

Genetic Algorithm Based Gear Shift Optimization for Electric Vehicles

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ABSTRACT

In this paper, an optimization method is proposed to improve the efficiency of a transmission equipped electric vehicle (EV) by optimizing gear shift strategy. The idea behind using a transmission for EV is to downsize the motor size and decrease overall energy consumption. The efficiency of an electric motor varies with its operating region (speed/torque) and this plays a crucial role in deciding overall energy consumption of EVs. A lot of work has been done to optimize gear shift strategy of internal combustion engines (ICE) based automatic transmission (AT), and automatic-manual transmissions (AMT), but for EVs this is still a new area. In case of EVs, we have an advantage of regeneration which makes it different from the ICE based vehicles. In order to maximize the efficiency, a heuristic search based algorithm - Genetic Algorithm (GA) is used. The problem is formulated as a multi-objective optimization problem (MOOP) where overall efficiency and acceleration performance are optimized. A mathematical formulation is provided to calculate the maximum possible efficiency for a given drive cycle. Non-dominated Sorting Genetic Algorithm (NSGA-II) is used to optimize the gear shift lines. A comparative study of fuel economy improvement is provided to validate the concept of using different downshift lines during regeneration.

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INTRODUCTION

With advent of increasing pollution and rising demand and price for crude oil, there has been a constant push to explore alternative source of energy. The concerns for environmental change and to maintain sustainability of conventional fuels have inspired researchers around the world to develop technology required for adoption of renewable sources of energy. A similar trend is seen in the automobile industry which has been craving to develop more efficient and less polluting vehicles. Alternative sources (hydrogen ICE, fuel cell, solar etc.) are being explored and evaluated to power the vehicles.

Most of the cities around the world are facing increased levels of smog, largely attributed to tailpipe emissions from ICE based vehicles. With emission norms becoming stringent over years, have forced original equipment manufacturers (OEMs) to look beyond optimization of ICE powertrain and solve the problem by introducing a partial or complete electrical solution. There has been a lot of thrust through government by investing in EV-enabling infrastructure and providing free charging stations. Incentives to ease burdens in terms of purchase, lease and taxes on EVs are other ways taken by governments to make it attractive for consumers, fleet owners and OEMs.

Proterra LLC's ProDrive™ have demonstrated operation of a permanent magnet motor to operate in high efficiency (92-95%) during traction and regenerative modes [1] using a three speed transmission. CodrinGrue et al. [2] have proposed a two AC traction motor electric axle configuration which successfully completed pilot run on a prototype truck. In [3], a fuzzy-logic based controller that optimizes power output of IC engine and motor is proposed. They had achieved close to 7% improvement in efficiency for urban cycles. Siemens AG also developed a direct drive configuration for a Bus Transit Line (BRT).

There have been an ample amount of research and studies to select right configuration, architecture and sizing of components for hybrid and EVs. However, the concept of using an automated transmission with an electric vehicle is relatively new and a limited amount of literature available for optimizing the shift control strategies for transmission based EVs. In this study, a slightly modified gear shift strategy is proposed. We have used Non-dominated Sorting Genetic Algorithm (NSGA-II [4]) to improve the efficiency of an EV by optimizing the shift strategy for both traction and regeneration mode. Gear shift strategy comprises of gear shift lines for upshift and downshift of transmission gear. Gear shift lines are optimized to operate the ICE/motor in the most efficient zone. In case of EV, we

have an advantage of regeneration. To ensure maximum regeneration, we need to have different downshift lines from the usual ones, so that most of the energy can be regenerated. In the current study, normal upshift and downshift lines as well as downshift lines during regeneration are optimized. The problem formulated here is a nonlinear problem with multiple contradictory objectives (efficiency and performance) and multiple operating points to be optimized (18 points for a 4 speed transmission in this work). Genetic algorithms are widely used where the objective functions are non-linear, a large number of parameters are required to be optimized and have multiple local minima. Keeping that in mind, we have used NSGA-II to optimize the gear shift lines. The key contributions to this paper are 1) novel gear shift strategy for electric vehicle, and 2) mathematical formulation to calculate global minima.

A mathematical approach is proposed to calculate optimal theoretical value of energy consumed per unit distance (EPD), which is used to check if the objective function is approaching global minima. Furthermore, a comparative study is done to validate the concept of using different downshift lines during regeneration.

This paper is organized in four sections. In the first part, a brief introduction of electric vehicle and gear shift strategy are provided. Next section talks about Non-dominated Sorting Genetic Algorithm, where the flow chart of the algorithm is presented. After that, an approach to calculate efficiency of an electric vehicle is proposed to obtain global minima for a given transmission, motor configuration. In the end, a detailed analysis of NSGA-II algorithm and modeling and simulation of electric vehicle are discussed.

BATTERY ELECTRIC VEHICLE (BEV)

Designing powertrain for an electric vehicle is relatively easier as the torque offered by a motor over lower range speed is high. With sophisticated motor control and a wide range of torque availability, eliminate the need for a clutch. For a small passenger car, motor is directly connected to the differential through a single gear reduction. There are similar direct drive solutions for other larger commercial vehicles like bus/trucks as well. However, challenge faced by the OEM's in electric buses with direct drive configuration is the startability and gradeability. Using a powerful and bigger motor is not the best solution as it not only makes the powertrain bulky but also the motor capability becomes redundant while cruising and normal city driving.

$$\text{Gradeability} = \tan \left[\sin^{-1} \left(\frac{F_t(t) - D(t)}{Mg} \right) \right] \quad (1)$$

$$\text{Startability} = \tan \left[\sin^{-1} \left(\frac{F_t(t)}{Mg} \right) \right] \quad (2)$$

Here, $F(t)$ is the traction force available on wheels after accounting friction, $D(t)$ includes all aero drag forces, M is mass of the vehicle.

The major challenge, however, still lies in extending the range of any electric vehicle. The available battery technology and its cost restrict the storage available for use in vehicles. Stringent goals have been set to reduce the cost of the batteries. 'Range anxiety' is one of the major barriers to large scale production of the electric vehicles. This involves providing charging solutions at various geographic locations and technology to quickly charge the battery.

Researchers are trying to develop strategies to improve utilization of available strong on-board batteries. There is always a trade-off between performance and range and it becomes more pronounced in case of a direct drive configuration. Also, an attempt made to increase motor size/power to meet vehicle performance adds to the cost of the design. A simple solution to dampen this trade-off is to go for a powertrain with an Automated Manual Transmission (AMT). The two major advantages are that it can lead to reduction in motor size without affecting performance and other being flexibility to allow motor to run in its most efficient zone. The total package size of the AMT with downsized motor is about 5-10% more than a direct drive configuration. The additional cost of the transmission can be realized in terms of savings due to improved efficiency and reduced cost of downsized motor.

Good hardware design without proper control may not produce intended results. Maximum benefits of adding an automated transmission can be harvested using an optimized shift strategy. Designing a shift control strategy has been an area of interest in the past for automated manual and automatic transmissions. Even as Hybrid Electric Vehicles (HEVs) gained popularity in market development of energy management system attracted a lot of attention [5]. Efforts to reduce energy consumption for EV bus and to improve comfort and shift quality have been made by Hongbuet et al. [6]. They have made an attempt to achieve this through efficient shifting control as well as some changes in the transmission synchronizer design. In another study by Jun-Qiang et al. [7], have shown that using a multi-speed transmission with proper control strategy for shifting enhanced efficiency by 9% with reduction in acceleration time by 18%. They had used vehicle speed and throttle input as the two main parameters that decide shifting thresholds.

In the current study, we have attempted to optimize the overall efficiency of a vehicle while satisfying minimum requirements for acceleration and gradeability. The powertrain, in an EV, has a different structure and dynamics than a conventional ICE powered vehicle. The formulation of a shift strategy involves allowing motor to operate in its most efficient zone during powering and regeneration mode. In figure-1, a motor map is presented, where the most efficient zone is marked by dark red color. An alternate strategy for downshifting, taken at the time of regeneration (brake pedal pressed), ensures maximum amount of kinetic energy from the vehicle is absorbed into the battery rather than using the normal downshifting lines. This is one of the key differentiator in this study.

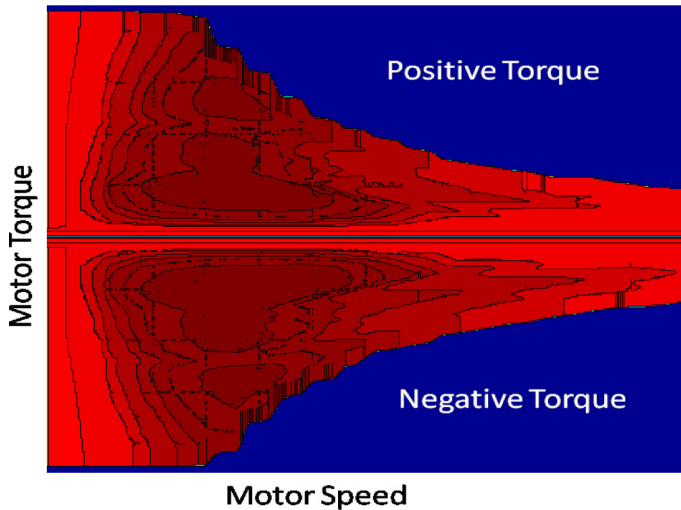


Figure 1. Motor Map [8]

The total energy consumed per unit distance (EPD) by an electric vehicle is given by

$$EPD_{EV} = \frac{\text{Energy Consumption}}{\text{Distance Travelled}} = \frac{\int P(t).dt}{\text{Distance}} \quad (3)$$

where P is the required power at time instant t

$$P = \frac{\omega_{\text{Motor}} \tau_{\text{Motor}}}{\eta_{\text{Motor}}} \quad (4)$$

ω_{Motor} , τ_{Motor} and η_{Motor} represent motor speed, torque and efficiency, respectively. In case of regeneration τ_{Motor} is going to be negative. Overall efficiency of an electric vehicle is inversely proportional to total energy consumed per unit distances.

In the current study, optimization problem is formulated to minimize EPD and drive cycle track error. Drive cycle track error is defined by subtracting the desired vehicle speed from the actual vehicle speed. The objectives are

$$\text{Min} f_1(X) = \text{EPD and Min } f_2(X) = \text{TrackError}, \quad (5)$$

To optimize f_1 and f_2 , a vector of 18 decision variables X is considered, subject to their upper and lower limits. These variables define upshift lines, downshift lines and downshift lines during regeneration, tabulated in Table-1. The upper and lower bound of each variable are defined based on the motor map and the step size of gears, explained in results section. In order to reduce the number of decision variables, the same shift line is considered for all the gears.

Table 1. Decision Variables for NSGA-II

Throttle Pedal (Percentage)	Upshift (RPM)	Downshift (RPM)	Downshift during Regeneration (RPM)
0	X(1)	X(7)	X(13)
20	X(2)	X(8)	X(14)
30	X(3)	X(9)	X(15)
70	X(4)	X(10)	X(16)
80	X(5)	X(11)	X(17)
100	X(6)	X(12)	X(18)

A typical shift pattern is shown in figure-2 for ICE based vehicles.

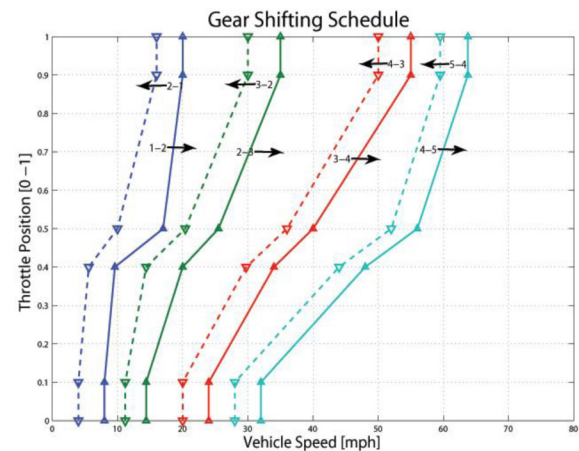


Figure 2. Pareto-Optimal front [9]

NON-DOMINATED SORTING GENETIC ALGORITHM-II

Genetic algorithms have been used to optimize nonlinear problems in various domains. It is a heuristic search based algorithm - a subset of evolutionary algorithms. Evolutionary algorithms are a process of modeling biological evolution. There are various types of genetic algorithms, mainly classified in two categories: binary-coded and real-parameter genetic algorithm. In the current study, NSGA-II, a real-parameter genetic algorithm is used for optimization. In [4], NSGA-II is claimed to have better performance compared with other constrained multi objective optimization algorithms.

Multi-objective optimization problem, in the case of conflicting objectives, has a number of possible solutions. To sort out these solutions, the concept of dominations is used where each solution is compared with other solutions. The solutions are categorized into two categories: (1) non-dominating solutions, and (2) dominating solutions. An exact definition of dominating and non-dominating solutions is given in [10], where a solution is said to be dominating if it outperforms other solutions in all objectives. The set of all non-dominated solutions is called the Pareto-optimal set and the curve formed by joining all non-dominated solutions is called Pareto-optimal front. In figure-3, solution spaces for two objective optimization problems are plotted by the gray area and Pareto-optimal fronts are plotted by solid dark lines.