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 loosing 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 baking 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.
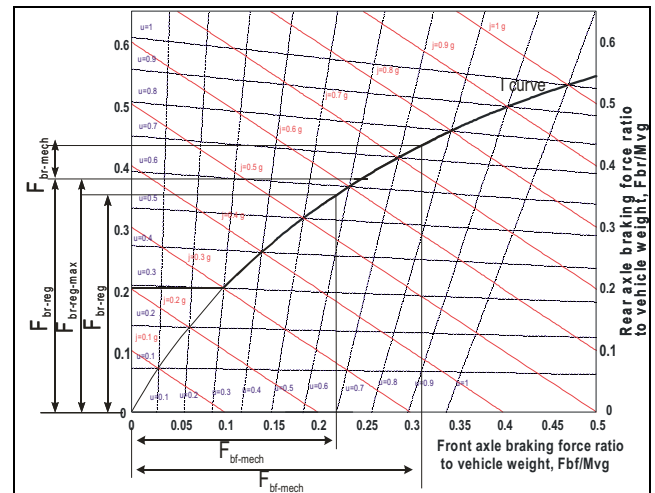

Figure 1: Series brake optimal feel strategy

When the vehicle is braked with an acceleration rate of j/g<μ, 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 μ=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 stearability.

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.
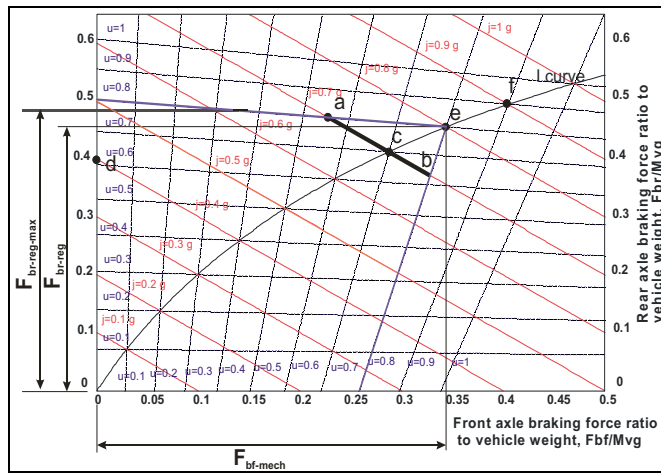
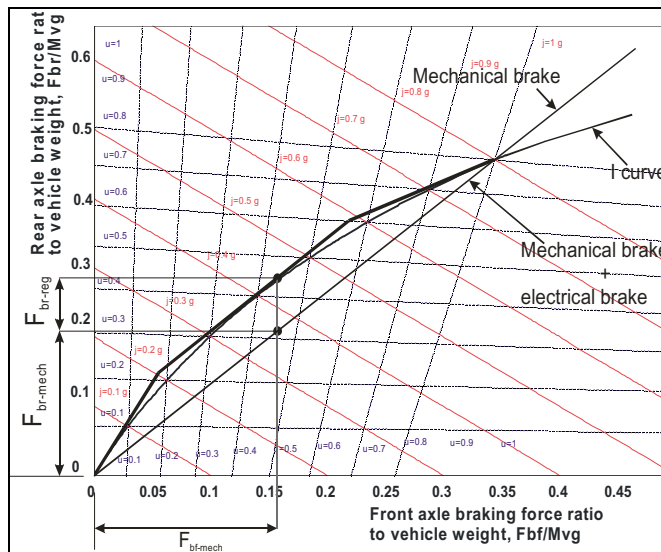Figure 2: Series brake optimal energy recovery strategy

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.
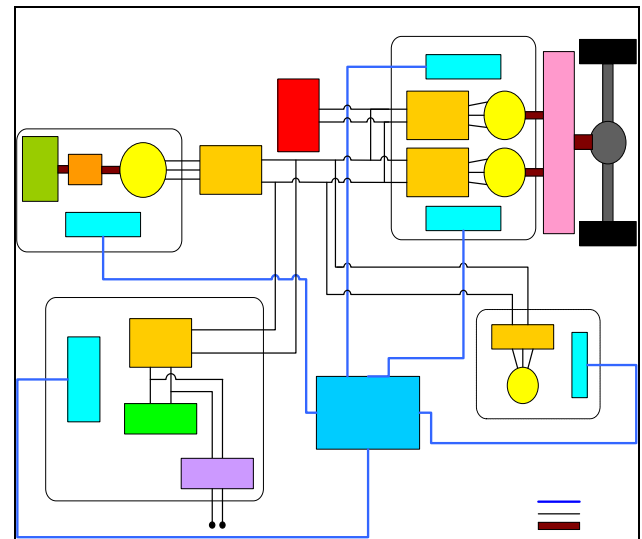
Figure 4: Hybrid drive train of O457 bus

Table 1: Hybrid bus specifications

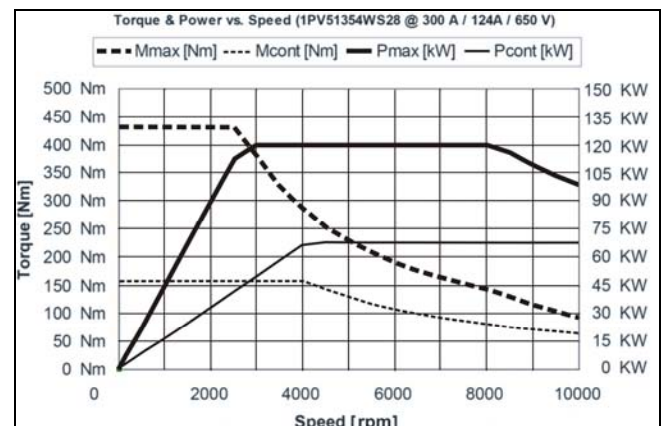|	
Drag coefficient	$C_D = 0.55$
Rolling resistance coefficient	$C_R = 0.01$
Frontal area	$A_f = 6.30 \ \text{m}^2$
Dynamic rolling radius	$R_w = 0.466 \ \text{m}$
Overall gearbox and differential efficiency	$EFF = 0.9$
Curb Weight	$M = 10230 \ \text{kg}$
Gross Weight	$M = 18000 \ \text{kg}$
Distance 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 axles. Brake forces at

the front and rear axles have been determined as a function of deceleration j:

$$F_{bf} = \frac{47}{1730} j + \frac{12}{6055} j^2 \qquad (1)$$

$$F_{br} = \frac{63}{865} j - \frac{12}{6055} j^2 \qquad (2)$$

These values are normalized by use of vehicle's weight $(M_v g)$. We have considered maximum of 0.8g for vehicle's deceleration. It means that maximum travel of brake pedal is equivalent with .8g deceleration. In addition, the pure regenerative criterion in series brake has been considered 0.1g.

MATLAB SIMULINK has been used for implementation of described braking strategies, it consists of an state flow controller which determines the braking mode according to desired equivalent deceleration and maximum generator phase torque of traction motors and then fraction of regenerative force, front brake force and rear brake force are calculated. At the end achieved values are translated to brake pressures and desired torque of traction motors according to the mechanical characteristics of brake and drive line systems. Figure 6 shows the implemented series brake-optimal feel Brake controller in SIMULINK.
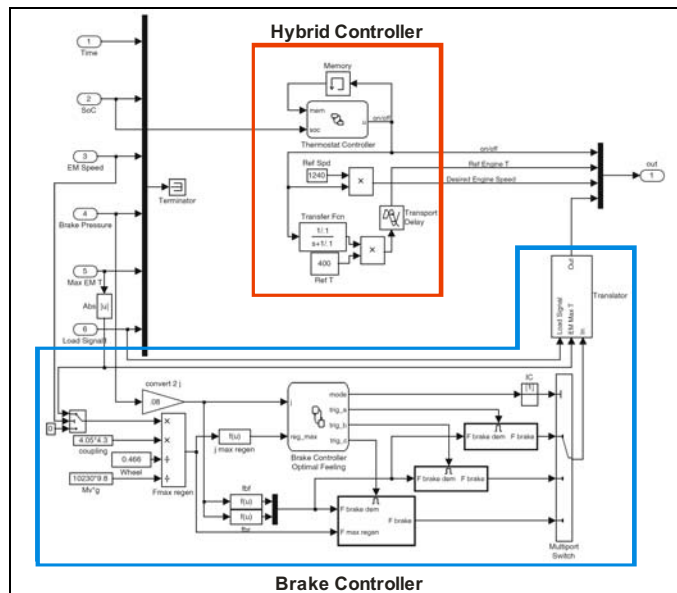
Figure 6: Central controller

There are to main parts in this controller, hybrid controller and brake controller that make the central controller of hybrid drive train together. Operation of hybrid controller is described in a separate paper which will be presented in the same conference. Three different central controllers have been developed and figures 7 to 9 show their output values versus percent of brake pedal travel which varies linearly from zero to 100 for the mentioned brake strategies.
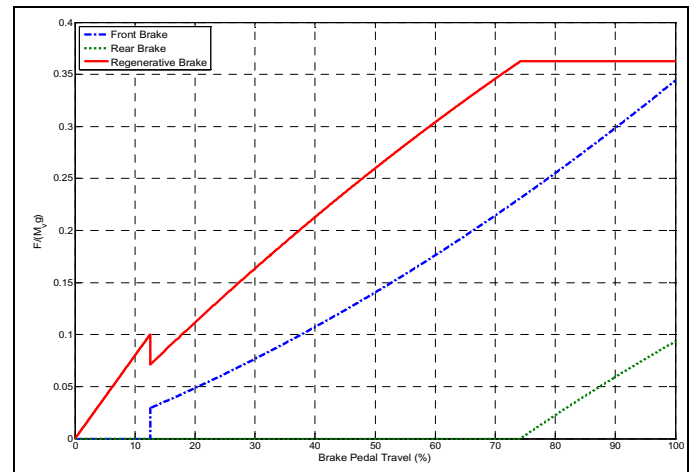

Figure 7: Distribution of braking force in series-optimal feel brake strategy
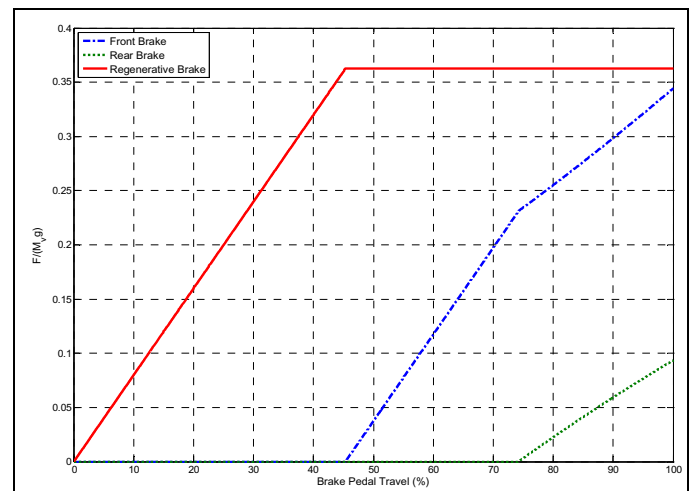

Figure 8: Distribution of braking force in series-optimal energy recovery brake strategy
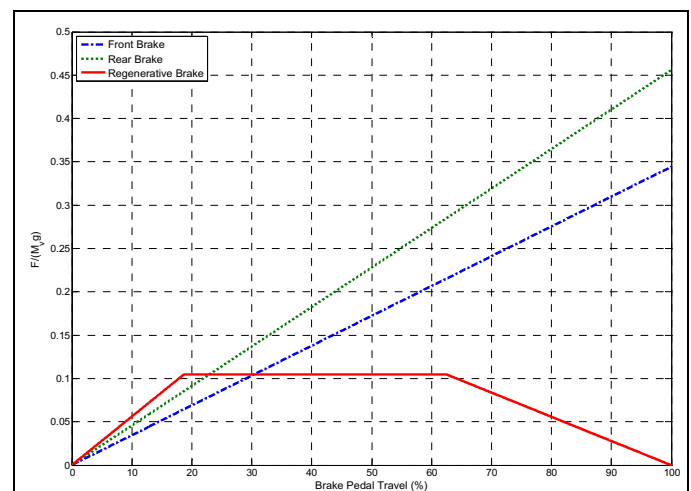

Figure 9: Distribution of braking force in parallel brake strategy

As seen in the Figure 7 and Figure 8, the value of regenerative braking force in optimal energy recovery strategy is more than in optimal feel strategy and consequently there is lower amount of force on the mechanical brake system. The value of regenerative braking force for parallel brake is less than the others

and so the mechanical brake system should bear more force in comparison with the former strategies.

To check the influence of developed brake controllers on fuel economy and braking performance, these controllers have been implemented in model of hybrid bus in Cruise Vehicle Simulation (Figure 10). Details of this modeling will be presented in the same conference in a separate paper.
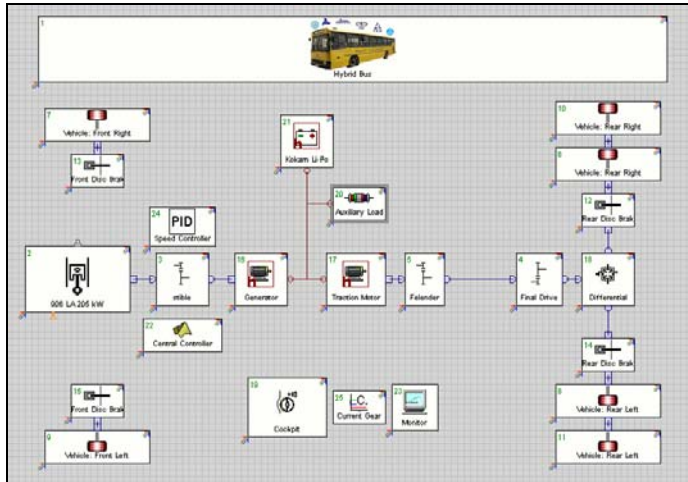

Figure 10: Model of hybrid bus in Cruise

Implemented controllers are converted to Dynamic Link Library file by use of Real-Time Workshop which is a tool of MATLB. Finally, the central controller has been integrated into the model by use of MATLAB Interface module of Cruise software. This model contains a vehicle module which stands for road loads and braking forces oriented from rolling resistance, drag force and grad force and brake modules which are capable of modeling different brake systems.

RESULTS

To simulate the bus in Cruise a drive cycle should be employed to investigate the performance of each of braking systems and compare the performance and energy recovery of different regenerative braking systems. The employed drive cycle is Nuremberg R36 city bus drive cycle. It is a European standard drive cycle and has lots of start and stop conditions, so it can distinct the ability of each brake strategy. The velocity profiles of Nuremburg drive cycle is illustrated in Figure 11.

Figures 12 to 14 present the total mechanical energy that is transferred to wheels from electric motor versus time when the vehicle passes the drive cycle and also the mechanical energy that is transferred to electric motor from wheels when it brakes for RBS with optimal feel, optimal energy recovery, and parallel brake, respectively.

The output mechanical energy follows the drive cycle and it is the same for all the strategies and is equal to 15966.8 kJ. But the input mechanical energy that electric

motor draws from the wheels depends on the strategies. The total input energy for the optimal feel strategy is 7932.9 kJ. This value for optimal energy recovery and parallel brake is 8626.2 kJ and 3710.4 kJ, respectively. It means that 50%, 54% and 23% of the output energy that leaves the electric motor can be recaptured for these braking strategies, respectively. As it can be seen this value for all the strategies is really considerable and the best result is for optimal energy recovery.
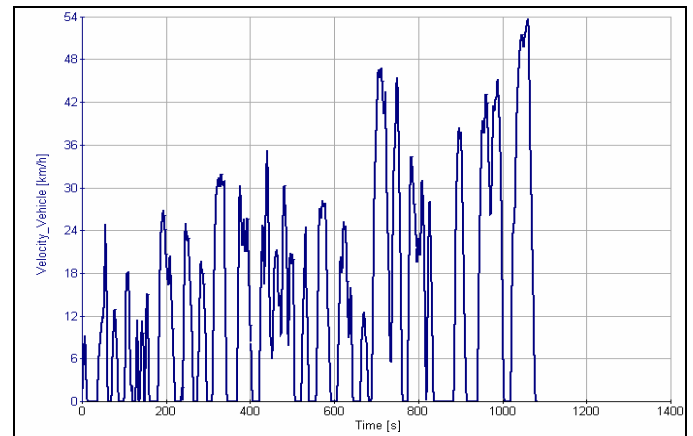

Figure 11: The velocity profile of NuremburgR36 drive cycle

In fact, the input mechanical energy that enters the electric motors is not equal to real value that saves in batteries because of electric motor, inverter and battery charging efficiencies. Considering these values leads to real amount of energy saving that is presented in figures 15 to 17 for the mentioned braking strategies, correspondingly. The overall output electric energy from batteries is the same for all the strategies and equals to 19580.5 kJ. To ensure that the amount of batteries output and input energies are equivalent to the electrical energy received by electric motors, simulations where performed in pure electric operation of vehicle to avoid the probable conflict with produced energy from diesel generator. The overall saved energy for the optimal feel strategy is 6092.6 kJ. This value for optimal energy recovery and parallel brake is 6669.5 and 2607.2, respectively. It means that 31%, 34% and 14% of the output electric energy can be recaptured for these braking strategies, respectively. As it can be seen this value for all the strategies is still considerable.
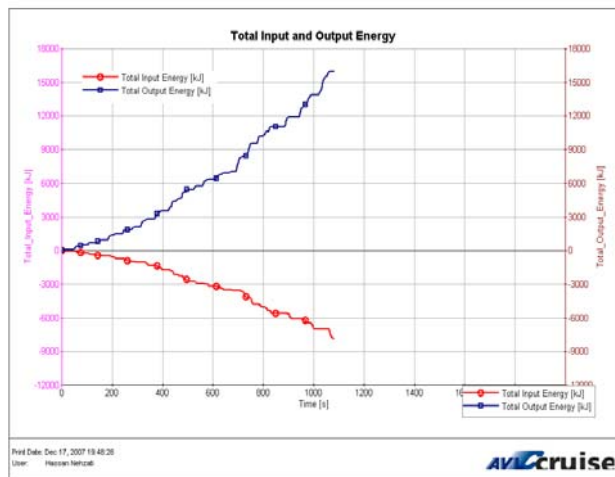
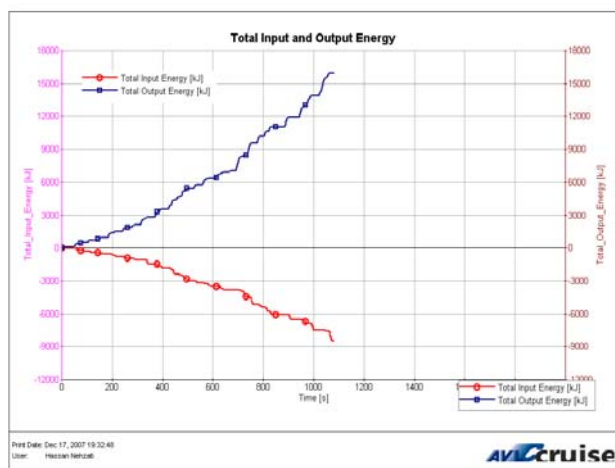Figure 12: Electric motor input and output mechanical energy for optimal feel strategy

Figure 13: Electric motor input and output mechanical energy for optimal energy recovery strategy
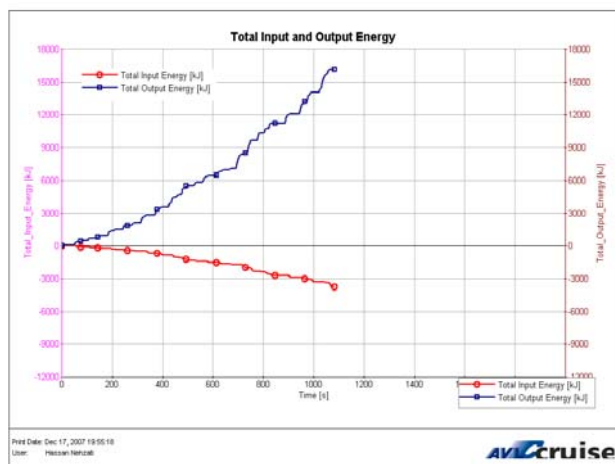

Figure 14: Electric motor input and output mechanical energy for parallel brake strategy
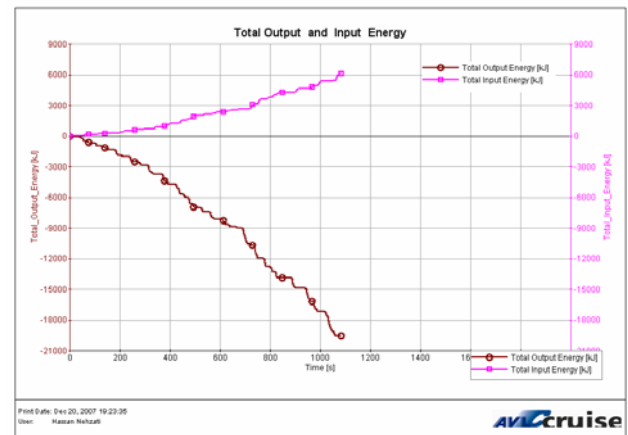

Figure 15: Overall input and output electric energy for optimal feel strategy

Figures 18 and 19 present the total mechanical energy entered the electric motor and total energy saved in batteries for the mentioned braking strategies for better comparison. All of the presented results are for empty bus. In order to study the effect of weight, the amount of saved energy in batteries for the braking strategies are presented for full load vehicle in Figure 20. As it is shown in this figure the trends are the same. The overall output energy for this case is 34209.5 and the total saved energy in batteries for the optimal feel, optimal energy recovery and parallel brake strategies is 10191.3, 12483.8, and 5029.9, respectively. It means that for full vehicle the amount of recaptured energy is equal to 30%, 36% and 15% of overall output electric energy for these braking strategies, correspondingly. The results for full vehicle are similar to empty vehicle to some how. The difference between two first strategies is more noticeable for this case, because for full vehicle the braking torque demand from electric motor is more and the optimal energy recovery can recapture more energy.
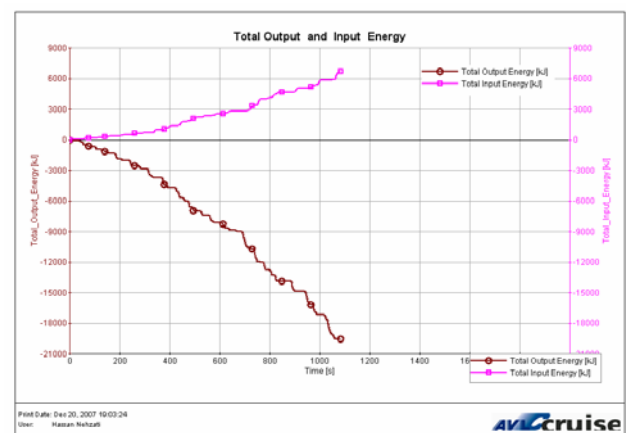

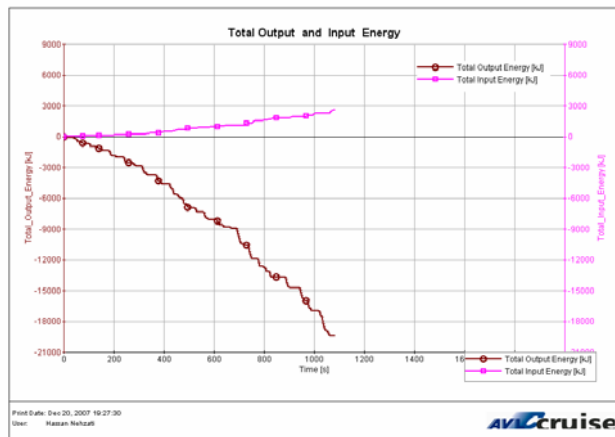Figure 16: Overall input and output electric energy for for optimal energy recovery strategy

Figure 17: Overall input and output electric energy for for parallel brake strategy

Figure 18: Input energy of Electric motor for the mentioned braking strategies

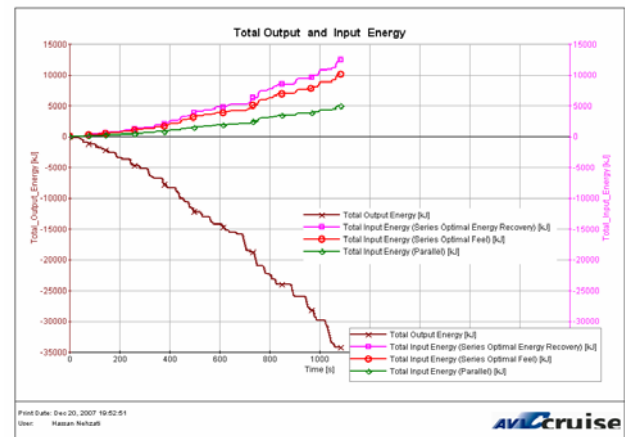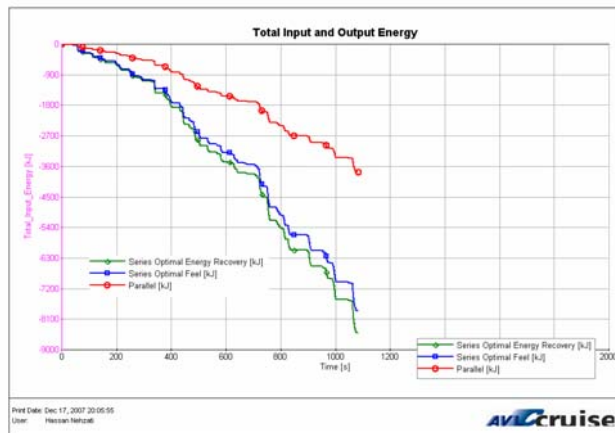Figure 19: Overall saved energy in to the batteries for the mentioned braking strategy

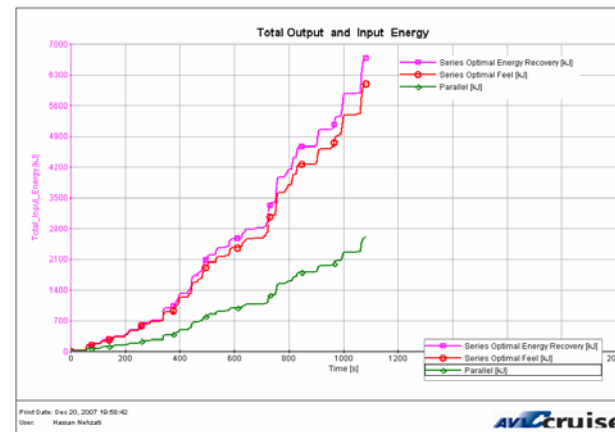Figure 20: Overall electric out put energy and saved energy in to the batteries for the mentioned braking strategy in full vehicle case

The fuel consumption for these strategies in Nuremberg drive cycles are 30.3 litre/100km, 29.55 litre/100km and 36.17 litre/100km for optimal feeling, optimal energy recovery and parallel brake strategy in empty bus case, correspondingly. This value for conventional bus is 45.01 litre/100km and for hybrid bus with a simple thermostat control strategy without RBS is 39.5 litre/100km resulting into 12.2% improvement. Details of the conventional bus simulation are described in another paper presented at the same conference. It means that the fuel consumption improves 32.7%, 34.3% and 19.6% for these strategies, respectively. It shows that in such a start-stop drive cycle how much the braking strategy is important in improvement of fuel economy with about 20% due to the RBS. The results for both optimal feel and optimal energy recovery are similar to some extend. It happens because the braking deceleration in most of the drive cycles is usually less than 0.1g and it leads to have the same performance for the both braking strategy. If the drive cycle has higher braking deceleration the difference between these two strategies can become significant.

In order to evaluate the performance of these braking strategies a deceleration test with same pedal force (50%) is performed. In this case, the vehicle brakes from its maximum speed, 85 km/h, and the amount of saved energy, the time, distance and deceleration curve and some other outputs are evaluated.

Figures 21 to 23 present distance, velocity and deceleration curves for each strategy. With the same pedal force the parallel brake makes the vehicle stop sooner because both mechanical and regenerative braking systems operate simultaneously. The results for electric motor torque, speed and mechanical input power during braking are shown in figures 24 to 26 for the different braking strategies. It can be seen that for the optimal energy braking the input power and the related torque of electric motor is more than the others leading to more energy saving. In Figure 27 the amount of energy saved in the batteries for the mentioned braking strategies are compared during braking from 85 km/h to stop condition. In this case the overall kinetic energy of

bus, $mv^2/2$, is equal to 2851 kJ. Figure 27 shows that in series optimal feel, series optimal energy recovery and parallel brake strategies 1018 kJ, 1090 kJ and 527 kJ of this energy can be saved, respectively. These values are equal to 35%, 38%, and 18% of the total kinetic energy of the vehicle. In fact, the deceleration of such a braking is high and in all strategies the mechanical braking is operating. If instead of deceleration about 0.4 g we have a value around 0.2 g, the percentage of saved energy will increase significantly because the mechanical braking system can not dissipate such a large value of kinetic energy.

Finally, for better understanding the value of SoC rise for this test in different control strategies are compared together. If the initial SoC at the start of braking process is equal to 55%, after vehicle stop this value will increase to 55.94%, 56.01% and 55.49% for the mentioned braking strategies, respectively. These results are illustrated in Figure 28.
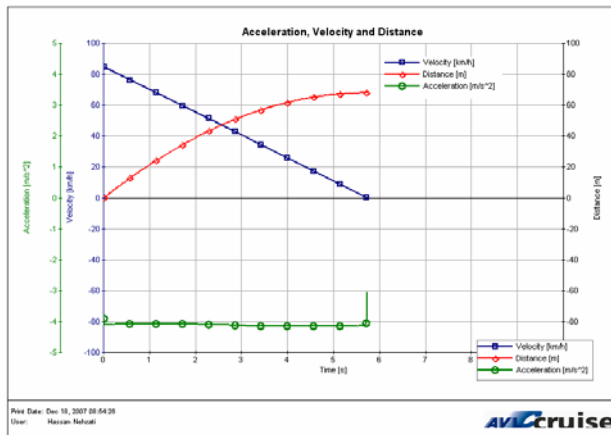

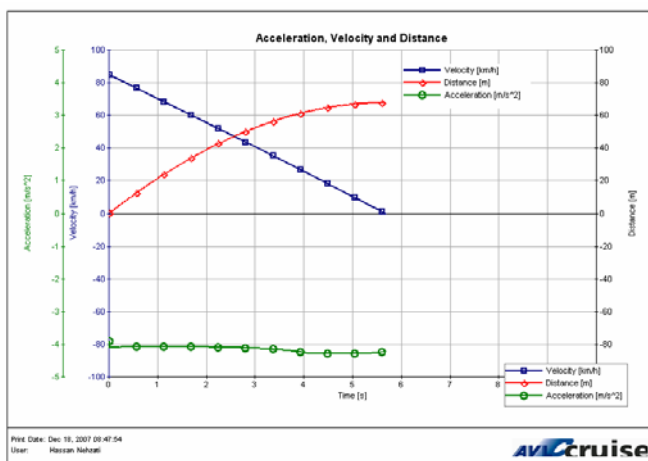Figure 21: Distance, velocity and acceleration curves for optimal feel brake strategy

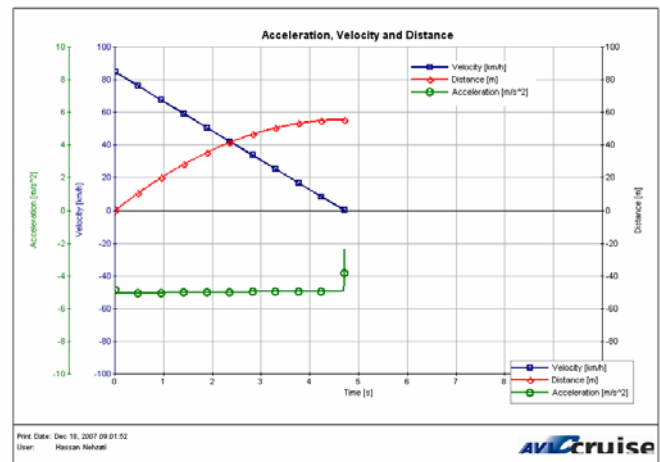Figure 22: Distance, velocity and acceleration curves for optimal energy recovery brake strategy

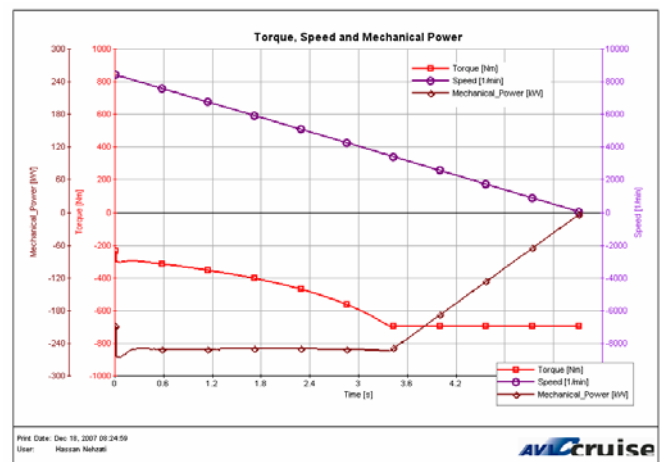Figure 23: Distance, velocity and acceleration curves for paralel brake strategy

Figure 24 Electric motor Torque, Speed and mechanical power curves for optimal feel brake strategy
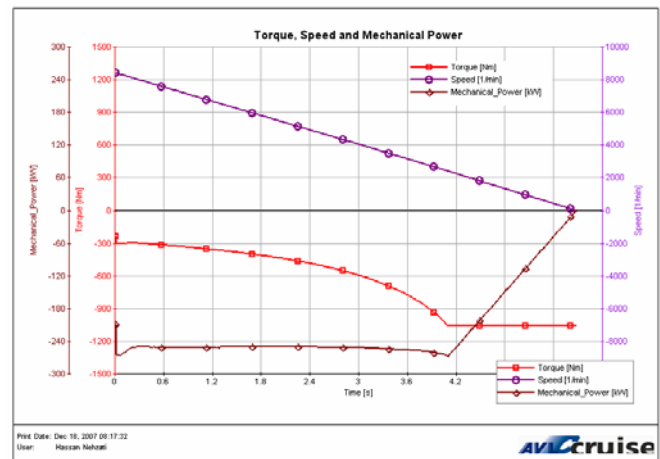

Figure 25: Electric motor Torque, Speed and mechanical power curves for optimal energy recovery brake strategy
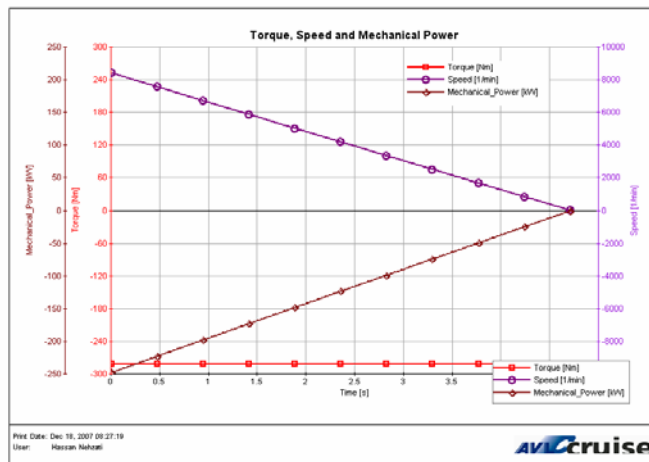
Figure 26: Electric motor Torque, Speed and mechanical power curves for parallel brake strategy
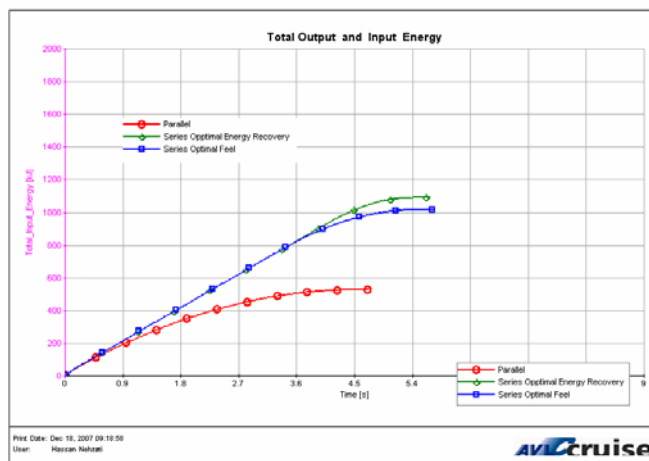

Figure 27: Total energy saved in batteries for all braking strategies in braking from maximum speed to zero
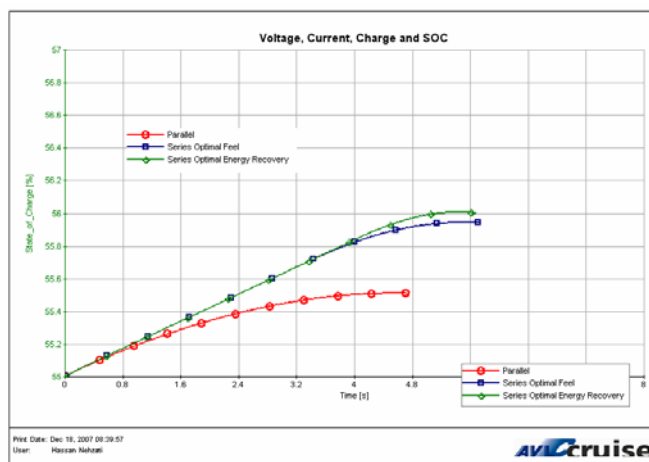

Figure 28: Batteries SoC rise for all braking strategies in braking from maximum speed to zero

It can be understood from the results of SoC changes during the constant deceleration braking test that in low velocities (large time), the change in SoC is very small due to low efficiency of electric motor. This is because the regenerated energy is very small even with the sufficient braking torque. Summery of improvement made on fuel economy is shown in Table 2.

Table 2: Summery of improvement made on fuel economy in NuremburgR36 drive cycle

Type	Consumption (L/100km)	Improvement (%)
Conventional	45.01	-
Hybrid without RBS	39.5	12.2%
Series braking with optimal braking feel	30.3	32.7%
Series braking with optimal energy recovery	29.55	34.3%
Parallel	36.17	19.6%

CONCLUSION

At first, an explanation about the hybridization advantage and some descriptions about the used structure for the hybrid bus are presented. Then the different braking strategies for regenerative braking system in hybrid vehicles are described. By simulating the bus with these braking strategies in AVL/Cruise the energy saving and the related fuel saving are evaluated for each strategies. It is observed that in a drive cycle like Nuremberg using these strategies leads to recapturing 30%, 36% and 15% of overall output electric energy, correspondingly. These amounts of energy saving in addition to other advantage of hybridization provide an improvement of 32.7%, 34.3% and 19.6% in fuel economy for these strategies related to conventional bus, respectively. It shows that in such a start-stop drive cycle how much the braking strategy is important in order to fuel economy improvement

The braking performance of the bus for all strategies is evaluated and it is concluded that it is considerably fine for all RBS strategies. During braking not only the safety of bus and braking performance are improved because of employing an extra braking system but also a considerable part of the kinetic energy recaptured in the batteries for future use instead of dissipation in mechanical braking system.

In addition, the capability of the Cruise software package in designing hybrid vehicles and analyzing the employed braking strategy is shown. The Cruise software provides valuable assistance to vehicle designers and significant understanding to researchers in the field of hybrid vehicles.

Finally, it can be concluded that the employed braking strategy has strong effect on both fuel economy and performance of the hybridized vehicle.

ACKNOWLEDGMENTS

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