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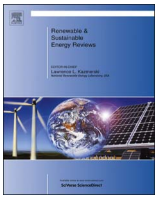

Driving electric vehicles at highway speeds: The effect of higher driving speeds on energy consumption and driving range for electric vehicles in Australia

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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.

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Nomenclature

N	number of samplings (for a sample rate of 1 s) [dimensionless]
m	vehicle mass [kg]
C_{RR}	tyre rolling resistance coefficient (depends on the specific tyres used) [dimensionless]
C_D	drag coefficient (depends on the vehicle's shape) [dimensionless]
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 [dimensionless]
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 min 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 optimisation, 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 (5100 km travelled), as shown in Fig. 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.