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Optimal driving during electric vehicle acceleration using evolutionary algorithms

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ABSTRACT

Due to the limited amount of stored battery energy it is necessary to optimally accelerate electric vehicles (EVs), especially in urban driving cycles. Moreover, a quick speed change is also important to minimize the trip time. Conversely, for comfortable driving, the jerk experienced during speed changing must be minimum. This study focuses on finding a comfortable driving strategy for EVs during speed changes by solving a multi-objective optimization problem (MOOP) with various conflicting objectives. Variants of two different competing evolutionary algorithms (EAs), NSGA-II (a non-dominated sorting multi-objective genetic algorithm) and SPEA 2 (strength Pareto evolutionary algorithm), are adopted to solve the problem. The design parameters include the acceleration value(s) with the associated duration(s) and the controller gains. The Pareto-optimal front is obtained by solving the corresponding MOOP. Suitable multi-criterion decision-making techniques are employed to select a preferred solution for practical implementation. After an extensive analysis of EA performance and keeping online implementation in mind, it was observed that NSGA-II with the crowding distance approach was the most suitable. A recently proposed innovization procedure was used to reveal salient properties associated with the obtained trade-off solutions. These solutions were analyzed to study the effectiveness of various parameters influencing comfortable driving.

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 than comparable internal combustion vehicles. It is well known that driving parameters, such as harshness of acceleration have an impact on the fuel economy [1–3] and that changes to the driving behavior can influence it [4]. However, there are only a few studies on quantifying acceleration effects on fuel economy and range, especially for EVs. Most of them focus on minimizing the energy consumption [5–8]. However, acceleration duration is also important because it affects the overall trip time. 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. In a recent study by Vaz et al. [9] in solving this multi-objective problem it was found that multiple acceleration values can optimize the energy and time better than a single acceleration value. Similar observations of minimizing energy using multiple accelerations were also noticed in other research studies [6,7]. On the other hand, comfortable driving of a vehicle is essential. Otherwise, it may lead to critical health effects for the occupants.

There are different ways to experience discomfort in vehicle driving: changing controls frequently [10], driver's position in the seat [11], jerk [12], etc. In the present work, only the issue of jerk (which is actualized during a change of acceleration) is considered in dealing with comfortable driving of the EV. Though the use of multiple accelerations reduces the overall energy consumption, it creates discomfort due to several jerks associated with multiple changes of acceleration. It has been suggested that the magnitude of the jerk affects the experience of acceleration [13] and creates oscillations. Oscillations have several complex impacts on the human body from causing slight discomfort to severe nausea [14], in addition to increasing the wear and tear on the EV. The concepts of comfort and discomfort are under debate and do not have a widely accepted definition [11]. It is generally agreed that the notion of

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comfort is subjective in nature and varies from driver to driver [15] and that low comfort is unacceptable from a user standpoint [10].

There are only a few studies on designing an optimal driving strategy using jerk as a comfort metric [16–18]. In [9], the authors suggested two "a posteriori" approaches to select a preferred solution from the Pareto front obtained after solving the multi-objective problem. The approaches were based on the concepts of comfort and Pareto fronts' knee [19]. In another study [10], the authors made an attempt by solving the multi-objective problem by minimizing total travel time, fuel consumption, and driving discomfort to present a Comfortable Driving Strategy (CDS). But this study has not been carried out for EVs. Moreover, those studies dealt with the entire driving cycle, which consists of different driving zones (acceleration, constant speed, etc.) that are related to different optimization objectives. Hence, such results have a high change to be a sub-optimal solution. Furthermore, in those works, authors used a crude metric to quantify discomfort [10], $J = \left|\Delta a\right|$. Here, J is the level of discomfort and Δa is the difference between two consecutive acceleration values. However, a more useful definition of comfort may be in terms of the jerk, i.e., the rate of change of acceleration, as proposed by Nilsson [12]. 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.

An efficient and comfortable driving strategy depends on the optimal values of driving parameters (velocity and acceleration) and how these values are achieved during a trip while maximizing range and minimizing trip time. A comfortable driving experience for an EV depends on many factors such as driveline dynamics, vehicle chassis, tires, road surface, etc. [20]. However, these factors are not controllable, i.e., they are present 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. Adopting multiple accelerations for a given speed change (S_c) in order to minimize the duration and energy means the EV driver experiences several jerk values. Naturally, it is also desirable to minimize the discomfort due to jerk in finding optimal acceleration(s) during speed changes. Thus, during speed changing, three objectives (namely minimization of acceleration duration, energy consumed during acceleration, and jerk) should be considered for an efficient and comfortable optimal driving strategy. In the present study, changing speed always indicates going from a lower speed to a higher speed.

The rest of the paper is organized as follows: Section 2 describes problem definitions of concerned multi-objective optimization problem. Formulations of objective functions are presented in Section 3. A brief description of the working procedure of two MOO algorithms that are implemented for solving the present problem, various metrics to analyze the Pareto fronts, and decision-making for preferred solution selection are presented in Section 4. Multi-objective optimization for designing comfortable driving of EV is presented in Section 5. A comparative study of approaches based on problem type is made in Section 6. In Section 7, analysis of the role of decision variables in comfortable optimal driving is carried out. An investigation of the proposed system for online implementation is presented in Section 8.

Optimization is one of the most common and pervasive issues in real-world systems including 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 functions 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 criterion 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. The present problem of finding optimal acceleration(s) with corresponding acceleration duration(s) and controller gains during speed changes deals with multi-objective optimization in order to maintain comfortable driving of an EV and it can be solved by a suitable multi-objective optimization tool.

2. Problem definition

From the previous section, it is realized that the manner of changing the EV speed affects driving comfort, energy consumption, and travel time. Once an optimal trip speed is chosen, the driver would like to accelerate the EV to this speed in the shortest duration with sufficient comfort while expending the least amount of energy possible. A separate method may be used to find an optimal trip speed, v_{ref} [21]. Medical studies suggest that the human body can tolerate no more than a certain level of jerk [22,23]. Additionally, the perception of discomfort varies from person to person subjectively. Therefore, depending on the desired comfort level, it is expected that different optimal solutions can be achieved toward minimization of both acceleration duration and battery energy consumption. Moreover, it is interesting to see how the optimization results vary with different speed changes for comfortable driving of an EV. Furthermore, for online implementation of such a system to maintain a comfortable driving strategy during EV running, the system computational time (response time) should be low. Based on these requirements, in the present work, a comfortable driving strategy (i.e., optimal acceleration(s) and duration(s)) in speed changing may be designed using three approaches by solving three different multi-objective optimization problems (MOOPs) categorized depending on problem complexity.

The formulation of multi-objective problems corresponding to these approaches is presented as follows. In MOOP I, two objectives, minimization of acceleration duration and minimization of energy consumption are considered. Here, comfort is considered as a constraint by restricting the maximum allowable jerk experienced by passengers to a particular value. In the MOOP II, in addition to the objectives in MOOP I, minimization of total jerk experienced by passengers during the entire acceleration period is considered as another objective. To carry out a deeper investigation, all three objectives are treated with equal importance in designing comfortable driving. On the other hand, MOOP III includes all the three objectives as well as the constraint of maximum allowable jerk.

2.1. Definition of MOOP I

Here, the maximum jerk value created during acceleration is considered to be limited by tolerable jerk for the human body. Definition of MOOP I is stated as follows: