumption. The value of the Figure is that it allows prediction of energy consumption for speeds above 110 km/h, the limit of the speeds in the road-testing. The same calibrated parameters were used to calculate the EVs theoretical drivable range under the different scenarios and situations.

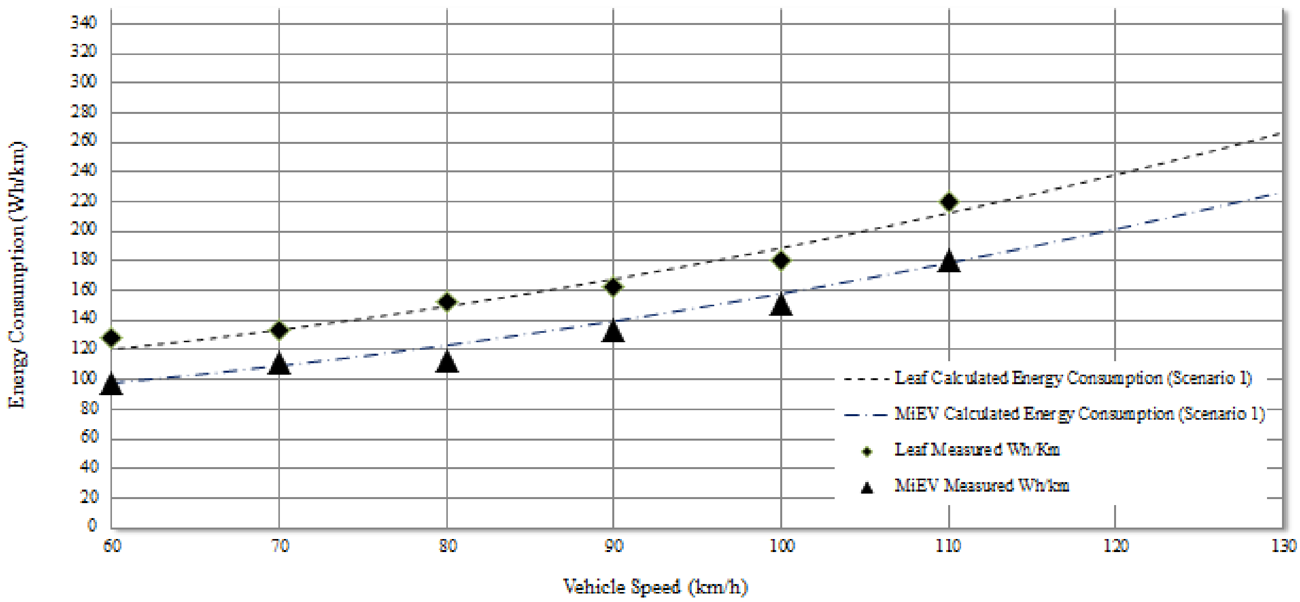


Figure 2: Measured and extrapolated energy consumption over a speed range of 60 to 130 km/h.

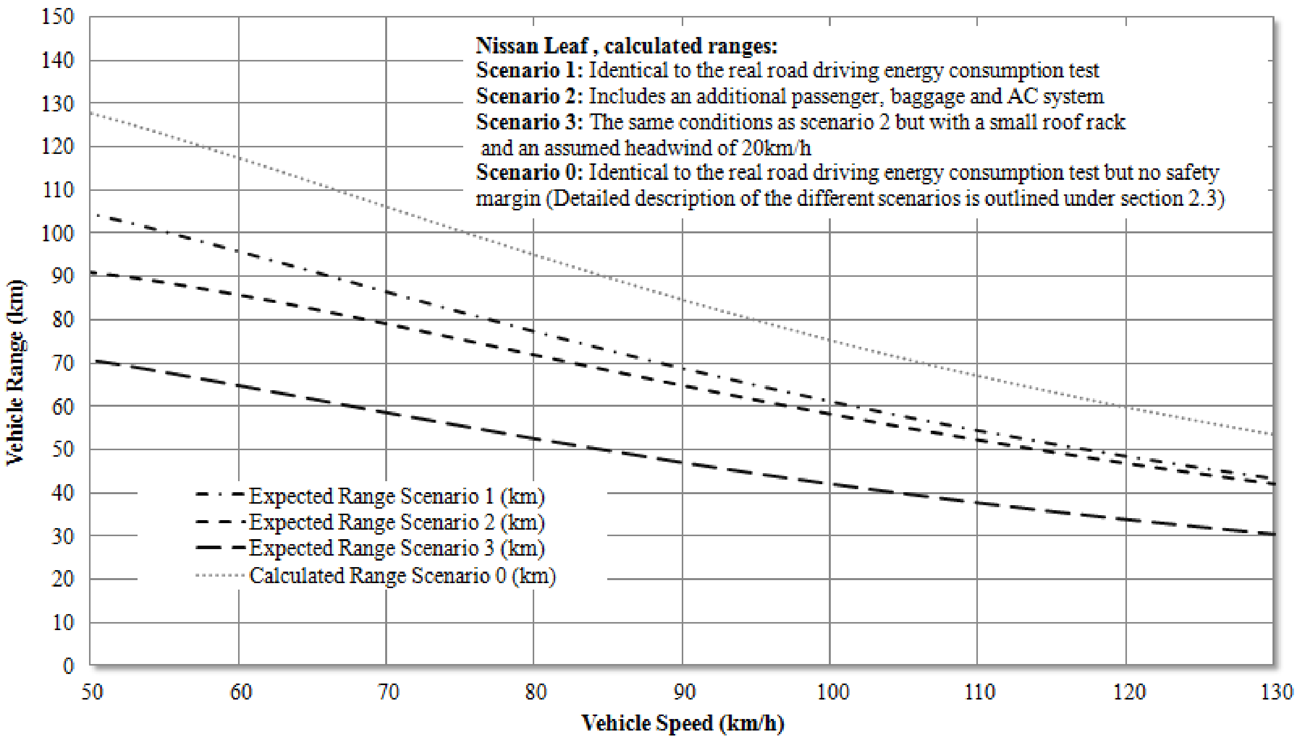
3.2. Energy consumptions and drivable ranges

Figure 3 shows the simulation for the Leaf (Fig. 3A) and i-MiEV (Fig. 3B) and the way in which drivable range reduces under higher speeds and loads. Scenario 1 shows calculated energy consumptions from the calibrated model and hence the output is identical to the real road energy consumption tests. Scenario 2 shows how the calculated range reduces by increasing the overall weight parameter in the model by assuming extra luggage and an extra passenger. The model suggests a much larger impact on reduced range by changing the model input by an assumed increased head wind speed of 20 km/h and an increased cross sectional area from a small roof rack carrying e.g. skis or a surfboard. Although the model parameter inputs for Scenario 0 (no safety margin) are the same as for Scenarios 1, the range for Scenario 0 is due to the extra theoretical available energy much larger than that for Scenarios 1, 2 and 3. Since under realistic road driving a vehicle cannot be fully discharged (no safety margin) the unrealistic range in Scenario 0 is difficult to achieve and therefore is not further discussed. Table 4 and Table 5 show the calculated range of the Leaf and i-MiEV under the three scenarios. Travelling at a speed of 110 km/h, the model suggests that the Leaf achieves a range of 54 km under Scenario 1, a range of 52 km under Scenario 2 and a range of only 38 km for Scenario 3. Reducing the speed to 80km/h would drive the Leaf 77 km, 72 km and 53 km for Scenario 1, 2 and 3, respectively. The drivable range under a speed of 50 km/h for the Leaf would be 104 km (Scenario 1), 91 km (Scenario 2) and 71 km (Scenario 3).

Table 5 shows the simulation of an i-MiEV, travelling at speeds of 110 km/h, 80 km/h and 50 km/h. The higher speed of 110 km/h would reduce the range to 57 km under Scenario 1, a range of 55 km in Scenario 2 and a range of only 40 km for Scenario 3. Simulating the range for 80 km/h the model suggests a range of 83 km, 76 km and 56 km for Scenarios 1, 2 and 3, respectively. Finally, the speed reduction to 50 km/h would drive the i-MiEV to 115km (Scenario 1), 96 km (Scenario 2) and 75km (Scenario 3).

Under all three scenarios, with increased vehicle speed, mass, increased cross-frontal area, extra auxiliary loads and headwind, the energy consumption consistently increases and hence the range significantly reduces. Based on the model and calculations it can be assumed that with further increase of loads, in particular speed and headwind the range will further reduce. This assumption is supported by the trend of declining range on the curves for Scenarios 1, 2, and 3 in Figures 3A and 3B.

A



B

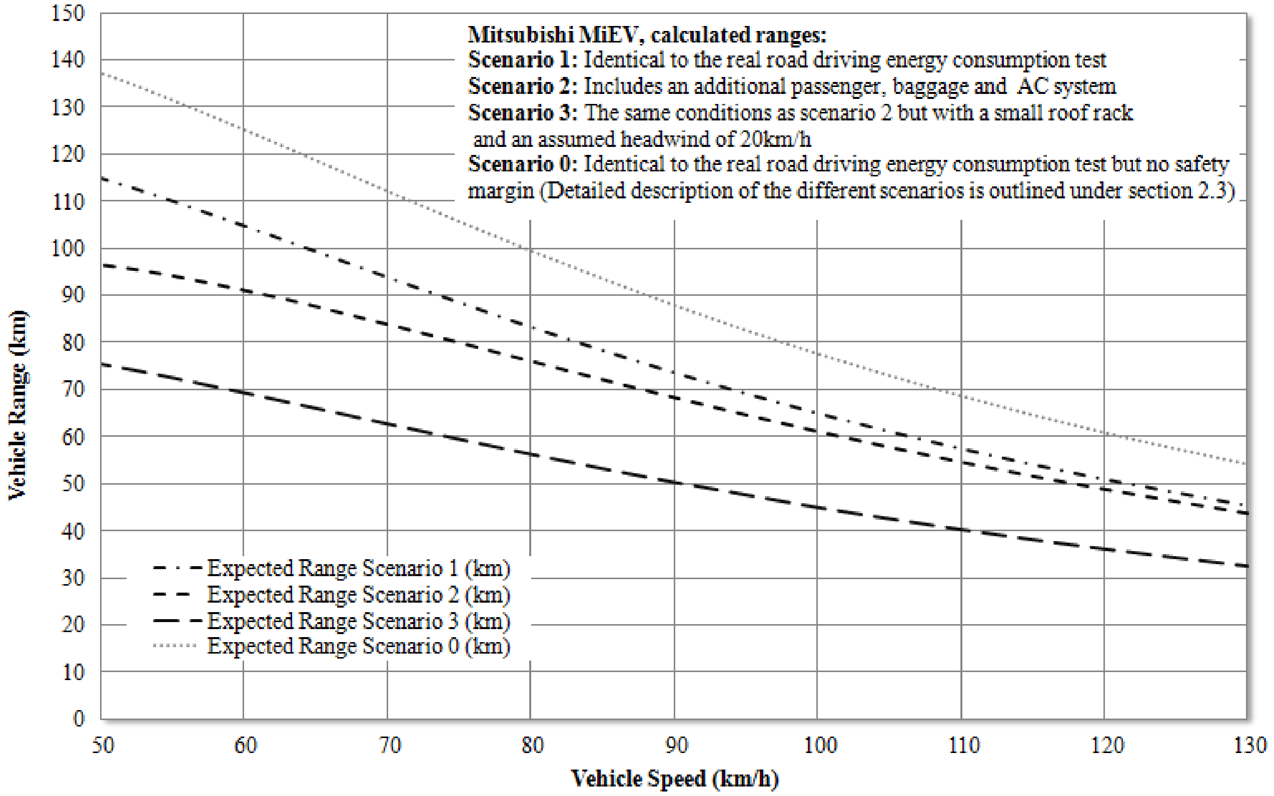


Figure 3: Leaf (A) and MiEV's (B) significant decline in drivable range due to an assumed battery discharge safety margin of 2 kWh, increased speed, mass and loads

Table 4: Leaf’s drivable range (km) under different loads and travelling speeds including a discharge safety margin

Speed (km/h)	*Scenario 0 (km)*	*Scenario 1 (km),*	*Scenario 2 (km),*	*Scenario 3 (km),*
50	128	104	91	71
80	95	77	72	53
110	67	54	52	38

Table 5: i-MiEV drivable range (km) under different loads and travelling speeds including a discharge safety margin

Speed (km/h)	*Scenario 0 (km)*	*Scenario 1 (km),*	*Scenario 2 (km),*	*Scenario 3 (km),*
50	137	115	96	75
80	100	83	76	56
110	69	57	55	40

4 Comparisons with EV Manufacturers’ Range Data

Nissan publishes a drivable range of up to 199 km [25] on an NEDC test driving cycle. Based on the published energy consumption data of 150 Wh/km it would be difficult to achieve this range on an NEDC driving pattern. Even assuming that all of the 24 kWh battery can be used the maximum drivable range would be 160km. In contrast, the predicted real road-range simulation in under Scenario 3 was just 38 km or only 19% of the published range. A similar much smaller range was observed on the i-MiEV with its 16 kWh battery. Mitsubishi states an energy consumption of 125 Wh/km and a range of 150 km [26]. To achieve such a range a battery with an accessible energy capacity of 20 kWh would be required.

It is worth emphasising that Scenario 3 is not a worst-case scenario. In some situations the safety margin would be required to be larger than just 2 kWh as assumed in the experiment. As a consequence the range would reduce further. Furthermore, there will be situations where there are speed limits higher than 110 km/h, headwinds stronger than 20 km/h, roof racks that reduce aerodynamic efficiency (C_d), changes in rolling resistance (C_{rr}), higher air conditioning or heating demand, climate impacts on traction batteries [34], battery conditioning issues, uphill driving slopes and vehicles loaded to their full capacity. Highway driving under these kinds of conditions would increase the Leaf's and i-MiEV's energy consumption and hence reduce the drivable range even further.

This research showed that real-road driving energy consumptions can be well predicted by a vehicle mathematical model. It was possible to predict the Leaf's and i-MiEV's drivable range under various loads. The simulation showed how significantly energy consumption increases and range reduces under relative high speeds, strong headwinds, increased vehicle weight, auxiliary loads and cross sectional area, the absence of energy recovery by an RBS, limited charge level from fast-DC charging, and limited access to the stored energy due to the requirement for a discharge safety margin. The experiments have shown significant differences between manufacturers published range and simulated scenarios based on data from real-road driving.

The simulations focused on the range impact of driving speeds and increased loads. Further studies could include sensitivity analyses of the different parameters in the model.

Fast-DC charging technology is a potential solution to be implemented along a highway to drive an electric vehicle over a long distance and is also a feasible option for frequently driven cars in cities. This research, however, found that inherent battery aging, discharge safety margins and fast-DC charging to a SoC of just 80% leads to inefficient battery capacity utilisation and a significant reduction in the vehicle's drivable range. These findings are very important for EV drivers and the efficient design of an electric highway between remote towns or an extended fast-DC charging network in cities. For them it is critical to understand how EV energy and recharging demands change under different driving patterns.

Based on the findings from this study, it appears that manufacturers overestimate their vehicles' range. Since EV drivers have some options to reduce EV energy consumption, e.g. reduce speed or shed unnecessary loads, EV manufacturers should communicate and increase EV drivers' and EV infrastructure planners' awareness. Too many fast-DC stations along a highway increases costs and might be considered financially inefficient. In contrast, by designing an electric highway according to manufacturers' published ranges and without driver awareness some EVs are likely to get stranded in rural areas. As a consequence, EV technology might suffer a poor reputation and negatively influence EV sales uptake.

5 Conclusions

Drivable range and recharge time are among the biggest hurdles for EV adoption. Little is known about the impact from the combination of fast-DC charging, increased aerodynamic loads, auxiliary loads, reduced battery capacity and high speed driving. In this study we aimed to investigate this impact on EV drivable range for two commercial EVs, a Nissan Leaf and a Mitsubishi i-MiEV. A marked difference between the nominal battery capacity and the usable capacity was observed on both vehicles, reducing their drivable range significantly. A vehicle mathematical model was developed to simulate vehicle traction power and energy demand, which showed good agreement with published energy consumption data from NEDC tests. The results show that driving at higher speeds, with headwinds or increased vehicle cross sectional area (roof racks) and large auxiliary loads reduce an EV's efficiency significantly and hence significantly reduce its drivable range. The key finding from this paper is that the energy consumption and drivable range figures published by EV manufacturers deviate significantly compared to real road EV driving scenarios and energy demands. EV infrastructure planners should be made aware of the discrepancies to prevent inefficient implementation of charging infrastructures.

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References

1. Agency, I.E., *Global EV Outlook, Understanding the Electric Vehicle Landscape to 2020*. 2013.
2. Motors, T. *Super Charger*. 2015 [cited 2015 10-03]; Available from: http://www.teslamotors.com/supercharger.
3. Project, T.R. *Electric Highway* n.d. [cited 2015 10-03]; Available from: http://revproject.com/trials/highway.php.
4. Moodie, C., *WA hoping to win race to build Australia's first electric car network*, in *ABC*. 2015.
5. Nissan, *2013 Leaf Owners Manual*. 2013.
6. Mitsubishi, *Mitsubishi i-MiEV - Owner's Handbook*. 2015.
7. Moore, T., *Tools and Strategies for Hybrid-Electric Drivesystem Optimization.* SAE Technical Paper 961660, 1996.
8. R.Farrington and J. Rugh, *Impact of Vehicle Air-Conditioning on Fuel Economy, Tailpipe Emissions, and Electric Vehicle Range*, in *Earth Technologies Forum*. 2000: Washington, D.C.
9. T.Yuksel and J. J.Michalek, *Effects of Regional Temperature on Electric Vehicle Efficiency, Range, and Emissions in the United States.* Environmental Science and Technology, 2015.
10. González Vayá, M., *Optimizing the electricity demand of electric vehicles: creating value through flexibility*, in *Department of Information Technology and Electrical Engineering* 2015, ETH-Zürich Zurich, Switzerland.
11. Yang, S.-N., et al., *Charge scheduling of electric vehicles in highways.* Mathematical and Computer Modelling, 2013. **57**(11–12): p. 2873-2882.
12. United-Nations. *Regulation No. 101* 2005 [cited 2015 21-06]; Available from: http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/r101r2e.pdf.
13. Thomas Bütler, H.W., Material Science & Technolgy, *Energy consumption of battery electric vehicles (BEV)*. 2012.
14. Mike Duoba, E.R., Mark Meyer, *Advanced Powertrain Research Facility AVTA Nissan Leaf testing and analysis*. 2012.
15. Shankar, R. and J. Marco, *Method for estimating the energy consumption of electric vehicles and plug-in hybrid electric vehicles under real-world driving conditions.* Intelligent Transport Systems, IET, 2013. **7**(1): p. 138-150.
16. Qin, Y., Z. Bei, and M. Kezunovic. *Optimization of electric vehicle movement for efficient energy consumption*. in *North American Power Symposium (NAPS), 2014*. 2014.
17. Kubaisi, R., F. Gauterin, and M. Giessler. *A method to analyze driver influence on the energy consumption and power needs of electric vehicles*. in *Electric Vehicle Conference (IEVC), 2014 IEEE International*. 2014.
18. Birrell, S.A., A. McGordon, and P.A. Jennings. *Defining the accuracy of real-world range estimations of an electric vehicle*. in *Intelligent Transportation Systems (ITSC), 2014 IEEE 17th International Conference on*. 2014.
19. Vaz, W., et al., *Electric vehicle range prediction for constant speed trip using multi-objective optimization.* Journal of Power Sources, 2015. **275**(0): p. 435-446.
20. Kambly, K. and T.H. Bradley, *Geographical and temporal differences in electric vehicle range due to cabin conditioning energy consumption.* Journal of Power Sources, 2015. **275**(0): p. 468-475.
21. Enjian, Y., Zhiqiang, Y, Yuanyuan, S, & Ting, Z, *Comparison of Electric Vehicle's Energy Consumption Factors for Different Road Types.* Discrete Dynamics In Nature & Society, 2013: p. pp. 1-7.
22. Bingham, C., C. Walsh, and S. Carroll, *Impact of driving characteristics on electric vehicle energy consumption and range.* Intelligent Transport Systems, IET, 2012. **6**(1): p. 29-35.

23. Maia, R.S., M. Araujo, R. Nunes, U. *Electric vehicle simulator for energy consumption studies in electric mobility systems*. in *Integrated and Sustainable Transportation System (FISTS), 2011 IEEE Forum on*. 2011.
24. Frank, R.C., G. Schmitz, R. Engel, T. *A novel eco-driving application to reduce energy consumption of electric vehicles*. in *Connected Vehicles and Expo (ICCVE), 2013 International Conference on*. 2013.
25. Nissan, *Nissan Leaf*. 2013.
26. Mitsubishi. *i-MiEV FEATURES*. 2015 [cited 2015 12-03]; Available from: http://www.mitsubishi-motors.com.au/vehicles/i-miev.
27. Mitsubishi. *MiEV Specifications*. n.d [cited 2015 13.03]; Available from: http://www.mitsubishi-motors.com/en/showroom/i-miev/specifications/.
28. John Allande, P.T., Eric Woodruff, *Nissan Leaf On Board Diagnostic Bluetooth Utility*. 2013.
29. Bart Benders, K.W., Christian Kolf, *Methodology of EV measurements*. 2013.
30. Hayes, J.G. and K. Davis. *Simplified electric vehicle powertrain model for range and energy consumption based on EPA coast-down parameters and test validation by Argonne National Lab data on the Nissan Leaf*. in *Transportation Electrification Conference and Expo (ITEC), 2014 IEEE*. 2014.
31. Larminie, J. and J. Lowry, *Electric Vehicle Technology Explained*. 2012, Wiley: Hoboken.
32. Roper, D., *Nissan Leaf Range Calculation*. 2012.
33. Ecos, *Passenger Tire Rolling Resistance Measurements From Ecos*. 2011.
34. Yuksel, T. and J.J. Michalek, *Effects of Regional Temperature on Electric Vehicle Efficiency, Range, and Emissions in the United States.* Environmental Science & Technology, 2015.