

Effect of Different Regenerative Braking Strategies on Braking Performance and Fuel Economy in a Hybrid Electric Bus Employing CRUISE Vehicle Simulation

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ABSTRACT

In regenerative braking system of a HEV, the power electronics are controlled such that the traction motor operates as a generator to provide negative torque on the wheels and to produce electric energy. To develop such an assembly of control functions it is necessary to model the behavior of the vehicle in a dynamic environment. AVL/CRUISE software is used to perform vehicle simulation and brake analysis. The simulation procedure for series braking with optimal braking feel, series braking with optimal energy recovery, and parallel braking strategies in CRUISE software is explained. Then the braking performance and fuel economy of each method is studied and compared with the others in different drive cycles. Finally, the advantages and disadvantages of each method are evaluated and discussed.

INTRODUCTION

Hybrid electric vehicles have drawn a lot of attention in the recent years because they reduce fuel consumption and emission [1]. An important system of hybrid electric vehicles is regenerative braking system (RBS). The RBS provides hybrid electric vehicles with capability to recover significant amount of energy during braking [2-3]. For this purpose, the electric motor in EVs and HEVs can be controlled to operate as a generator to convert the kinetic and potential energy of the vehicle into electric energy. The recovered electric energy is stored in batteries for future use.

Generally, the braking torque required to decelerate the vehicle is much larger than the torque that an electric motor can provide. Most HEVs employ conventional braking system in addition to a RBS. Thus, the proper design and control of both mechanical and electrical braking systems are major concerns. In the area of regenerative braking in HEVs, some studies have been focused on developing regenerative models [4], simulation of regenerative system models [5] and motor control [6].

To develop a complex assembly of control functions in regenerative braking system, it is necessary to model the behavior of the vehicle in a dynamic environment. AVL/CRUISE software is used to evaluate vehicle performance and fuel economy using each brake strategy. This beneficial software is utilized to develop and optimize low emission engines, reliable power trains and sophisticated control systems of engines, cooling, transmission, and braking systems.

There is more complexity while designing a regenerative braking system in the hybrid electric vehicles compared with designing conventional braking systems. The way of distributing the required braking force between regenerative braking system and the mechanical friction braking system so as to recover the kinetic energy of the vehicle as much as possible without losing the necessary braking performance is the main problem, and it faces the designer with many different braking strategies.

To develop such braking system, a hybrid series electric bus is considered in this research. The vehicle under study is an O457 city transit bus which is hybridized to a series hybrid electric bus in "Vehicle, Fuel, and Environment" Research Institute, University of Tehran.

In this article, after describing the concept of three main different brake control strategies of series braking with optimal braking feel, series braking with optimal energy recovery, and parallel braking the way of simulating these strategies in CRUISE software is explained. Then the braking performance and fuel economy of each method is studied and compared with the others in a drive cycle. Finally, the advantages and disadvantages of each method are evaluated and discussed separately.

BRAKE STRATEGIES

There are two important problems in designing the regenerative braking system. First, how to distribute the total braking forces required between the regenerative brake and the mechanical brake in order to recover the

kinetic energy of the vehicle as much as possible; second, how to distribute the total braking forces on the front and rear axles so as to minimize the stopping distance and conserve the vehicle stability. Usually, regenerative braking is effective only for the driven axle, which is the rear axle in this study. The traction motor must be controlled to produce the proper amount of braking force for recovering the kinetic energy as much as possible and, at the same time, the mechanical brake must be controlled to meet the braking force command from driver. Basically, there are three different brake control strategies: series braking with optimal braking feel, series braking with optimal energy recovery; and parallel braking. Ehsani et al. have defined these strategies as follows [7].

The series braking system with optimal feel consists of a braking controller that controls the braking forces on the front and rear wheels. The purpose of this strategy is to minimize the stopping distance and optimize the driver's feel. The shortest braking distance and good braking feel require the braking forces on the front and rear wheels to follow the ideal braking force distribution, curve I [8].

Figure 1 illustrates the principle of this braking control strategy. When the commanded deceleration is less than a certain value (0.2 g, for example), only the regenerative braking on the rear wheels is applied which emulates the engine retarding function in conventional vehicles. When the commanded deceleration is greater than 0.2 g, the braking forces on the front and rear wheels follow the ideal braking forces distribution curve I, shown by the thick solid line in Figure 1.

In our case the braking force on the rear wheels (driven axle) is composed of two parts: regenerative braking force and mechanically frictional braking force. When the braking force demanded for rear axle is less than the maximum braking force that the electric motor can produce, only electrically regenerative braking will apply. But when the commanded braking force is greater than the available regenerative braking force, the electric motor will operate its maximum braking torque, and the remaining braking force is provided by mechanical braking system.

The principal of series braking system with optimal energy recovery is to recover the braking energy as much as possible in the condition of meeting the total braking force demanded for given deceleration, according to Ehsani et al [7]. This principal is illustrated in Figure 2.

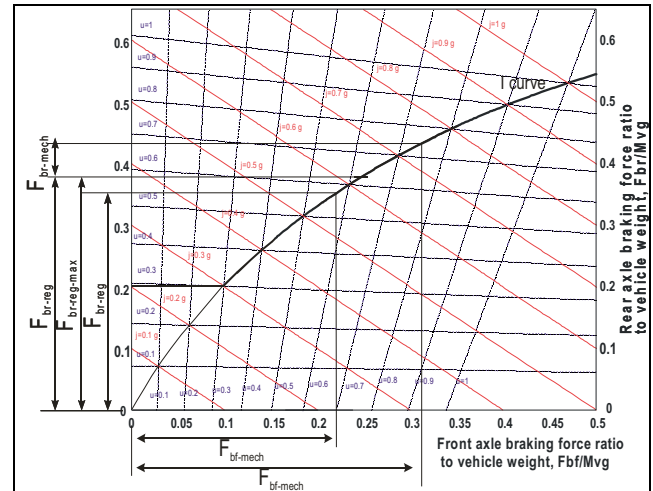


Figure 1: Series brake optimal feel strategy

When the vehicle is braked with an acceleration rate of $j/g < \mu$, the braking forces on the front and rear wheels can be varied in a certain range. This variation range of the front and rear axles is shown in Figure 2 by the thick solid line a-b, where $\mu=0.8$ and $j/g=0.7$. In this case, regenerative braking should be used in priority. If the available regenerative braking force (maximum braking force produced by the electric motor) is within this range, the braking force on the rear wheels should be developed only by regenerative braking without mechanical braking (point a). If, on the same road, the available regenerative braking force is less than the value corresponding to point b, the electric motor should be controlled to produce its maximum regenerative braking force. The front and total rear braking forces then should be controlled at point c (on the curve I) so as to optimize the driver feel and maintain vehicle's stability and steerability.

The parallel brake system includes both an electrical (regenerative) brake and a mechanical brake, which produce braking forces in parallel and simultaneously. The operating principal is illustrated in Figure 3, in which regenerative braking is applied only to the rear wheels. The parallel brake system has a conventional mechanical braking which has a fixed ratio of braking forces distribution on the front and rear wheels. Regenerative braking adds additional braking force to the rear wheels, resulting in the total braking force distribution curve. The mechanical braking forces on the front and rear axles are proportional to the hydraulic pressure in the master cylinder. Because the regenerative braking force available is a function of motor speed and because almost no kinetic energy can be recovered at low motor speed, the regenerative braking force at high vehicle deceleration (e.g. $j/g=0.8$) is designed to be zero so as to maintain braking balance. When the demanded deceleration is less than this deceleration, regenerative braking is effective.

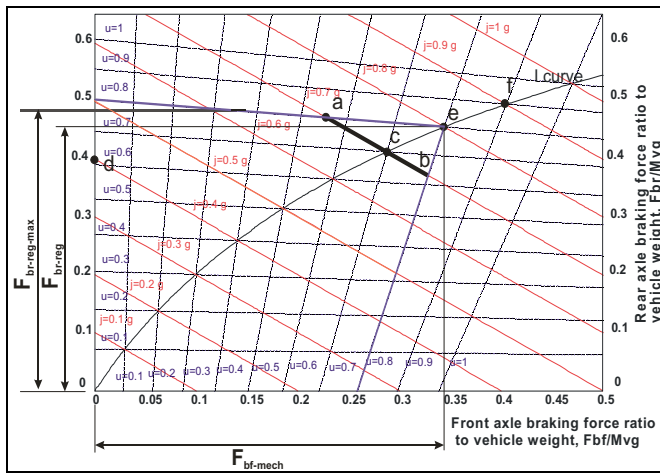


Figure 2: Series brake optimal energy recovery strategy

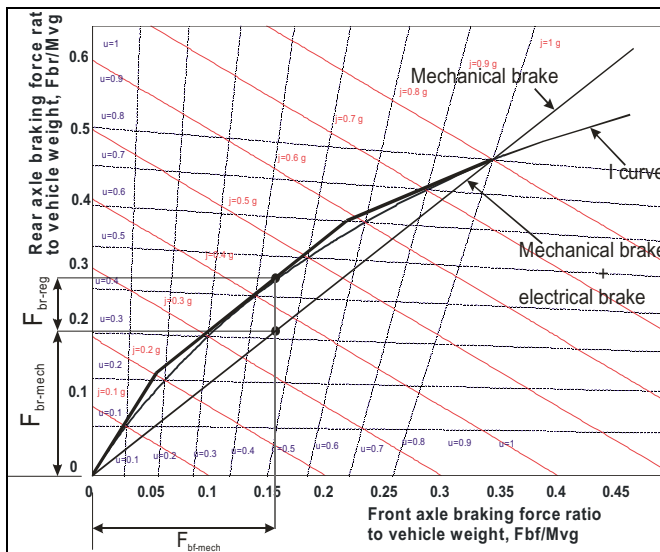


Figure 3: Parallel brake strategy

IMPLEMENTATION

The first step in development of brake system is to understand vehicle performance requirements and vehicle's geometrical properties such as position of center of mass. The vehicle which is used for current investigations is hybrid version of O457 bus which has been converted to a series hybrid vehicle at "Vehicle, Fuel, and Environment (VFE)" Research Institute, University of Tehran (figure 4). Specification of the bus after hybridization is given in Table 1.

In HEVs the most important component which can affect the amount of regenerated energy is the traction motor. Characteristic map of our traction motors is shown in Figure 5.

Two traction motors have been used in the design of hybrid drive train and in our modeling [1] we have one motor instead with characteristics of one motor multiplied by two.

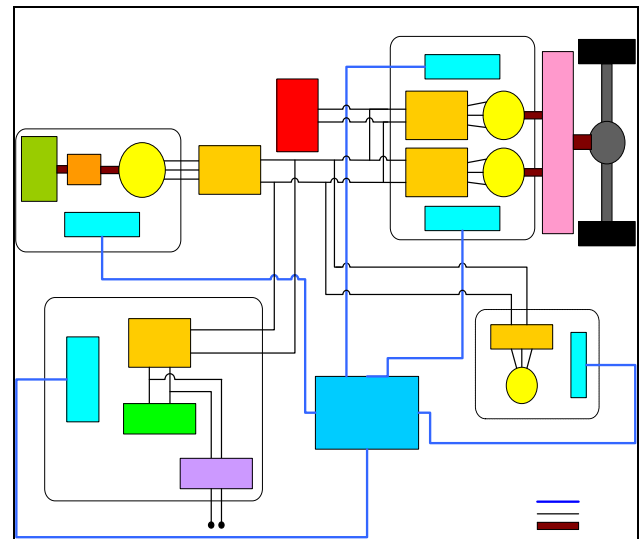


Figure 4: Hybrid drive train of O457 bus

Table 1: Hybrid bus specifications

Drag coefficient	$C_D = 0.55$
Rolling resistance coefficient	$C_R = 0.01$
Frontal area	$A_f = 6.30 \text{ m}^2$
Dynamic rolling radius	$R_w = 0.466 \text{ m}$
Overall gearbox and differential efficiency	$EFF = 0.9$
Curb Weight	$M = 10230 \text{ kg}$
Gross Weight	$M = 18000 \text{ kg}$
Distance of gravity center from front axle	$L_a = 4.410 \text{ m}$
Distance of gravity center from rear axle	$L_b = 1.645 \text{ m}$
Height of gravity center	$h_g = 0.95 \text{ m}$

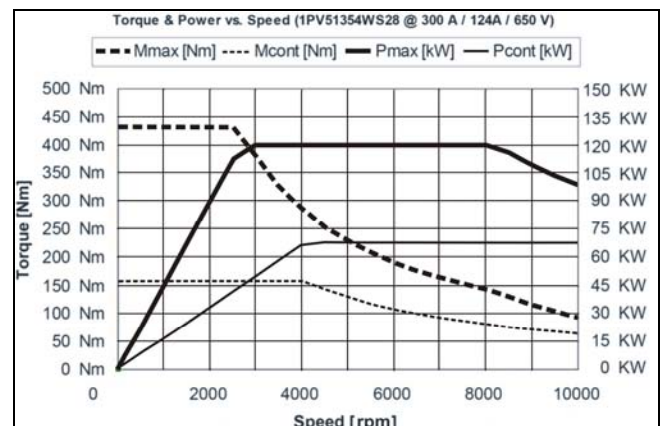


Figure 5: Traction motor characteristics map

As described in previous sections, the major function in design of brake system is I curve which is result of braking forces at rear and front axes. Brake forces at