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Development of a driving cycle to evaluate the energy economy of electric vehicles in urban areas

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HIGHLIGHTS

- Development of a driving cycle to evaluate energy economy of electric vehicles.
- Improves on existing driving cycles by using real world data from electric vehicles.
- Driving data from different road types and traffic conditions included.

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ABSTRACT

Understanding real-world driving conditions in the form of driving cycles is instrumental in the design of efficient powertrains and energy storage systems for electric vehicles. In addition, driving cycles serve as a standardised measurement procedure for the certification of a vehicle's fuel economy and driving range. They also facilitate the evaluation of the economic and lifecycle costs of emerging vehicular technologies. However, discrepancies between existing driving cycles and real-world driving conditions exist due to a number of factors such as insufficient data, inadequate driving cycle development methodologies and methods to assess the representativeness of developed driving cycles. The novel aspect of the work presented here is the use of real-world data from electric vehicles, over a six month period, to derive a driving cycle appropriate for their assessment. A stochastic and statistical methodology is used to develop and assess the representativeness of the driving cycle against a separate set of real world electric vehicle driving data and the developed cycle performs well in that comparison. Although direct comparisons with internal combustion engine driving cycles are not that informative or relevant due to the marked differences between how they and electric vehicles operate, some discussion around how the developed electric vehicle cycle relates to them is also included.

1. Introduction and background

Using electricity for vehicle propulsion offers the possibility to substitute oil with a secondary energy source. This could ensure the security of energy supply and a broad use of renewable and carbon-free energy sources in the transport sector which could assist global CO_2 emission reduction targets. Electric vehicles (EV) produce less effective CO_2 per kilometre (i.e. including CO_2 emitted from electricity generation) travelled and produce no local pollution such as PM_{10} and NO_2 [1,2].

Recent research on electric vehicles is broad ranging. Onat et al. [3] studied vehicle options across 50 US states taking into account state specific average and marginal electricity generation mixes, regional driving patterns, and vehicle and battery manufacturing impacts. In addition they evaluated the widespread use of solar energy to charge EVs and plug-in hybrids (PHEV). EVs were found to be the least carbon intensive vehicle option in 24 states while hybrid EVs were found to be the most energy-efficient option in 45 states. Mallouh et al. [4] developed a model to compare, using experimental data that was recorded from a testing vehicle (taxi) running in the streets of Amman city, an ICEV with a hybrid fuel cell/battery vehicle by replacing only the powertrain and keeping all other parts the same. Their simulation results confirmed that hybrid FC/battery vehicles have superior performance in terms of fuel economy, drivability, emissions, and efficiency, when compared with ICEVs.

Saxena et al. [5] show that the energy storage limits of today's EVs are outweighed by their high efficiency and the fact that driving in the US seldom exceeds 100 km of daily travel. The normal

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daily travel of 85–89% of drivers can be satisfied with EVs charging with standard 120 V wall outlets at their home only. 77–79% of drivers on their normal daily driving will have >60 km of buffer range remaining for unexpected trips. Similar findings were noted by Weldon et al. [6]. Wikstron et al. [7] presents findings from a 3 year study of 550 EVs and their users in Sweden. They found that winter conditions seem to result in an unjustified decrease in use and a substantial share of battery capacity is redundant. They found that this was not due to the technical constraints of the vehicles but concerns of the drivers using the EVs in those conditions. Morrissey et al. [8] showed that the charging behaviours of EV users vary depending on the location of the charging infrastructure.

Weldon et al. [9] showed that the environmental impacts of EVs in Ireland are highly influenced by the charging behaviours of individual users, and night-time charging was found to produce the largest environmental impact as a result of grid management decisions. Meng et al. [10] found that frequency instability caused by intermittent wind generation is reduced by the frequency response from the EV clusters. Large scales of EVs utilized as a demand response resource can promote the development of wind generation in the Great Britain power system.

Schill and Gerbaulet [11] examine the impact of future scenarios of EVs on the German power system. They found that the impact on the load duration curve strongly differs between charging modes. They also found that the overall energy requirements of EVs should not be of concern to policy makers for the time being whereas their impact on peak loads should be. They also suggested that policy makers should be aware that cost optimised charging not only increases the utilization of renewable energy but also of low cost emission intensive plants.

Saxena et al. [12] used powertrain modelling to estimate that average city energy use is 33 W h/km for electric scooters, 84 W h/km for low power 4-wheel electric vehicles and 123 W h/km for high power electric 4-wheeler vehicles. Seedam et al. [13] developed an onboard system for installation on a motorcycle to measure the on-road driving pattern. The developed onboard system was applied to collect the on-road driving pattern of the motorcycle driving along the road network of the Khon Kaen city, Thailand for developing a motorcycle driving cycle.

Rangaraju et al. [14] used real-world energy consumption data for an environmental assessment of electric vehicles compared with diesel and petrol vehicles. The influence of charging profile on the well to tank emissions of EVs is discussed by using hourly emissions and different possible peak and off-peak charging time frames. The study noted the importance of taking the driving behaviour of users and auxiliary energy consumption into account. In the absence of an electric vehicle driving cycle they used the New European Driving Cycle for the assessment. The results revealed that the auxiliary energy consumption is responsible for nearly 1/3 of the well to tank emissions.

Wang et al. [15] found that electric vehicles in Beijing, including HEVs, PHEVs and BEVs, yield more fuel reduction benefits than in the U.S. because of the severe driving conditions and short driving ranges. They also confirmed that the Chinese current suggested label values based on NEDC cycle underestimate the fuel consumption of vehicles and fuel reduction benefits of electric vehicles in Beijing. They point to the importance of developing and using real-world driving cycles in designing and evaluating electric vehicles; a gap the research presented here addresses.

The design of efficient powertrains and energy storage management systems for EVs relies on an in-depth understanding of real-world driving conditions. Driving cycles have been developed to provide velocity–time profiles that are intended to be representative of real-world driving conditions. They are then used to assimilate driving conditions on a laboratory chassis dynamometer or in a vehicle simulation model. The battery capacity, battery chemistry and the sizing of electrical components in the drivetrain are all dependent on the desired driving range of the vehicle. The peak power demands of a cycle influence the size of the battery whereas battery state of charge fluctuations influence battery health and thermal management [16]. In addition to playing an important role in design, driving cycles also serve as a standardised measurement procedure for the certification and evaluation of the fuel economy, emissions and driving range of emerging vehicular technologies. Furthermore, real-world driving cycles are required for realistic lifecycle analyses and for evaluating the impacts of EVs on the electricity grid.

Existing driving cycles have been designed such that they can be applied to a variety of vehicles irrespective of the intended real-world operating conditions of the vehicle. There are two types of driving cycles, transient cycles such as the Federal Test Procedure (FTP-75) [17] and modal cycles such as the New European Driving Cycle (NEDC) [18]. The primary difference is that modal cycles are a compilation of constant acceleration and constant velocity periods, whereas transient cycles involve many velocity variations, typical of on-road driving conditions. There are two categories of driving cycles, legislative and non-legislative. Legislative driving cycles such as the NEDC and the FTP-75 are used by regulatory authorities to certify a vehicle's emissions and fuel economy within their respective jurisdictions. Non-legislative driving cycles such as the Hong Kong cycle [19], the Edinburgh cycle [20], the Athens cycle [21], the Toronto waterfront cycle [22] and the Singapore cycle [23] have broad applications in research from vehicle design to life cycle analyses.

Driving cycles are useful for comparison purposes because they provide an estimation of fuel economy, emissions and driving range. However, there is poor correlation with real-world driving conditions and their effects on fuel consumption and emissions, particularly in relation to modal cycles. There are significant variations in real-world driving conditions compared to test procedures and this variation causes a significant difference in emissions, fuel economy and driving range in real-world operating conditions [24]. Tzirakis et al. [21] developed a driving cycle for Athens using data collected from an internal combustion engine vehicle (ICEV). Depending on the vehicle tested, fuel consumption and emissions were found to be 9–79% and up to 300% higher respectively than those observed over the NEDC. Seers et al. [25] developed two driving cycles for utility vehicles using data from on-board loggers, and revealed a major difference of 31% in fuel consumption over the FTP-75 cycles. The German Ministry of Transport, Building and Urban Development measured the fuel consumption of more than one hundred cars and found that the majority of the vehicles consumed 25% more fuel and thus emitted more CO_2 emissions than certified [26]. It was reported that 40% of the cars exceeded their certified limit, while 2% of the vehicles had a fuel consumption of up to 70% higher than certified.

Real-world driving conditions in the US have also been analysed. Fellah et al. [27] analysed 110 real-world cycles in Kansas City and found that real-world cycles are more aggressive than the American certification cycle, the Urban Dynamometer Driving Schedule (UDDS), resulting in a larger energy requirement per unit distance travelled. Tate et al. [28] used 621 GPS driving cycles from Southern California to assess the performance of plug-in hybrid electric vehicles (PHEV). The authors found that the associated power and speed values of the driving samples were higher than those associated with the UDDS cycle. It was noted that 94% of vehicles have a larger average energy consumption per unit distance travelled in real-world driving conditions compared to the UDDS and the Highway Fuel Economy Test cycle (HWFET) [29]. Patil et al. [30] simulated a PHEV over real-world GPS driving cycles logged in south-eastern Michigan. It was found that 90% of the trips in the dataset consumed more fuel per mile than the