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Regenerative Braking System For A Hybrid Electric Vehicle[1]

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ABSTRACT

This paper discusses a Regenerative Braking System (RBS) for a Parallel Hybrid Electric Vehicle (PHEV) that performs regenerative energy recovery based on vehicle attributes, thereby providing improved performance, efficiency and reliability at minimal additional cost. A detailed description of the regenerative braking algorithm will presented along with simulation results from a dynamic model of the PHEV exhibiting the regenerative braking performance.

INTRODUCTION

The vehicle powertrain consists of nonlinear systems such as a powerplant, transmission, differential and axle system that drive the wheels. Furthermore, various accessories are connected to the powerplant such as power steering, power brakes, and air conditioning systems. The vehicle powertrain is a composition of electrical, mechanical, chemical, and thermodynamic devices connected as a nonlinear dynamic integrated system, with the primary objective of providing the power source for transportation.

A Hybrid Electric Vehicle (HEV) combines an Electric Vehicle (EV) powertrain system with conventional powertrain components, such as an internal combustion engine. A PHEV includes an electric motor powertrain system and a conventional powertrain system that provide power to the drive wheels simultaneously. By combining an auxiliary powerplant, such as an internal combustion engine/alternator combination, with a conventional EV powertrain, an HEV can potentially extend the vehicle performance envelope and fuel economy, while reducing emissions relative to a conventional internal combustion engine powertrain. [1,2,3,4]

Most HEVs employ both a conventional braking system and a RBS. The conventional braking system typically includes frictional drum or disc braking assemblies selectively actuated by a hydraulic system. The RBS utilizes the electric motor, providing negative torque to the driven wheels and converting kinetic energy to electrical energy for recharging the battery or power supply. The dissipation of kinetic energy during braking, by an electric or hybrid vehicle can be recovered advantageously by controlling power electronics such that the electric traction motor behaves as a generator. The energy recovered during this process can be returned to the energy storage device for future use.

GENERAL HYBRID OPERATIONAL STRATEGY

The PHEV consists of a Coordinated Controller (CC), an Spark Ignited (SI) Internal Combustion Engine (ICE), variable field alternator, lead acid battery, dry clutches for the engine and traction motor, automated manual layshaft transmission, regenerative and hydraulic brake system, and an ac induction motor electric drive system.

The driveline accepts engine torque and motor torque (in a regenerative mode or a motoring mode), and delivers torque to the vehicle wheels through the differential and halfshafts. The motor torque is delivered, via a transaxle, to the differential through a 4x4 coupler connected to a halfshaft, and currently summed with the engine torque at the differential. The engine is connected directly to the differential through the clutch, transmission and a final drive, as in a conventional powertrain. A simplified diagram, representing this nonlinear dynamic PHEV powertrain is illustrated in Figure 1.

The PHEV CC provides motoring and regenerative commands to the motor controller for corresponding positive and negative motor torque, and throttle blade commands to the engine controller. These commands may be based on the battery State of Charge (SOC), motor speed versus torque limits, motor torque current, motor field current, transmission gear, driver pedal position, engine clutch state, motor clutch state, engine speed, average power at the drive wheels, shift status, estimated engine torque, and estimated engine torque available. In addition, the CC provides motor clutch control during braking, or hybrid operation. Braking commands are generated and sent to the brake system.

The torque may be partitioned to operate in an engine only mode, a motor only mode, or a two traction device mode (hybrid mode). The engine only mode supplies no regenerative braking. Hybrid mode operation consists of motor only operation, engine operation, motor torque application during shifting, motor assist during power boost, and regenerative braking. The powertrain will provide negative torque via the motor during braking for energy recovery.

The vehicle launches in motor only mode for optimal driveability, emissions, and fuel economy. When the average power at the vehicle wheels reaches a level where operation of the engine is beneficial, the motor is no longer operated. The engine can be started during a shift, and the engine clutch can be engaged once the engine is cranked. While the engine clutch is engaging the motor torque is reduced in a manner seamless to the vehicle occupants. With the engine fully engaged the motor clutch can disengage, reducing inertia drag. The motor assists the engine, when the engine cannot meet the driver demand. The motor clutch can be engaged for regenerative braking. The engine clutch can be disengaged to reduce engine compression braking drag during regen. [5,6]

REGENERATIVE BRAKING CONTROL ALGORITHM

The RBS algorithm was modeled using MATRIXx and the analog MATRIXx algorithm was then discretized and code

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was developed using MATRIXx Autocode. The resultant code was downloaded in the controller and was tested in a development vehicle.

A parallel braking system applies regenerative braking torque, to the driven wheels, in addition to hydraulic braking torque provided by the foundation braking system. Compression braking, determined in the motor controller based on PHEV CC commands, is electric motor braking without application of hydraulics and gives the driver the feeling of engine drag present in an internal combustion engine vehicle while advantageously recovering kinetic energy, and is used in addition to a parallel braking system. Hydraulic brake torque is commanded by application of the brake pedal from the driver. Regenerative brake commands are predetermined as a function of master cylinder pressure in the traction motor controller and are based on PHEV CC commands. The electric brake torque added to the hydraulic brake torque in the parallel braking system is determined as a function of the Master Cylinder Pressure (MCP). [7,8,9,10]

The electric brake torque added to the hydraulic brake torque in the parallel braking system is determined as a function of the MCP. The following equation is used to determine the relationship between electric brake torque and hydraulic brake pressure:

$$T_e = \left[\frac{(g's \cdot R_W \cdot W_v) - (2 \cdot BF_f \cdot P_f) - (2 \cdot BF_r \cdot P_r)}{g_{4x4} \cdot g_{axle}}\right] \quad (1)$$

The front and rear brake pressure is a function of the sensed master cylinder pressure and is determined as follows:

$$P_f = P_{mc},\ P_r = P_{mc} \quad for\ P_{mc} \le X \quad (2)$$

$$P_r = X + \delta(P_{mc} - X) \quad for\ P_{mc} > X \quad (3)$$

The amount of electric brake torque that can be added to the hydraulic brake torque is shown in Figure 2 as a function of static brake force relationships, motor torque characteristics, driver feel, and the tire/road surface interface.

Static brake force relationships are determined by plotting a static brake force graph that includes front and rear brake lockup characteristics for several road surfaces, front and rear brake proportioning relationships, and vehicle deceleration. The front and rear brake lockup curves are the maximum force that the front and rear brakes can deliver to the road surface without the front and rear brakes attaining lockup for various road surfaces. Brake forces applied above lockup curves results in lockup on the corresponding axle. These lockup curves are plotted as front vs. rear brake forces and are shown in Figure 2.

The vertical axis represents the front brake force and the horizontal axis represents the rear brake force. [11] The slopes and intercepts for the maximum front and rear brake forces are as follows:

$$F_{\max f} = \frac{\mu_p (W_v B / L)}{1 - \mu_p H / L} \quad (4)$$

$$F_{\max r} = \frac{\mu_p (W_v A / L)}{1 + \mu_p H / L} \quad (5)$$

$$slope_{f\max} = \frac{\mu_p H / L}{1 - \mu_p H / L} \quad (6)$$

$$slope_{r\max} = \frac{-\mu_p H / L}{1 + \mu_p H / L} \quad (7)$$

The front and rear brake forces are related to the brake pressure, as shown in the following relationships:

$$F_{rear} = \frac{2 \cdot BF_r \cdot P_r}{R_w} \quad (8)$$

$$F_{front} = \frac{2 \cdot BF_f \cdot P_f}{R_w} \quad (9)$$

Vehicle deceleration, in g's, is plotted as a function of the total brake force, which is the sum of front and rear brake forces divided by the vehicle weight:

$$F_t = F_{front} + F_{rear} = \left(\frac{W_v}{g}\right) a_x \quad (10)$$

If a deceleration rate of 0.6 g's is requested by the driver on a 0.8 μ (road surface/tire adhesion coefficient) road surface, then any combination of front and rear brake force would satisfy the drivers request, while maintaining vehicle stability, as long as it exists in the triangle bounded by the deceleration line and the front and rear maximum brake force lines for the 0.8 μ road surface.

The optimal regenerative brake control strategy selects a proportioning ratio that will satisfy all of the design goals (stopping distance, front lockup first, etc.), allowing the total brake force to fall in the desired bounded triangle, while maximizing the percentage of braking performed on the axle that does regenerative braking.

The additional force that can be added to the front hydraulic brakes is determined from the static brake graph and a pressure versus vehicle deceleration graph shown in Figure 3.

The pressure versus deceleration graph determines the relationship between the electric torque added to the foundation braking system and the road surface. The foundation brake curve is plotted as a function of pressure versus vehicle deceleration in g's as shown in the following equation:

$$decel = \frac{2 \cdot BF_f \cdot P_f + 2 \cdot BF_r \cdot P_r}{W_v \cdot R_w} \quad (11)$$

The road surface limit is chosen as 0.7 μ, because according to the static brake graph this vehicle can attain a 0.7 g stop on a 0.8 μ road/tire surface adhesion without lockup. A road surface limit higher than 0.7 g will cause premature lockup and thus prevent energy recovery. Another limit that determines the electric braking is driver feel. Compression braking occurs at zero brake pressure.

The maximum braking deceleration acceptable to the driver, without a driver brake command, is determined by jury evaluation to be 0.1 g. At 0 psi on the pressure versus vehicle deceleration graph, 0.1 g is plotted. A normal brake stop that a driver commands approaching a red traffic light is 0.2 g. At 100 psi, 0.2 g is plotted as an upper bound that a driver would accept for a light brake pressure application. The driver feel curve is completed by allowing greater electric braking torque to be added at greater vehicle deceleration rates.

The electric motor torque can then be converted to force at the wheel, added to the front hydraulic brake force, and plotted against the rear brake force on the static brake force graph. Finally, motor torque as a function of pressure can be plotted as shown in Figure 4.

The traction motor controller provides positive and negative torque commands to the motor within the torque versus speed envelope of the motor. The magnitude of positive motor torque available is determined as a function of motor speed versus torque as follows:

$$T_{available} = \frac{P_{rated}}{\omega_m} \cdot 5252\ , \quad \omega_m > \omega_b \tag{12}$$

$$T_{available} = T_{rated}\ , \quad \omega_m \leq \omega_b \tag{13}$$

The magnitude of regenerative braking torque available is determined as a function of motor speed versus torque:

$$T_{regenavail} = \frac{P_{rated} \cdot 5252}{\omega_m} - T_{compression}\ , \quad \omega_m > \omega_b \tag{14}$$

$$T_{regenavail} = T_{rated} - T_{compression}\ , \quad \omega_m \leq \omega_b \tag{15}$$

The CC will determine the amount of positive and negative torque to be commanded to the motor.

All negative motor torque is reduced linearly at low vehicle speeds where no energy can be recovered. Compression braking torque allows braking to occur while recovering the maximum energy, due to all braking being performed electrically. The amount of compression braking to perform is equivalent to that which the engine can provide. This is necessary to make the compression braking torque feel the same whether being performed by the engine, if the energy storage device is too full to except regenerative energy, or the traction motor. Compression braking torque is determined as follows:

$$T_{compression} = \frac{g' \, s \cdot R_w \cdot W_v}{g_{4x4} \cdot g_{axle}} \tag{16}$$

The traction motor torque delivered is a function of motor and inverter dynamics, nonlinearities, and losses in both the motor and inverter as a function of motor speed. The traction motor torque limit is characterized as follows:

$$T_m = \frac{P_{rated} \cdot 5252}{\omega_m} \quad \omega_m > \omega_b \tag{17}$$

$$T_m = T_{rated} \quad \omega_m \leq \omega_b \tag{18}$$

where

$$T_e - T_m \cdot 1.3558 = J_m \dot{\omega}_r \tag{19}$$

The inverter load current is a function of traction motor speed, torque delivered, and terminal voltage of the battery as described below during motoring and during regeneration :

$$I_{load} = \frac{T_m \cdot \omega_r}{e_{tb}} \cdot \frac{1.3558}{\eta} \qquad I_{load} = \frac{T_m \cdot \omega_r}{e_{tb}} \cdot \eta \cdot 1.3558 \tag{20}$$

The control algorithm requires the following inputs: brake switch, accelerator pedal position (percent), engine clutch status, motor clutch status, motor speed, motor torque estimate, select mode logic, Iq current actual and MCP. The algorithm produces the following outputs; Hybrid Clutch Request (HY_CLU_REQ), Torque Current Request (Iq request), and Hybrid Throttle Demand (HY_THR_DEM).

A *select mode* signal is used to determine if the driver wants to run the vehicle in hybrid mode or motor only mode. If the vehicle is operating in hybrid mode, the hybrid strategy determines if the vehicle is using the engine only, the motor only, or both the engine and the motor simultaneously. During regenerative braking the engine clutch is disengaged allowing the motor only to operate. If a motor only condition or a *braking logic* condition or a shift condition exists then the *throttle angle command* is over ridden, idle throttle is commanded, and the engine clutch is disengaged. In engine only mode regenerative braking will not occur, and the engine clutch will be commanded to disengage if braking is commanded. In hybrid mode during braking the engine clutch is disengaged, the engine is ramped to idle speed, and the transmission continues to shift allowing the transmission to be in the proper gear when an engagement is requested. A linear clamp is applied so that the *regenerative brake torque* is phased out at low speed.

HY_THR_DEM is the throttle demand to the engine. *HY_CLU_REQ* is a signal that can force the engine clutch disengagement, if for example regenerative braking is commanded. If *HY_CLU_ REQ* is zero, the closing of the engine clutch is under the control of the transmission controller and the CC does not override this signal. This means that the engine clutch will close, if the closing of the clutch is desired by the transmission controller. If *HY_ CLU_ REQ* is one, then the CC will override the transmission controller and open the engine clutch.

Iq request is the torque current request, in Amperes, to the traction motor. This current value is within the positive and negative torque current envelope of the motor.

The *motor torque available* as a function of motor speed is also determined. The 4x4 multiplies this maximum motor torque available as a function of speed and transaxle gear ratios to become the *maximum motor torque available referred to the wheels signal (TmATwheelsMAX).* If the absolute value of the *unclamped motor torque command* in Nm is less than the peak motor torque available as a function of motor angular velocity then the unclamped motor torque command referred to the motor becomes the limited motor torque command referred to the motor. Otherwise if the absolute value of the unclamped motor torque command is not less than the peak motor torque available then the limited motor torque command becomes the peak motor torque available as a function of motor angular velocity referred to the motor. The limited motor torque signal then gets multiplied by the retained sign value determined from the unclamped motor torque command, to become the total motor torque command referred to the motor.

The regenerative brake algorithm receives brake pressure commands as a psi signal from a pressure sensor in the master cylinder. This signal is eventually converted to electric brake torque (Nm) that the motor will provide to assist the hydraulic brakes. The brake switch is also used to detect braking as a system backup. If the brake switch and master cylinder sensor read low, the driver is not commanding braking. If a brake sensor command is present, then the driver is commanding braking.

Then accelerator pedal position is also monitored. *The accelerator* position represents the driver accelerator command. If *accelerator position* is greater than some calibrated value or *brake switch* is high, then a pedal condition exist and the driver is asking for braking, acceleration or both. This OR condition is sent through a not gate and this constitutes a *no pedal* condition, used for compression braking to emulate engine drag in an internal combustion engine. The *no pedal* signal and *brake switch* are both sent through an OR gate to form a signal called *braking logic* which is high when the brakes are depressed or when compression braking exists i.e. when negative motor torque can be applied.

The engine clutch status is high when the clutch is engaged and is low when the clutch is disengaged. The motor speed and motor torque estimate are also received. The motor angular velocity and the motor torque estimate are multiplied and converted into wheel power from the motor in kWatts.

The Iq actual signal is used by the motor controller to determine the Motor Torque Estimate (Nm). The Iq actual signal is within the positive and negative torque current envelope of the motor and the motor torque estimate is within the positive and negative torque versus speed envelope of the motor in Nm.

The algorithm determines the total motor torque command (Nm), and computes the Iq request in amps.

The no pedal torque is determined as a function of vehicle velocity. This allows the vehicle to decelerate at a rate of .1g with no pedal input from the driver. The amount of compression braking commanded is the no pedal torque as a function of vehicle velocity.

TEST DATA AND SIMULATION RESULTS

A post transmission parallel hybrid electric vehicle was built and test data was taken. The vehicle was driven in engine only mode, motor only mode and hybrid mode while test data was taken.

Figure 5 shows a simulation of low acceleration/deceleration profile repeated on a 10% grade hybrid operation. This simulation shows a strip chart of vehicle velocity in mph, throttle angle in degrees, engine speed in rpm, gear number, halfshaft torque in Nm, engine torque in Nm, motor torque in Nm, accelerator position in per unit, velocity error between the command and vehicle in mps, and clutch position in per unit.

During second gear the motor does not assist the engine due to a less than 80% driver accelerator command. During third gear motor assistance is necessary due to the driver commanding more than 80% throttle. During fourth gear the driver continues to accelerate the vehicle, then begins to brake the vehicle.

During vehicle braking the vehicle decelerates; the throttle angle is commanded to idle; the engine speed is driven to idle; the vehicle remains in forth gear; the halfshaft torque becomes negative; the motor is operated as a generator and performs regenerative braking supplying negative torque to the drive wheels; the accelerator position is zero; the vehicle velocity error becomes negative; the clutch disengages. As the vehicle decelerates, the transmission down shifts. The vehicle comes to zero speed. The engine remains at idle. Gear one is obtained. The halfshaft torque and motor torque become zero, and the clutch remains open. The driver commands acceleration at about 35 sec. The vehicle launches with motor only until gear two.

CONCLUSIONS

This paper discussed a new and improved parallel regenerative braking system for a PHEV that maximizes the regenerative braking force based on various vehicle attributes, without adding additional cost to the vehicle. The regenerative braking is performed through a high efficiency, single gear, direct drive transaxle for optimum braking efficiency. The engine is disengaged from the drive wheels during regenerative braking, eliminating engine frictional losses. This optimizes energy recovery and improves braking performance due to the elimination of regenerative brake torque at the drive wheels. This regenerative brake system was simulated and tested on a vehicle.

NOMENCLATURE

A = *distance from front axle to cg, ft*

a_x = *vehicle acceleration,* ft/s^2

B = *distance from cg to rear axle, ft*

BF_f, BF_r = *front, rear brake factor respectively, lbf-ft/psi*

e_{tb} = *battery terminal voltage, Volts*

F_{front}, F_{rear} = *front, rear brake force respectively, lbf*

$F_{\max f}$ $F_{\max r}$ = *max front, rear brake force y axis intercept respectively, lbf*

F_t = *total brake force, lbf*

g = *acceleration due to gravity,* ft/s^2

g_{axle} = *transaxle gear ratio, where* $g_{axle} = \dfrac{G_{axle\_cm}}{G_{axle\_m}}$

g_{4x4} = *4x4 gear ratio, where* $g_{4x4} = \dfrac{G_{4x4\_diff}}{G_{4x4\_cmt}}$

$g's$ = *vehicle acceleration (deceleration) /acceleration due to gravity, unitless*

G_{axle_cm} = *transaxle gear on the motor clutch*

G_{axle_m} = *transaxle gear on the motor*

G_{4x4_cmt} = *4x4 gear on the motor clutch*

G_{4x4_diff} = *4x4 gear on the differential*

$g's$ = *vehicle deceleration due to gravity, unitless*

H = *vehicle cg height, ft*

J_m = *motor inertia, lbf ft s^2*

L = *wheelbase, ft*

P_f = *front brake pressure, psi*

P_{mc} = *master cylinder pressure, psi*

P_r = *rear brake pressure, psi*

P_{rated} = *rated motor power, hp*

R_w = *wheel radius, ft*

$slope_{f\max}$, $slope_{r\max}$ = *max front, rear brake force slope*

T_e = *electric brake torque, lbf ft*

$T_{available}$ = *motor torque available, lbf ft*

T_{rated} = *rated motor torque, lbf ft*

$T_{regenavail}$ = *regen brake torque available, lbf ft*

$T_{compression}$ = *compression brake torque, lbf ft*

T_m = *mechanical motor torque, lbf ft*

W_v = *vehicle weight, lbf*

ω_m = *mechanical motor speed, rpm*

ω_b = *base motor speed, rpm*

X = *master cylinder pressure at which brake proportioning changes, psi*

δ = *brake proportioning*

η = *motor & inverter combined efficiency*

μ_p = *peak coefficient of friction*

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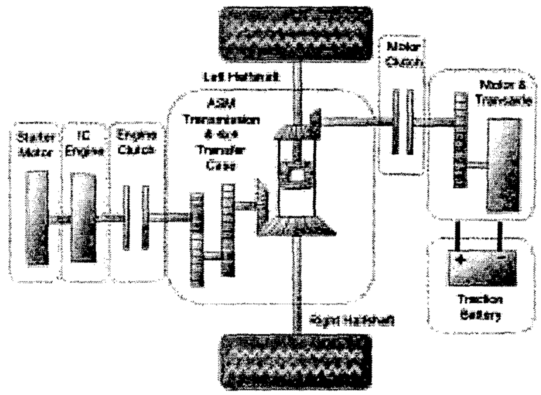

Figure 1 PHEV Powertrain

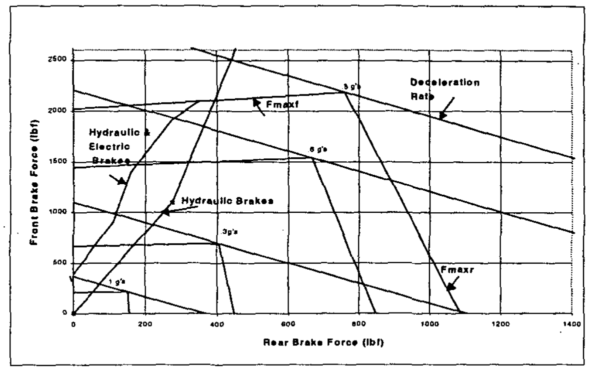

Figure 2 Static Brake Force Curves

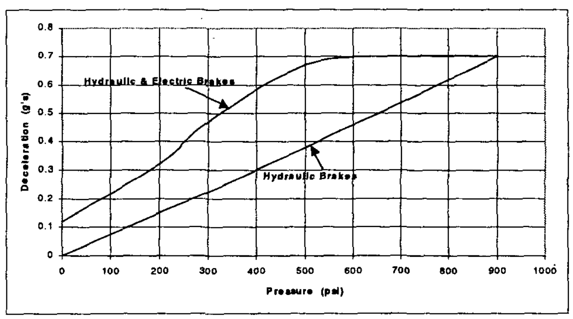

Figure 3 Electric and Hydraulic Brake Curves

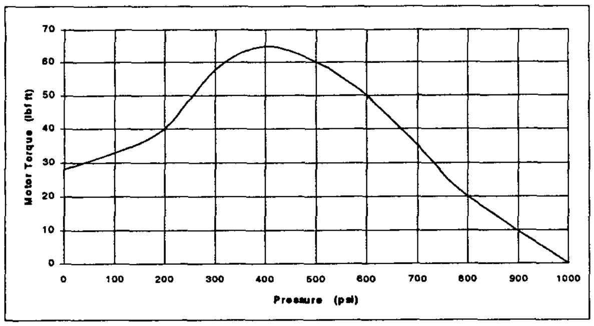

Figure 4 Regenerative Brake Torque

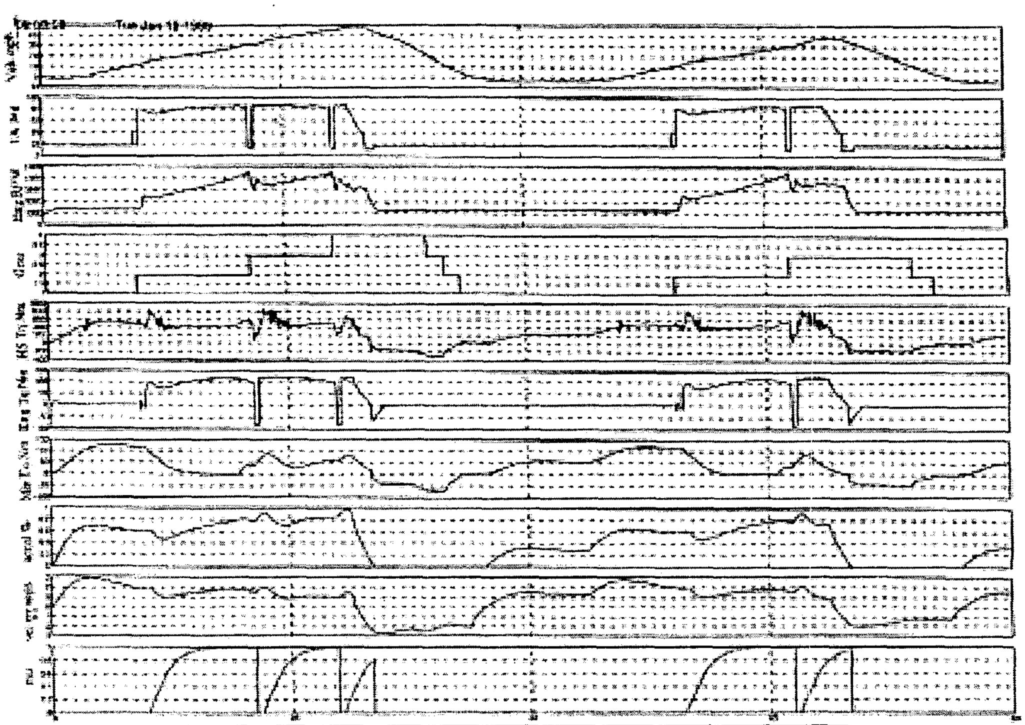

Figure 5 Acceleration/Deceleration Profile on 10% Grade