Regenerative Braking Control Strategy for Hybrid and Electric Vehicles Using Artificial Neural Networks

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\textbf{Abstract.} One of the fundamental advantages of hybrid and electric vehicles compared to conventional vehicles is the regenerative braking mechanism. Some portion of the kinetic energy of the vehicle can be recovered during regenerative braking by using the electric drive system as a generator with the appropriate control strategy. The control requires distribution of the brake forces between front and rear axles of the vehicle and also between regenerative braking and frictional braking. In this paper, we propose solving the optimal brake force distribution problem using an Artificial Neural Network based methodology in order to maximize the available energy for recovery while following the rules for stability. Using the proposed approach, we find that for urban driving pattern, UDDS, up to 37\% of the total energy demand can be recovered. Then we compare the amount of recovered energy for different driving cycles and show that aggressive driving reduces recoverable energy up to 7\%. An increase in the energy recovery rate directly translates into improvements in fuel economy and reductions in emissions.

\textbf{Keywords:} Regenerative braking, artificial neural networks, brake force distribution, electric vehicle.

1 Introduction

In a conventional, internal combustion (IC) engine powered vehicle, the power flow occurs from the IC engine towards the wheels via a transmission system. The mechanical energy that is produced is used up to overcome aerodynamic drag, rolling resistance, frictional forces and to accelerate the vehicle [1]. These are all unavoidable components of energy expenditure. In the case of braking or deceleration of the vehicle, the kinetic energy of the vehicle that was built up during acceleration phase has to be reduced in order to reduce the speed of the vehicle. However since there is no mechanism in place to convert this kinetic energy into some other form to store away, all of the energy gets dissipated in the form of heat via the friction brakes. This

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energy is lost and additional fuel needs to be burnt when the vehicle needs to accelerate again. In urban environments, where vehicles are subjected to intermittent start-stop motion, this effect is even worse due to the higher frequency of application of brakes [2]. The problem is the inability of the conventional vehicle to recover energy while braking. This ultimately leads to low fuel economy and has negative economic implications especially given the size of transportation sector.

Electrified vehicles on the other hand, including hybrid, plug-in hybrid and battery electric vehicles, offer one fundamental advantage in this front. Through appropriate control strategy, the electric motor that drives the wheels can be used as a generator [3] that provides braking torque when the brakes are applied and also regenerates energy by converting the kinetic energy of the vehicle back into electrical energy which is then stored in the batteries. This technique can save considerable amount of energy increasing the fuel economy by reducing energy consumption and helps reduce emission of greenhouse gases [4].

Therefore to satisfy the features of regenerative braking as well as safety requirements, the brake system must provide a braking force that is a controllable combination of motor torque as well as mechanical frictional force. There are many architectures for achieving this [5], while the simplest one being parallel hybrid braking architecture [6].

Braking control strategy has two parts to it: (1) distribution of brake force between electric motor torque and mechanical friction forces, (2) distribution of forces to the front wheels and to the rear wheels (Section 2.1). In existing literature, this problem has been approached by using fuzzy logic in [7], [8] and [9] or designing specific solutions for a particular drive cycle like in [6]. Compared to the simple ANN model proposed in this paper that can solve the aforementioned problem, fuzzy logic is much more dependent on the membership functions one chooses to model. Designing specific solutions is not effective due to the variations in driving patterns. In this paper, we propose solving this distribution problem using an artificial neural network model in order to maximize the available energy for recovery while following the rules for stability. The ANN model is used on standard drive cycles [12] to get a quantitative estimate of available energy for recovery and comparison is provided. In the next section, we introduce the proposed methodology and then follow with the results and finally discuss conclusions.

2 Methodology

2.1 Problem Definition

Braking theory and design principle of conventional vehicle using frictional mechanism have been well established [6], which emphasizes distribution of total braking force on the front and rear wheels in order to obtain short braking distance and prevent the rear wheel being locked earlier than the front wheel locked in order to maintain the vehicle directional stability. Further, in an electric powertrain, we not only have to distribute brake forces between the front and rear axles but also between mechanical friction braking and electrical regenerative braking.

In this paper, we consider a hypothetical vehicle powertrain with the following parameters [6] in order make quantitative estimates about braking power. There are many architectures for the braking system [5]. In this paper we employ a parallel