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Design of a comfortable optimal driving strategy for electric vehicles using multi-objective optimization

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HIGHLIGHTS

- A multi-objective approach is used to design a comfortable optimal driving strategy.
- Energy consumption, acceleration duration, and jerk are considered as objectives.
- Pareto-optimal fronts were obtained using NSGA-II.
- “knee” and reference-point-based methods were used for decision-making.
- A comfortable optimal driving zone was identified for efficient EV driving.

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ABSTRACT

Due to the limited amount of stored battery energy available for electric vehicles, it is important to use the energy in an optimal manner. This study proposes a novel comfortable optimal driving strategy (CODS) to change a speed that presents a number of optimal acceleration(s) to the driver, along with the total acceleration duration and range corresponding to a desired driving comfort. The design of CODS is done by solving a multi-objective optimization problem (MOOP) of minimizing acceleration duration and battery energy consumption. The acceleration jerk was used as a metric to quantify driving comfort. Based on the realization that the system response time should be low without sacrificing solution optimality for online implementation, two MOOPs were solved: constraining the jerk to a maximum level and minimizing the jerk as an optimization objective. Pareto-optimal fronts were obtained and it was found that consideration of minimizing total jerk is more convenient in finding CODS. A plot of the predicted range, time, and comfort for optimal acceleration(s) to a chosen speed change was presented and a comfortable optimal driving zone was identified. The system response time was found to be around 1 s, indicating its suitability for online implementation.

1. Introduction

Electric vehicles (EVs) have received a lot of attention recently due to being classified as zero emissions vehicles, in addition to having a higher energy efficiency [1]. However, efficient use of the stored energy in the EV is critical in order to cover a maximum range since charging stations for EVs are not as plentiful as fueling stations for internal combustion engines. Moreover, it takes much longer to recharge an EV than to refuel a conventional diesel or gasoline vehicle. In past research studies [2–4], it was observed that driving parameters, such as harshness of acceleration, have an impact on the fuel economy and that changes to the driving behavior can significantly improve the vehicle energy consumption [5]. The influence of driving pattern on fuel economy was also noticed in the study conducted by Hu et al. with a fuel cell/battery hybrid bus [6]. On the other hand, in some recent studies of acceleration control of EV [7,8], it was observed that adopting multiple accelerations during a speed change can reduce the energy consumption more than applying a constant acceleration value. In general, acceleration and deceleration comprise a small portion of a highway trip, but a much larger portion of urban and neighborhood

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trips [9]. Additionally, the power associated with accelerating an EV to a constant speed is generally much higher than the power associated with maintaining that constant speed [10]. Thus, it is very important to design a driving strategy by finding optimal acceleration value(s) along with respective duration(s) so that the EV uses the stored battery energy in the most efficient way while performing a speed change. In this study, the distance covered during acceleration was properly taken into consideration while designing an optimal driving strategy during acceleration/deceleration of an EV, which will be beneficial for trip planning based on available usable energy.

Comfortable driving of a vehicle is essential; otherwise it may lead to undesirable health effects for the driver/passengers. It may also cause traffic accidents. Moreover, it has been suggested that the magnitude of jerk affects the experience of acceleration [11] and creates oscillations. Oscillations have several complex impacts on the human body from causing slight discomfort to severe nausea [12], in addition to increasing the wear and tear on the EV. The concepts of comfort and discomfort are under debate and don't have a widely accepted definition [13]. However, it is generally agreed that the notion of comfort is subjective in nature and varies from driver to driver [14] and that low comfort is unacceptable from a user standpoint [15]. Thus, the optimal driving strategy to be designed for a speed change should be comfortable for the driver.

The acceleration duration is also important because it affects the overall trip time. Therefore, a comfortable optimal driving strategy (CODS) comprises optimal values of driving parameters (speed and acceleration) and information about how to achieve these parameters during vehicle operation to maximize range and minimize time duration. A comfortable driving experience for an EV may depend on many factors, such as driveline dynamics, vehicle chassis, tires, road surface, etc. However, these factors are not controllable during the EV operation, i.e. they exist regardless of the selected driving strategy. By ignoring these factors, the sole source of discomfort is due to the generation of jerk during the change of accelerations. It is considered in the present work to design comfortable optimal driving for EV, taken to mean optimal driving. In the present study, an acceleration controller was used to achieve the optimal acceleration values. In using the acceleration controller, jerk is primarily developed during the transient periods and adopting multiple changes of acceleration leads to more discomfort in driving [16]. How comfortably a controller performs a speed change depends on the controller gains (proportional gain (k_p) and integral gain (k_i), for a PI controller).

There are studies on optimal acceleration based on various considerations, such as maintaining a constant EV power [17], minimizing energy consumption [7,8,17,18], etc. However, studies on quantifying acceleration effects on fuel economy and range are limited, especially for EVs. EV data presented by Ref. [19] confirms the notion that the acceleration value greatly influences energy consumption of EV. No studies were found that find optimal accelerations considering both minimization of energy consumption and time duration. Moreover, a limited number of studies on designing a driving strategy were found where jerk was considered as a comfort metric [20–22]. In [15], the authors made an attempt by solving a multi-objective problem by minimizing total travel time, fuel consumption, and driving discomfort to present a comfortable driving strategy. But this study has not been carried out for EVs. In these works, authors used a crude measurement metric of discomfort [15], $J = |\Delta a|$, where J is the level of discomfort and Δa is the difference between two consecutive acceleration values. However, a better definition of comfort may be in terms of the jerk, i.e. the rate of change of acceleration, as proposed by Ref. [16]. This definition accounts for the time duration during which the change in acceleration is in effect as opposed to only considering the magnitude of the differences in the acceleration values.

Optimization is one of the most common and pervasive issues in real-world systems including energy and engineering. It is a technique to arrive at one or more solutions, which correspond to either minimum or maximum values of one or more objectives (in the form of objective/subjective function or performance indices) satisfying certain conditions. Optimization, specifically multi-objective optimization (MOO) is at the heart of any decision-making task in which a choice must be made between several alternatives corresponding to multiple, sometimes conflicting objectives. Real-world problems commonly involve more than one objective. The extreme value principle is not applicable in situations where all the objectives are equally significant. In this case, a number of solutions may be produced to create a compromise among different objectives. A solution that is extreme with respect to one objective requires a compromise with other objective(s). This restricts the choice of a solution which is optimal with respect to only one objective. Therefore, a number of sets of solutions are obtained and then the designer has to select a set from these sets of solutions, which will serve the purpose originally intended. The latter search is also known as multiple criteria decision making (MCDM). Thus, the primary objective of solving truly multi-objective optimization problems is to find the so-called Pareto-optimal front. The Pareto-front is formed by the solutions in which any change in any of the decision variables aimed at improving a particular performance index will produce deterioration in some of the other performance indices. Depending on the use of decision making based on preferences, a multi-objective optimization method can be categorized with a priori articulation of preferences, with a posteriori articulation of preferences, and with no articulation of preferences. A survey of various multi-objective optimization methods corresponding to these categories for engineering applications is presented in Ref. [23].

From the above discussion, it is realized that the way of changing the EV speed affects the driving comfort, energy consumption, and travel time. Once a speed is chosen, the driver would like to get to accelerate the EV to this speed in the shortest duration with sufficient comfort while expending the least amount of energy possible. Ideally, the driver would like to accelerate the EV to a chosen speed with both minimum energy and minimum time. But, these two objectives are conflicting, meaning an improvement in one leads to deterioration in the other. The conflicting nature of energy consumption and acceleration duration is realized following to the typical nature of EV energy consumption and efficiency as a function of the electric motor speed [24]. For example, for a given speed change, to accelerate the EV in the shortest duration possible, the acceleration value(s) must be as high as possible. However, to effect a high acceleration value, the electric motor must exert a high torque value, which causes the energy consumption to be large. On the other hand, a low acceleration, while keeping the energy consumption low, results in an undesirable long acceleration duration, which may be unsuitable for practical driving. Intuitively, one may think that in the case of a high acceleration value, since the duration is low, the energy consumption should be the same as the case of a low acceleration value where the duration is correspondingly high. However, for a given speed change, it has been shown [8,18,19] that the energy consumption varies according to the chosen acceleration value(s). The issue of energy consumption and acceleration time with multiple accelerations is clarified by way of an example in Section 5. Moreover, the use of multiple accelerations minimizes energy consumption during EV acceleration, but increases the jerk due to multiple changes of acceleration. In this work, a system is proposed to formulate an optimal driving strategy during speed changing based on three objectives, namely, minimization of