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# Sensitivity analysis for energy demand estimation of electric vehicles

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ABSTRACT

We present a sensitivity analysis for a mechanical model, which is used to estimate the energy demand of battery electric vehicles. This model is frequently used in literature, but its parameters are often chosen incautiously, which can lead to inaccurate energy demand estimates. We provide a novel prioritization of parameters and quantify their impact on the accuracy of the energy demand estimation, to enable better decision making during the model parameter selection phase. We furthermore determine a subset of parameters, which has to be defined, in order to achieve a desired estimation accuracy. The analysis is based on recorded GPS tracks of a battery electric vehicle under various driving conditions, but results are equally applicable for other BEVs. Results show that the uncertainty of vehicle efficiency and rolling friction coefficient have the highest impact on accuracy. The uncertainty of power demand for heating and cooling the vehicle also strongly affects the estimation accuracy, but only at low speeds. We also analyze the energy shares related to each model component including acceleration, air drag, rolling and grade resistance and auxiliary energy demand. Our work shows that, while some components make up a large share of the overall energy demand, the uncertainty of parameters related to these components does not affect the accuracy of energy demand estimation significantly. This work thus provides guidance for implementing and calibrating an energy demand estimation based on a longitudinal dynamics model.



## Introduction

Battery electric vehicles (BEVs) have the potential to significantly reduce oil dependency, decrease carbon emissions and noise, avoid tail pipe emissions and increase energy efficiency of transportation. Several car manufacturers have released new types of BEVs and in many European countries the charging infrastructure for BEVs is constantly expanded. Additionally, funding programs and research activities have been started, aiming at improving different aspects of electric mobility. Experts are confident that in the near future BEVs will achieve a significant market penetration (Situ, 2009).

Regarding energy efficiency of driving (tank to wheel efficiency), a BEV performs much better than an internal combustion engine vehicle (ICEV). It is worth noting that this does not include the energy efficiency of fuel production or electricity generation, which varies significantly depending on the mix of energy sources that are available in a certain region or

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country. Given a high efficiency of energy production, the overall efficiency (well to wheel) of BEVs can be up to twice the overall efficiency of ICEV (Kromer and Heywood, 2007).

A reason for the better tank to wheel efficiency of a BEV is the higher efficiency of the electric motor (up to 95%, EVO Electric, 2014) compared to a combustion engine (up to 35% for gasoline fuels, Treiber and Kesting, 2010). Electric motors are able to provide a high torque for a broad range of rotational speeds. Therefore only a single gear transmission is needed, which further increases the efficiency of the drive train. In general, a BEV contains fewer moving and rotating parts than an ICEV, resulting in lower maintenance costs (Kampker et al., 2013; Pelletier et al., 2014). Energy efficiency is further increased by the ability of the electric motor to act as a generator. During decelerating and driving downhill, energy can be transformed into electric energy and transferred back to the battery, instead of being dissipated by friction brakes.

Although energy efficiency of BEVs is high, their driving range without charging is much shorter than typical ICEV driving ranges. Currently available BEVs reach driving distances of approximately 150 km with a fully charged battery. Among BEVs, the largest driving range of approximately 420 km is possible with the Tesla Model S, equipped with a 85 kW h battery. In contrast, an average ICEV can easily cover a distance of 800 km and more with one tank of gasoline. The situation is aggravated by very hot or cold ambient temperatures, which increase the energy demand for cooling or heating.

The reason for short driving ranges is the relatively small amount of energy that can be stored in the battery. A battery has a much lower specific energy (energy capacity per unit mass) than a fossil fuel. Nowadays, lithium-ion batteries, as used in the automotive industry, achieve a specific energy of up to 130 W h/kg, but specific energy of gasoline is approximately ten times higher (1233 W h/kg, Young et al., 2013). Other battery types currently used in BEVs (Ni-MH, Zebra) do not achieve higher specific energy values than lithium-ion batteries. Moreover the price (in costs per capacity) of a standard lithium-ion battery is about 250USD/kW h (Young et al., 2013; Pelletier et al., 2014). Building larger batteries for larger driving distances would therefore increase price and weight of the vehicle. Additional weight also means increased energy consumption and reduced efficiency. Therefore, it is a challenge for car manufactures to find a good trade-off between driving range, price and weight.

Because of the small energy storage capability of batteries, it is necessary to know, how much energy is consumed by the BEV, in order to estimate the maximum driving range. In the literature, a model, which describes the vehicle behavior based on the general principles of mechanics, is often used to estimate the (electric) energy demand. We refer to this model as longitudinal dynamics model (LDM), because it describes the movement behavior of a vehicle along its longitudinal direction. An LDM contains several parameters related to properties of the vehicle and its environment. The literature provides various references for setting parameters to specific values. Due to varying indications in the literature and different properties of environment and vehicles, all model parameters are subject to uncertainty within a certain range, which causes a variation in energy consumption estimation. The question is, which of the model parameter uncertainties have a higher influence on the accuracy of the energy consumption estimation and therefore have to be configured more thoroughly. The answer to this question is also relevant for finding measures to reduce the energy consumption. This paper aims at analyzing the sensitivity of the LDM and thus the BEV's energy consumption. Moreover, the composition of the total energy estimate, based on the individual LDM components, is investigated.

The key contribution of this paper is to assess the variance of energy consumption estimation due to the uncertainty of parameters of the LDM. A sensitivity analysis is carried out, in order to investigate the influence of individual parameters. The analysis is based on recorded GPS tracks of a BEV. The uncertainty of parameters is specifically determined for a Mitsubishi i-MiEV but is equally applicable for other BEVs.

Our analysis results provide a basis for LDM users to focus on important parameters, which need to be determined exactly, while assuming standard values for less important ones. Thus, the calibration of an LDM can be improved in terms of accuracy and performance, by using only the most important parameters, thus reducing parameter search space.

The remainder of the paper is organized as follows: In Section "Longitudinal dynamics model" we give a detailed description of the LDM and summarize different applications for the LDM found in literature. We describe the theory and application of sensitivity analysis in Section "Sensitivity analysis" and discuss the data base used for conducting the sensitivity analysis in Section "Trip database". In Section "Energy shares" we perform a preliminary analysis regarding the energy shares related to each component of the LDM. Results are presented in Section "Sensitivity analysis results". Conclusions are drawn in Section "Conclusions" including recommendations for users of the LDM and future research activities.

## Longitudinal dynamics model

The movement behavior of a vehicle along its moving direction is completely determined by all forces acting on it in this direction (Ehsani et al., 2009). Fig. 1 shows the forces for a vehicle moving uphill. Air drag, rolling and grade resistance are the external forces. Tractive effort to overcome these forces and to accelerate has to be provided by the internal (electric) engine.

### *Definition*

Firstly we give a description of the relation between external forces, acceleration and basic energy consumption. During a vehicle's movement, the external resistances are trying to stop it. According to Newton's second law, the relationship between forces and acceleration can be written as