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Development and Use of a Regenerative Braking Model for a Parallel Hybrid Electric Vehicle

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ABSTRACT

A regenerative braking model for a parallel Hybrid Electric Vehicle (HEV) is developed in this work. This model computes the line and pad pressures for the front and rear brakes, the amount of generator use depending on the state of deceleration (i.e. the brake pedal position), and includes a wheel lock-up avoidance algorithm. The regenerative braking model has been developed in the symbolic programming environment of MATLAB/ SIMULINK/STATEFLOW for downloadability to an actual HEV's control system. The regenerative braking model has been incorporated in NREL's HEV system simulation called ADVISOR. Code modules that have been changed to implement the new regenerative model are described. Resulting outputs are compared to the baseline regenerative braking model in the parent code. The behavior of the HEV system (battery state of charge, overall fuel economy, and emissions characteristics) with the baseline and the proposed regenerative braking strategy are first compared. Subsequently, a series of parametric studies are conducted with the proposed model to illustrate the tradeoffs involved in HEV component sizing with and without using regenerative braking.

INTRODUCTION

The need for a more fuel-efficient and environmentally conscious means of transportation is receiving increased attention in the automotive industry, in response to environmental, political and socioeconomic pressures. In this context, the HEV has emerged as a credible alternative to conventional vehicles which are solely propelled by Internal Combustion Engines (ICE). The HEV premise lies in that it incorporates the benefits of two or more power units that jointly supply the necessary performance requirements at their own complementary zones of maximum efficiency and/or minimum emissions levels.

In a broad sense, HEV designers are investigating practical combinations of electric motors, charge storage devices, and fuel energy converters, such as the ICE or the fuel cell. The power and cost density, reliability, acceptability and dominance of the ICE technology renders ICE power-assisted HEV's a natural next step in the pursuit of Zero Emission Vehicles (ZEV) [1]. The advanced, electronically-controlled diesel engine, in particular, is an attractive choice because of its higher overall thermal efficiencies, compared to the spark-ignition engine.

The (auxiliary) diesel engine can be coupled with an electric motor in a variety of configurations, e.g. series, parallel, or mixed, as described in detail in the open literature [2]. Proper matching of the diesel engine, the motor, and the battery pack, and proper modulation between the motor and engine power flows is crucial to minimizing emission levels, while simultaneously increasing overall vehicle fuel efficiency and performance. Preliminary simulation and field studies have indicated that this outcome is plausible, provided that sophisticated power electronics and control management strategies are employed [3][4].

Depending on the HEV configuration, vehicle fuel economy can be enhanced by up to 15% [5] through the application of regenerative braking (REGEN), a storage and retrieval capability for energy that would normally be wasted as heat during braking. Mechanical, hydro-mechanical, or electro-magnetic means such as flywheels, pressure reservoirs linked with hydro-mechanical machines, or generators that recharge batteries have been considered to accomplish REGEN goals [6]. Though flywheels have been used in buses, their higher space demands make them less attractive for passenger car applications. While hydro-mechanical motors have higher efficiencies to drive the wheels than

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electric motors, in their pumping/storage mode they are significantly less efficient than batteries. Consequently, generator-battery REGEN technology is the most promising option for mid-sized HEV's, such as passenger cars that are the subject of the present investigation.

Several research institutions, e.g. [7][8] are presently investigating how to optimize control strategies for ICE-assisted HEV's employing REGEN technology. Since HEV configurations and project missions are vast in scope, no universal REGEN strategy can be developed that would be optimum for all applications. Instead, the increased system complexity associated with REGEN HEV's has produced a need for simulation tools that would enable researchers to quantify and optimize potential REGEN benefits. Such software tools include proprietary packages at automotive companies and readily available, public domain HEV codes, such as ADVISOR [9], developed at the National Renewable Energy Laboratory (NREL) in MATLAB-SIMULINK. While many of these tools incorporate provisions for simulating the impact of REGEN on vehicle fuel economy, the employed REGEN strategies are often generic and not optimized for constraints imposed when actually implementing them in a production HEV. Consequently, estimates of fuel economy gains resulting from REGEN application may have been somewhat unrealistic.

The present study introduces a physics-based REGEN simulation for a diesel-assisted HEV which also takes advantage of graphical, symbolic simulation tools available in the MATLAB-SIMULINK-STATEFLOW. Our model is capable of dealing with REGEN issues every time braking occurs, while in normal, emergency, or driving in reverse mode. Next, it incorporates features to prevent wheel locked-up in all three cases. The incorporation of these provisions would allow HEV designers to realistically predict fuel economy and emissions improvements for parametric and optimization studies. Furthermore, the model's implementation in MATLAB-SIMULINK-STATEFLOW makes it compatible with popular HEV simulations and, at the same time, it makes the strategy readily downloadable to the electronic control modules of actual HEV's.

For demonstration purposes, our REGEN model has been implemented in ADVISOR [10][11]. Therefore, this paper first briefly describes ADVISOR, the generic, regenerative braking strategy available in ADVISOR, and the necessary steps that must be taken in order to implement other strategies. Then, the physics behind the proposed REGEN model and its incorporation within the ADVISOR framework are presented. Finally, case studies have been performed to demonstrate the enhancements added by the new model to more realistically quantify fuel economy benefits in representative driving cycles.

ADVISOR: A BRIEF DESCRIPTION

ADVISOR is a MATLAB/SIMULINK-based, feed-backward simulation for HEV powertrains. A schematic of the top level of the SIMULINK model is shown in Figure 1. ADVISOR allows quick analysis of the performance, emissions, and fuel economy of conventional, electric, and hybrid vehicles. The component models in ADVISOR are empirical, relying on input/output relations measured in the laboratory, and quasi-static, using data collected in steady state tests and correcting them for transient effects, such as the rotational inertia of drivetrain components. ADVISOR allows the designer much versatility in changing many of the models found within it.

Each block in Figure 1 represents a component of the calculation that determines vehicle fuel economy and performance metrics for a specified driving cycle. The block diagram starts on the far left with data regarding the actual cycle through which the vehicle is to be driven. Next, vehicle velocity is passed to a load-calculating block that finds the total load on the vehicle (including inertial, aerodynamic and rolling resistance). Then, the proceeding blocks calculate the loads and speeds that the engine and motor must output in order to accelerate the vehicle to the required vehicle speed.

The ADVISOR simulation style is called feed-backward since the flow of control begins with the torque required at the tire and ends at the fuel flow rate required by the engine. In real life, a vehicle operator has control of the fuel pedal and varies its position in order to get the required torque to achieve a desired speed.

ADVISOR: REGENERATIVE BRAKING MODEL

The regenerative braking control strategy used within ADVISOR is not centrally located within a single SIMULINK block. This lack in modularity makes it very difficult for the REGEN system designer to thoroughly investigate the strategy or to even apply it to other vehicle simulators. Several key parameters found in ADVISOR's input files will be discussed.

The major subsystem dealing with this control strategy is found within the 'vehicle controls' module. Look-up tables that are used to determine the amount of generator force available during a regenerative braking event are found in the 'braking strategy' block within the 'vehicle controls' module above. These look-up tables are valid for one specific vehicle size, and are only intended for preliminary estimates. They should be adjusted accordingly for the particular system configuration investigated by the designer since a valid scaling procedure does not exist.

A typical look-up table yielding the distribution between the brake forces supplied by the front and rear frictional brakes and the generator is shown in Figure 2 below.

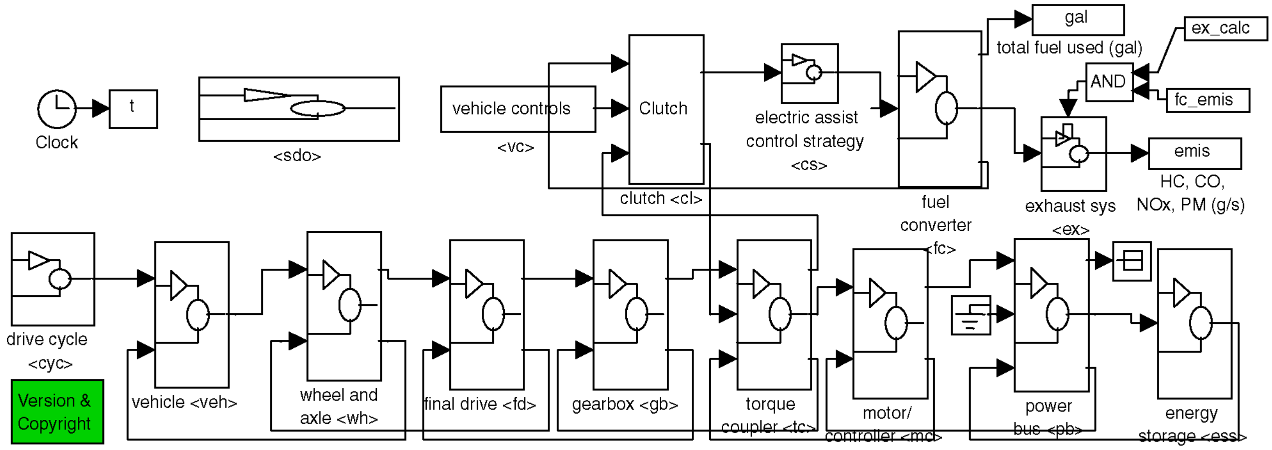


Figure 1.   SIMULINK block diagram schematic of ADVISOR

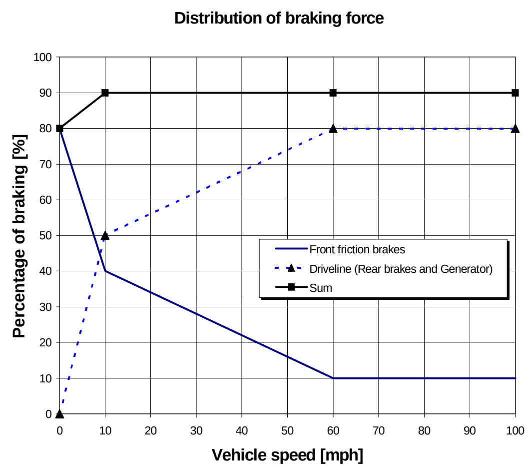


Figure 2.   Brake proportioning diagram.

The balance of braking is performed by other vehicle resistances (aerodynamics[4], inertial losses, rolling resistance, etc.). Note that the generator and rear brakes supply nearly 80% of the braking system's requirement at high vehicle speeds. The reasoning behind this strategy is that higher generator torque is necessary for braking at higher speeds, which conveniently allows for higher battery charging efficiencies. At lower speeds, relatively little current is being produced by the generator to ensure desirable battery recharge efficiencies. Therefore, at these speeds, the frictional brakes are applied to decrease electrical cycling through the generator and batteries. It has been implied in the literature that the life of the electrical system, especially the batteries, is adversely affected by this 'micro-cycling' process [13].

Because limited data have been collected regarding deep discharging of different types of batteries, it has also been suggested that battery life would be lengthened only if this load leveling device (LLD) be used as a buffer for engine power. Brake designers must understand the role of regenerative braking in overall system behavior in order to guarantee individual component life. In this manner, ADVISOR is equipped with charging and discharging resistance curves used when calculating generator current to the batteries, which can be used by the designer to constrain the battery SOC to be cycled within acceptable limits.

Though the user may define a more accurate brake proportioning look-up table, physics-based calculations are unavailable in ADVISOR for these quantities, and are necessary for detailed analyses of braking system kinematics. Analytical methods must be implemented to allow the designer more accurate distribution of the forces involved in braking and energy conversion. In addition, a technique which would allow for feed-forward brake pedal signals is necessary. Thus, the hope is to increase fuel efficiency, decrease emissions levels, and to minimize the cycle discharge depths and frequencies of the battery. A new model must be developed which accomplishes all these goals and is easily downloadable to a real vehicle.

PROPOSED REGENERATIVE BRAKING MODEL: BASIC CONCEPTS

The proposed regenerative braking model was written to aggressively retrieve and store as much available vehicle kinetic energy as possible. At the onset of this project, the research was focused on two main objectives. First, to provide a high fidelity, feed-forward, modular braking simulation that could be used in conjunction with ADVISOR for online testing and prediction. And second, to build a capability into the simulation which would allow the control strategy to be downloaded directly to a driven vehicle.

In order to prevent errors between ADVISOR and the new control strategy interface, the pertinent variables within the former were extracted. Also, the outputs resulting from ADVISOR's braking model had to be suppressed. For the model to be downloadable to a vehicle, it not only had to be programmed within MATLAB/STATELOW, but it also had to be a feed-forward simulation, contrary to the way ADVISOR operates. The blocks affected by these

4. Extensive simulation and experimental studies have shown that aerodynamic drag alone can constitute up to 50-75% of the total (non-braking system) retarding forces on a vehicle, especially for current production vehicles at high speeds (C_d's ~ 0.3, speeds ~ 70 mph) [12]. Practical retrieval of this energy is impossible.

changes, as well as the associated variable names, have been highlighted in Figure 3.

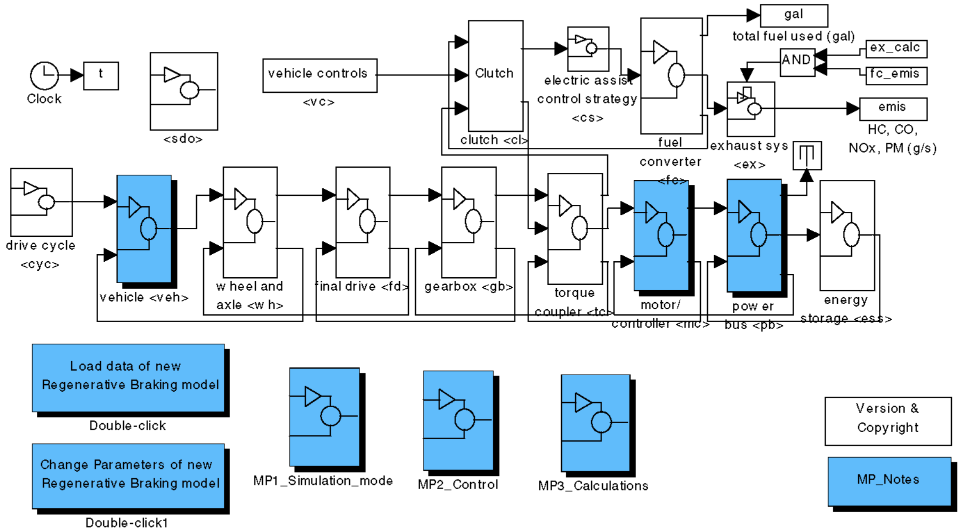


Figure 3. Highlighted blocks that were modified for the new braking model.

The control strategy of the new model produces as much regenerative braking from the generator as is physically possible. In that manner, the average battery SOC is kept at a higher level than with previous strategies. In order to produce this REGEN power, the brake controller verifies that the generator can supply all the brake force necessary for deceleration at the front brakes. If so, the generator provides the retarding force with a constant proportioning with the rear brakes to prevent lock-up. Otherwise, the additional required braking force is supplied by the frictional brakes (both front and rear, if necessary).

Note that provisions have been made within the simulation to prevent the current through the power electronics and the batteries to reach dangerous levels. Such instances occur during emergency stop situations, which can also be handled by the new model. In this case, the brake pedal acceleration is picked up by a sensor and, if it is above a certain threshold, only the frictional brakes are used.

In order to allow for longer component life and more efficient use of the batteries, a brake designer need only vary the look-up table parameters in Figure 2, run the simulation, and analyze these results. This procedure readily lends itself to incorporation within an optimization framework. However, these parameters cannot be chosen arbitrarily; the user must have experimental results. If these data do not exist, a model must be devised which would accurately predict brake forces and generator power. An appropriate model based on first principles will allow the designer to rely less on experimental data.

A wheel lock-up avoidance algorithm has been implemented along with a braking strategy for the relatively few times that the vehicle actually drives in reverse. These provisions were made for use by the experimental vehicle. The computations and flow of signal control will be discussed after the physical relations behind this new model are described.

MATHEMATICAL MODEL DESCRIPTION

A vehicle that is being modeled within ADVISOR is typically run through a particular driving cycle. The prescribed driving schedule is representative of the vehicle use proposed by the project mission. In this work, the Federal Urban Driving Schedule (FUDS) has been chosen because of the relatively high regenerative currents possible through harder braking, contrary to its highway cycle counterpart. This schedule is shown in Figure 4 below. Studies in the past suggest that an HEV's range for in-city driving can be extended between 14 and 40% by using REGEN [14]. The user must define an industry standard or an arbitrary velocity trace that most closely resembles the driving pattern being investigated.

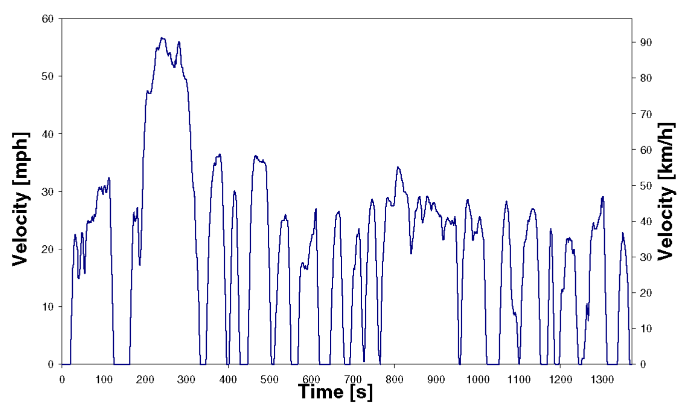


Figure 4. Federal Urban Driving Schedule velocity trace.

At each time step of operation, the new brake controller determines whether a brake event is occurring. In actuality, a linear potentiometer at the brake pedal receives a digitized signal, which is subsequently sent to the controller. When this pedal position is received by the ECU, it is correlated to a braking force for the front wheels. Next, this force is converted to an appropriate brake line pressure, which is used for brake master cylinder actuation, or an appropriate generator use state if the motor is to used for braking.

The equations for the static and dynamic loading on the wheels can be found in any textbook on vehicle dynamics [15], and are thus briefly summarized below. These equations do not include wind and driveline drag or rolling resistance losses because these forces were already calculated in other modules within ADVISOR, and linked to the new regenerative module.

BRAKE FORCES AND GENERATOR CURRENT

The degree of deceleration experienced by the vehicle must first be determined. This quantity is calculated from the velocity (v) of the current (f) and previous (i) time step in the velocity trace, where t represents the time interval. Please refer to the nomenclature section at the end of this paper for variable definitions.

$$D_x = \frac{v_i - v_f}{\Delta t} \tag{1}$$

From Newton's Second Law, we find the force necessary at the wheels:

$$F_x = D_x M \tag{2}$$

where D_x is the deceleration, F_x is the total of all longitudinal retarding forces on the vehicle, and M is the gross vehicle mass.

Next, the dynamic loading on the front and rear axles is found. W represents the weights at the front (f) and rear (r) axles, as well as the static (s) and dynamic (d) loads present there.

$$W_f = \frac{c}{L}W + \frac{h}{L}\frac{W}{g}D_x = W_{fs} + W_d \tag{3}$$

$$W_r = \frac{b}{L}W + \frac{h}{L}\frac{W}{g}D_x = W_{rs} - W_d \tag{4}$$

$$W_d = \frac{h}{l}\frac{W}{g}D_x \tag{5}$$

and:

$$b = L - c \tag{6}$$

where L is the vehicle wheelbase and c is the distance from the front axle to the center of gravity. Likewise, b is the distance from the center of gravity to the rear axle. From these equations, we find the maximum brake force on each axle as follows:

$$F_{mf} = \mu_p W_f = \mu_p (W_{fs} + \frac{h}{L}\frac{W}{g}D_x) \tag{7}$$

$$F_{mr} = \mu_p W_r = \mu_p (W_{rs} + \frac{h}{L}\frac{W}{g}D_x) \tag{8}$$

Here, g is the gravitational constant, 9.81 m/s^2, and μ_p is the peak coefficient of friction at the tire contact patch. The brake ratio between these forces is such that the deceleration of the vehicle is limited to approximately 0.6g's. Note that these are the maximum forces at the wheels, since μ_p is the peak frictional coefficient. A tire slip model is included in ADVISOR to calculate the actual forces seen at the tire contact patch.

Referring to Figure 5, we can continue to solve for the brake line pressures as follows:

$$F_{line} = pA \tag{9}$$

$$F_{disc} = \mu_{pad} F_{line} \tag{10}$$

$$F_{tire} r_w = F_{disc} r_{pad} \tag{11}$$

$$p = \frac{r_w c_{fac}}{\mu_{pad} A_{pist} r_{pad}} F_{tire} \tag{12}$$

and,

$$p_f = F_f \, fac_p \tag{13}$$

$$p_r = F_r \, fac_p \tag{14}$$

where

$$fac_p = \mu_{pad} A_{pist} r_{pad} \tag{15}$$

The brake line pressures are subsequently converted to voltages for use by the pedal controller:

$$ped_{pos} = \frac{p_f \, ped_{\max}}{p_{\max}} \tag{16}$$

where p_{max} is 21 MPa (3000 psi) in this case, and ped_{max} is between 0 and 5 volts. Here, the variable ped_{pos} is the voltage at the brake pedal that can be converted to an associated pedal position. In turn, this pedal position then becomes an input to the new REGEN strategy. This variable is the link between the feed-forward and feed-backward simulation styles.

The flow of control mentioned above is for the feed-backward simulation style. ADVISOR calculates the brake pedal position from the equations above and feeds those quantities into the new model. This process emulates a driver's response on the road. The new modules in ADVISOR have been written in a manner to allow the flow of control to occur once onboard the vehicle controller. The proposed REGEN strategy then calculates the generator power and braking forces exerted on the ground.

As was implied earlier, the generator is used to supply as much of the front brake force as possible. Any additional frontal force is produced by the front frictional brakes, if needed. At all braking instances, the rear brakes are activated in order to sustain traction and to prevent vehicle instability, as shown in any common brake-biasing diagram.

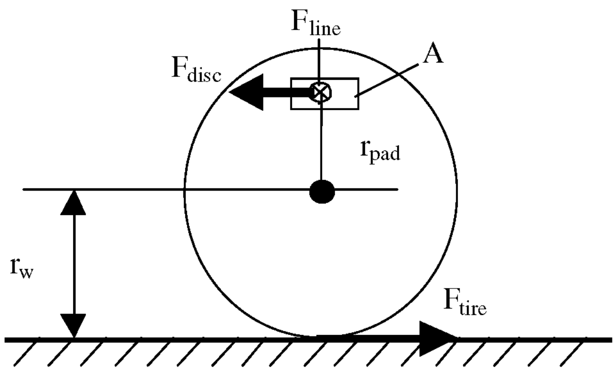


Figure 5. Schematic of braking model.

At this point, one must ascertain the amount of current produced by the generator during these braking events. The charge current (I) depends upon the generated power (P) and the bus voltage (U). A quadratic equation of the form:

$$PI^2 + UI + R = 0 \tag{17}$$

results, from which, the positive root is the charge current. The simplified equation for generator power is as follows:

$$P = F_{gen} v_{veh} \tag{18}$$

where the applied generator force is F_{gen} and the vehicle velocity (from the FUDS speed trace) is v_{veh}. From here, the power and current are sent to the ADVISOR module, which replenishes the battery SOC, while adhering to the recharge inefficiencies present in the LLD. The reverse mode and emergency braking conditions will not be described because they are not implemented during a FUDS cycle.

As indicated in the STATEFLOW block diagram in Figure 6, braking can be performed under four different modes on the front brakes. These modes include partial and full braking for the cases of mixed retarding sources as well as for individual sources. These modes are discussed in detail shortly.

BRAKING STATES

All braking events are categorized into only one of four basic states. The force requirements at the wheels, brake pads, and generator for a representative braking event in each state are illustrated in Figure 7. The relationships between these forces determine the level at which the generator and the frictional brakes contribute to the total retarding force. States 1 and 2 are for braking events requiring forces at the front wheels that are lower than the calculated wheel lock-up force. Conversely, States 3 and 4 deal with instances where wheel lock-up would occur if the required braking force at the front wheels were applied.

Each state in Figure 7 consists of four columns that depict the force distributions on the front brakes during the different types of braking events. The first column denotes the maximum generator force possible; the second refers to the force required at the wheels for the specified deceleration to occur; the third shows the braking force that, if applied, would cause wheel lock-up; the fourth indicates the maximum force delivered by the front frictional brakes during that state. Each state is detailed individually below.

STATE 1 – This state becomes active when neither the electric nor the hydraulic maximum braking forces can separately provide enough force to stop the vehicle. The maximum generator force is calculated and the balance is produced by the front frictional brakes.

STATE 2 – Here, the amount of maximum front braking force is less than the wheel lock-up limit and also less than that which the generator is capable of providing. Therefore, the generator delivers all of this force in this 'only-electric' case.

STATE 3 – When the required braking force for the front wheels reaches and/or exceeds a wheel lock-up scenario, either the generator alone supplies this force (when the maximum generator force is greater than the wheel lock-up force) or the generator and frictional brakes supply the retarding force (when the maximum generator force is less than the wheel lock-up limit).

STATE 4 – This case is also known as an 'only-electric' mode. Here, the maximum braking force required at the wheels is greater than the lock-up force, but smaller than the maximum generator force available. Therefore, a 'purely' electric braking event occurs.

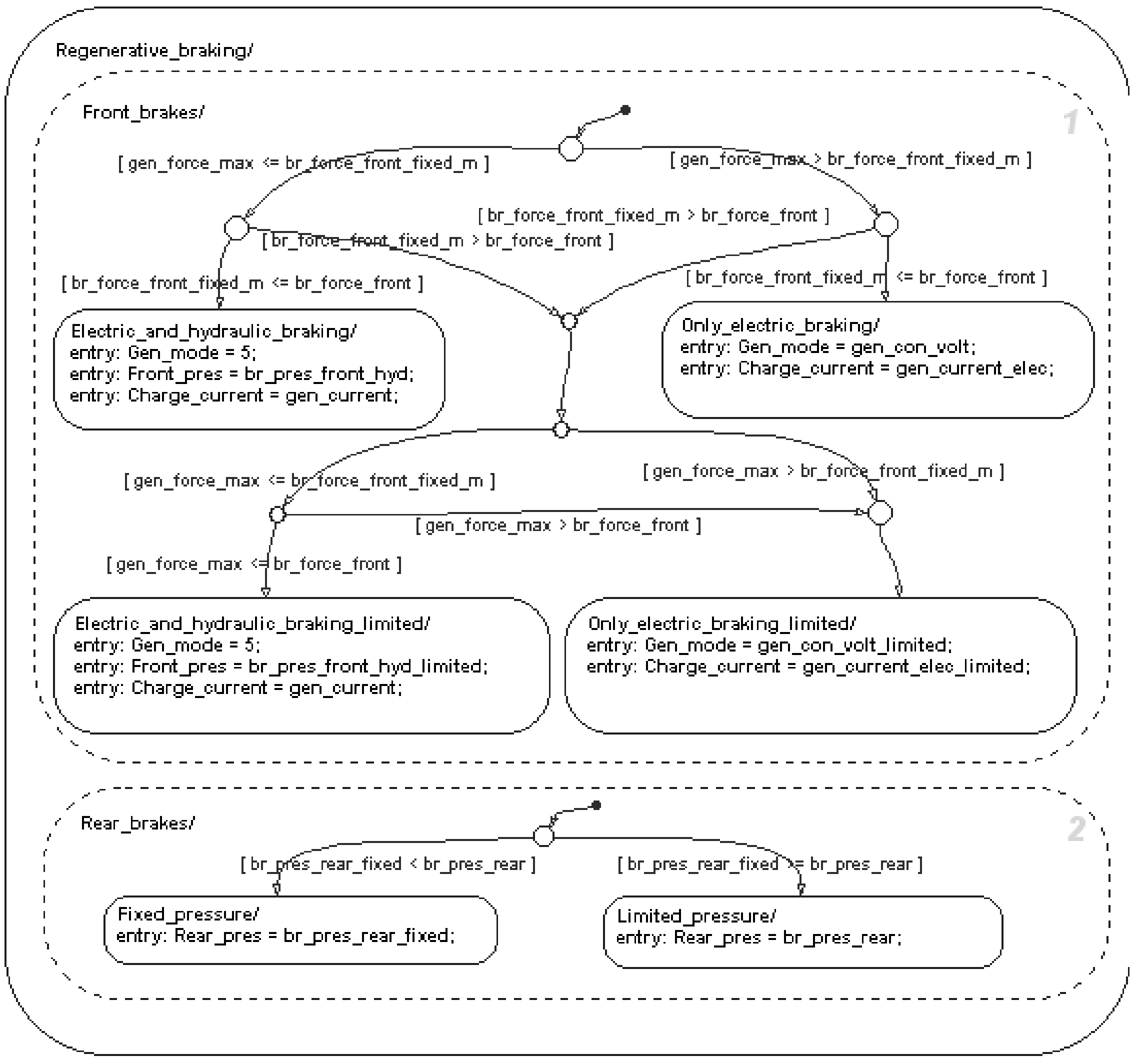


Figure 6. STATEFLOW schematic.

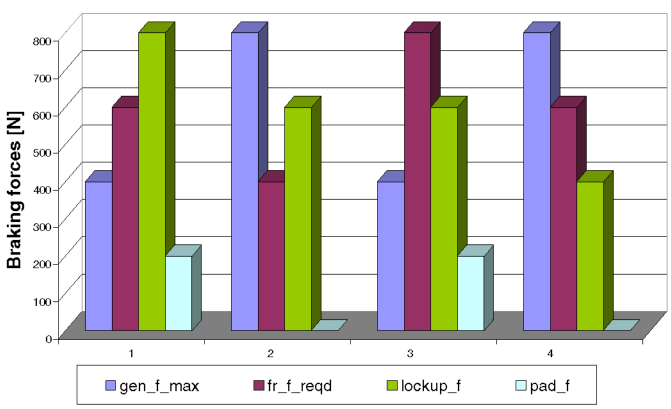


Figure 7. Representative braking force requirements and maximum system outputs for the four braking states on the front axle.

Note that the rear braking forces for the non-regenerative case, the ADVISOR model, and the proposed model are identical. Braking must occur in the rear to prevent wheel lock-up and vehicle instability.

COMPARISONS TO ADVISOR

Until recently, HEV system optimization has been performed mainly through parametric studies involving existing components [16]. Though scarce, optimization methodologies have been developed to provide the user with an added freedom to design virtual subsystems, including the motor, batteries, and/or engine [17][18][19].

The components, which were used in these studies, can be found in the ADVISOR library of components. Only the motor, batteries, and engine sizes were altered; primary specifications of each are given in Table 1(a-c). They represent components that are currently the most popular in diesel-based HEV's developed at the university level [20] [21]. Components that have been designed specifically for these vehicles have not been added to ADVISOR's library.[5]

All of the above combinations between motor, batteries, and engine were simulated for situations without regenerative braking, with ADVISOR's embedded

5. The ADVISOR component library only contains experimental data on a need-driven basis.

strategy, and with the new model. For brevity, only five configurations, which are representative of the different types of resulting outcomes, will be discussed in detail.

RESULTS AND DISCUSSION

Fuel economy predictions reported in Figure 8 clearly show that regenerative braking improves fuel economy in the FUDS cycle by 4%-19%, depending on the powertrain modules employed and the REGEN model used for the predictions. It appears that, regardless of the regenerative braking model used, the configurations with the smallest motor tend to yield lower improvements. Because the motor cannot produce enough torque on demand during braking, it thereby cannot provide adequate current to the batteries for recharging. In addition, the brake demand on the generator occurs at points of relatively low efficiency, a major factor which affects the performance of both models in the same fashion.

The highest benefit (an estimated 19% by the new REGEN strategy) occurs with the E2M3B3 component combination. Because this system has the largest motor and battery pack available, the 'pure electric' braking state is invoked more frequently, thereby recharging the batteries more often. Since the batteries are larger, they offer the motor a larger potential for charge acceptance.

Table 1. Description of various components used in parametric study.

Engine	E1	E2	E3
Displacement [l]	1.5	1.9	2.5
Power [kW]	37	67	88
Max.Torq.[Nm]	85	217	261
Mass [kg]	154	214	380
Efficiency [%]	34	39	42

(a)

Motor	M1	M2	M3
Power [kW]	25@ 1500rpm	75@ 3500rpm	83@ 11400rpm
Max.Torq.[Nm]	55	271	203
Max.current [A]	210	480	385
Min.voltage [V]	70	120	200
Mass [kg]	75	91	110
Peak eff.	90%	92%	94%

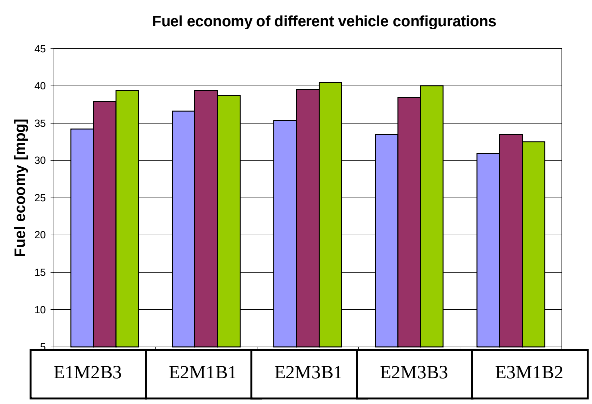
(b)

Battery	B1	B2	B3
# of modules	25	25	25
Voltage [V]	300	300	350
Capacity [kWh]	3.5	21.8	30.8
Mass [kg]	120	623	447

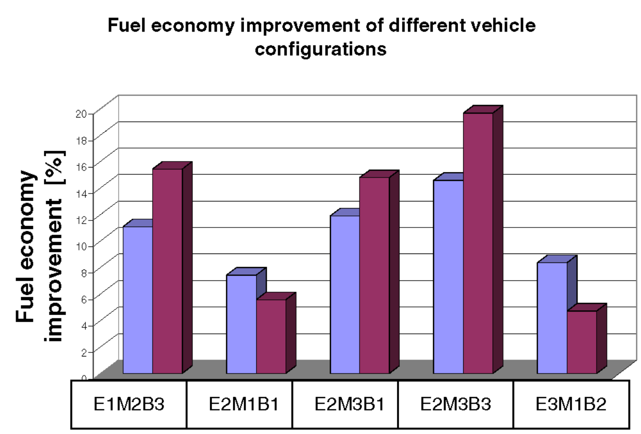
(c)

Though neither model was validated with an experimental vehicle under each baseline configuration, the correlation between results is encouraging. One must note that the control strategy in the new model has been downloaded to an experimental vehicle; validation of this model and comparison against ADVISOR's predictions will be a topic for future publication.

The new REGEN model systematically predicts improvements higher than those of ADVISOR for cases when the motor is relatively large. These trends can be attributed to the fact that the new REGEN strategy requires a larger motor for higher REGEN capability. This motor, in turn, requires a larger battery capacity for a proper match. Because this combination depends heavily on the electrical portion of the new model, it also possibly captures physical system aspects that become dominant in this case. When the hardware configurations contain smaller motors, the new model consistently predicts lower improvements than ADVISOR. This may be attributed to an overprediction on ADVISOR's part, as to possible generator power.



(a)



(b)

Figure 8. Fuel economy results (a) and percent difference (b) between braking models.

Emissions are also a critical performance metric for these vehicles. The only available emissions data within ADVISOR corresponded to a 1.9 liter VW engine (E2).

This engine was configured with motor and battery combinations that are typical of university prototypes. In Table 2, A refers to the non-regenerative case, B to the ADVISOR regenerative case, and C for the new model. It is apparent that either regenerative braking model predicts modest improvements in emissions ratings. Because these results are limited to only one engine, one can only deduce that proper component matching will further aid a designer in achieving, and surpassing, the ever-stringent emissions regulations for the future.

In general, the results above show that the new model performs comparably with those currently predicted by ADVISOR for HEV's with medium-sized motors. As was the case with fuel economy, one cannot necessarily depend on regenerative braking for better fuel and emissions characteristics when the motor size is mismatched with the vehicle. In other words, the motor has to be large enough to be able to provide for a significant percentage of the braking and it must be able to operate efficiently in the torque and speed range demanded by that strategy. While these predictions are similar in magnitude, it should be restated that the new model predictions are based on laws of motion rather than empirical look-up tables. Neverteheless, the ultimate test of the new model's higher expected fidelity is through experimentation.

Let us now review the predicted differences in battery SOC's for this cycle, shown in Figure 9. This graph plots the difference between the SOC histories of the ADVISOR regenerative braking model and the new model, for an HEV configuration consisting of an undersized motor and one with an appropriately sized motor. Again we see that motor and battery sizing and matching are crucial in the design of a REGEN system. Note that the largest discrepancies occur during hard decelerations in the FUDS cycle (the lowest valleys on the E3M1B2 plot). From this plot, we can conclude that the objective is to find a combination which would allow these histories to consistently stay over the SOC = 0 line.

Figure 10 shows the proportioning of braking forces which occur for the front and rear brakes and the generator during the FUDS cycle. The left-hand column (a) illustrates the usage fractions for a vehicle configuration incorporating a relatively small motor. Next, column (b), on the right, is for a case with a motor which is more appropriately matched to the rest of the system. We see that the motor in the former case (a) cannot supply the braking forces necessary, thereby allowing more front frictional braking. On the other hand, the motor in the latter configuration (b) is performing much of the front braking. Many instances where only the generator is used can be seen from this plot. As mentioned earlier, the rear braking usage curves would be identical for a configuration when regen is on or off.

Table 2. Emissions results from parametric studies

	Case	Subsystem Configuration		
		E2M1B1	**E2M3B1**	**E2M3B3**
HC [g/km]	A	0.199	0.200	0.199
	B	0.191	0.190	0.190
	C	0.194	0.186	0.185
CO [g/km]	A	0.707	0.691	0.731
	B	0.698	0.692	0.675
	C	0.709	0.684	0.649
NO_x [g/km]	A	0.879	0.940	1.109
	B	0.792	0.807	0.920
	C	0.818	0.769	0.861
PM [g/km]	A	0.069	0.072	0.081
	B	0.066	0.066	0.074
	C	0.067	0.065	0.071

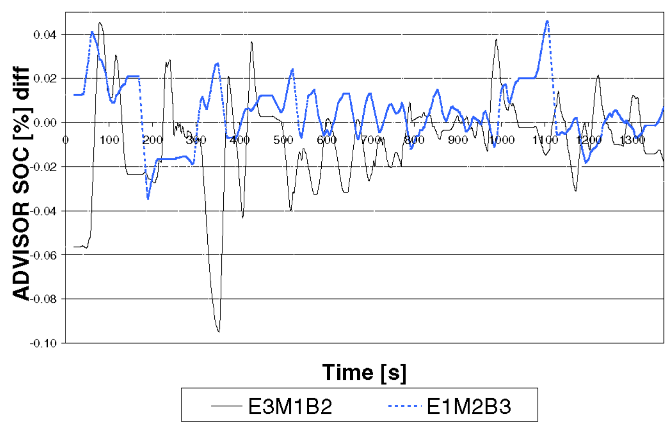


Figure 9. Percent difference of the SOC, with resepect to baseline vehicle during FUDS cycle.

The new model has been downloaded successfully to the experimental vehicle in the laboratory. Downloading was performed directly from STATEFLOW, on a laptop computer, to the vehicle ECU via a PC-based translator program. Validation and road testing is expected in the near future. On-road verification of these models is crucial in deteriming their real effectiveness.

CONCLUSIONS AND FUTURE WORK

A physics-based regenerative braking control strategy has been presented in this work for use in computer simulations and on-board HEV development. Simulation case study results for an HEV without regenerative braking, with a model present in the NREL simulator, ADVISOR, and a model proposed in this paper were contrasted. Fuel economy, emissions, and battery SOC results were compared for these three cases.

In general, the predictions between the ADVISOR and the new REGEN models were within 4% of each other. This illustrates a potential for improvement in fuel economy and emissions once implemented on a vehicle and validated. More importantly, the versatility that the new REGEN model offers the designer during the verification process is valuable. The user no longer needs experimental data in look-up tables that must be varied every time a new study is to be performed.

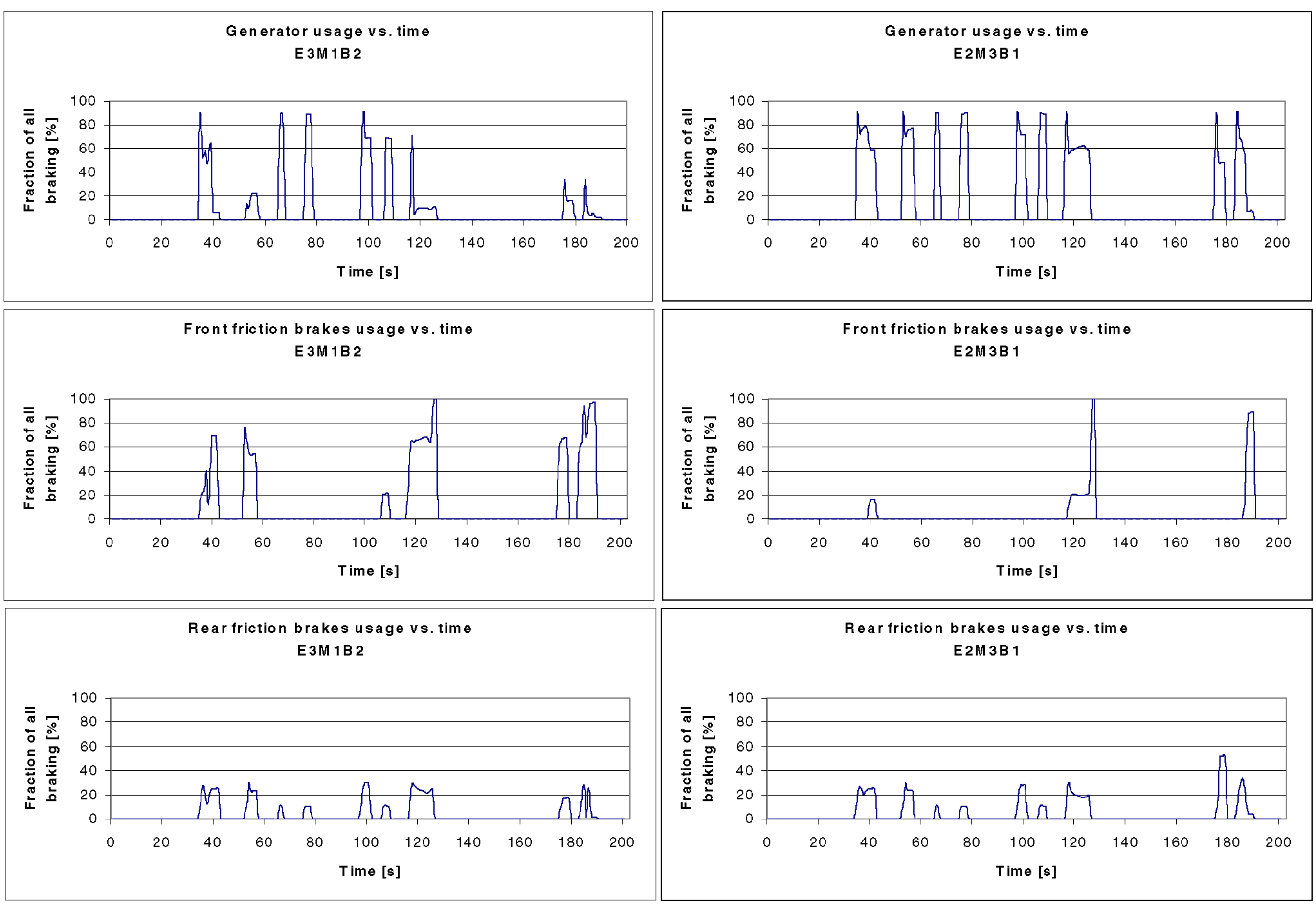
The proposed model not only has a different control strategy than ADVISOR's, but the fact that it is analytical also explains the contrasting outputs. Because of its aggressive treatment of the generator's available braking force, the new model depends on a relatively powerful motor that can supply the currents necessary for braking.

Though the empirical relations in ADVISOR closely resembled the physical models in the new strategy, deviations from real-life results may have occurred in both simulations. Therefore, the importance of validation and verification studies in the future cannot be overstressed.

A wheel lock-up prevention routine, as well as methods to treat reverse driving and emergency braking situations, has been included in the new code. These enhancements and added capabilities were not present in ADVISOR before this research was performed. Also, researchers using ADVISOR can now treat regenerative braking in a feed-forward manner, thereby predicting outputs from a driver's brake actions. The modularity of the new model adds a flexibility that can be used by an optimization engineer to study different controller and driving schedule scenarios.

Ongoing studies include the implementation of different driving cycles with more aggressive 'stop-and-go' schedules which would allow researchers to vary the models accordingly. In addition, various configurations and control strategies must be studied to understand the percentage of fuel economy savings attributable to this, and other, REGEN controllers. Finally, constraints must be developed and placed on the electrical component cycling events to ensure subsystem life. These limits are not available at this time, but should be considered by the designer when performing these types of studies.

Furthermore, the added versatility brought on by coding this new strategy in STATEFLOW allows researchers to perform online simulations for various braking situations, while simultaneously being able to validate the model on an experimental vehicle. Results from this ongoing project will be presented when validation occurs.



(a) (b)

Figure 10. Brake event location and proportioning diagrams

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NOMENCLATURE

A	brake pad area
A_{pist}	brake piston area
b	distance from rear axle to vehicle center of gravity
c	distance from front axle to vehicle center of gravity
D_x	longitudinal deceleration
fac_p	conversion factor for piston
f_{disc}	force on brake disc
F_{gen}	generator force
F_{line}	brake line force
F_{mf}	maximum force on front axles
F_{mr}	maximum force on rear axles
f_{tire}	force on tire
f_x	Longitudinal force

g	Graviational constant
h	height of vehicle center of gravity
I	charge current
l	Wheelbase
M	gross vehicle mass
P	Power
p	Pressure
p_{max}	peak pressure
ped_{pos}	pedal position
ped_{max}	maximum pedal position
p_f	pressure in front brake line
p_r	pressure in rear brake line
R	Resistance
r_w	wheel radius
r_{pad}	distance from center of wheel to center of brake pad
U	bus voltage
v_i	vehicle velocity at t = i
v_f	vehicle velocity at t = i + 1
v_{veh}	vehicle velocity
W	gross vehicle weight
W_d	longitudinal weight transfer
W_f	weight on front axles
W_{fs}	static weight on front axles
W_r	weight on rear axles
W_{rs}	static weight on rear axles
μ	coefficient of friction, as noted in context

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