

A Simulation Program for Demonstration and Analysis of Closed Loop Negative Feedback Control

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Abstract

Increased emphasis on fuel consumption minimization and energy efficiency encourages more careful attention to control strategies for automobile vehicle systems. Simplified yet accurate simulation propulsion system models are needed to provide the control system designer an analytical platform for experimental assessment of novel and atypical control approaches.

The structure of a simulation model for an automobile system including power train (energy supply) and propulsion (energy consumption) contributors is explained. This model has been developed for use in studying closed loop negative feedback control systems using ON/OFF, PID, and other control algorithms. Results from exercising the simulation model are illustrated for several vehicle operation scenarios, including steady state, acceleration, and deceleration, with future work targeted at terrain varying conditions. The approach to the development of the vehicle system model is explained, and examples of the dynamic operation of the model are provided. This model provides an easily modifiable process description that can be used to show visually and quantifiably the benefits and shortcomings of selected control strategies, as well as the influence of gain magnitudes on system stability and response. Further, this paper provides illustration of the model operation with a simple ON/OFF control strategy, as well as a straightforward proportional control strategy to demonstrate the potential of using the simulation model to produce useful results. Global energy efficiency parameters of merit are identified and sample calculations are provided to illustrate potential benefits of alternative strategies.

Introduction

The control of the modern combustion engine for automotive power train applications consists of the microprocessor control of many electrically interfaced actuators. The

control algorithms rely upon empirical sensing of numerous output variables that provide the microprocessor with the necessary information about the engine operation to optimize critical performance enhancing parameters. This approach has improved engine efficiencies and reduced fuel usage (consequently improving mile per gallon ratings). However, this approach has primarily focused on optimizing power plant operation and on improving the efficiency of conversion of the potential energy of the fuel to power delivery to the power train. Although the success of this approach has been admirable, the improvements have resulted in diminishing returns. The power plant as an entity is nearing its achievable optimized efficiency. This is apparent from the growing interest in alternative power plants (electric, diesel, fuel cell, and hybrid).

Historically, the design drivers of the automobile have pursued the goal of delivering desired performance (horsepower, acceleration rate, load carrying capability, and comfort) and allowed fuel economy to be a secondary issue. Load carrying capability, engine displacement, vehicle weight, and other primary design parameters have, to a large extent, been treated as givens in the power train development exercise. To some extent, shift points in the transmission, fuel delivery (fuel injection) development, optimization of intake and exhaust geometries, and other less significant design parameters have been focused on reducing fuel usage, while maintaining a performance capability that has been the focus of marketing advertisement programs. Little attention has been placed on the minimization of fuel usage (efficiency) when compromised performance would be the result. Fuel cost was too insignificant to warrant compromising performance. The recent dramatic increase in fuel expense in the world markets appears to be altering this less concerned attitude.

One approach that may offer potentially large improvements (greater than 20 percent) in fuel savings for the same engine performance is to focus on the efficient use of energy to achieve desired vehicle effects and allow fuel consumption quantity to be the dominant feedback parameter for vehicle propulsion system control. By developing control strategies that can result in substantial fuel savings payoffs, improvements in the fuel economy with small compromises in performance might result in substantial overall vehicle efficiencies. This is similar to the strategy used in aircraft control, where engine performance is optimized to achieve propulsion power with high fuel usage efficiency, but mission definitions (take off power usage, climb rate, descent rate, and cruise altitude) are often optimized for fuel savings, as well as other parameters such as time to destination, altitude for drag minimization, wind and weather considerations, etc. It is time to focus on the overall automotive vehicle system as a means of reducing energy waste.

To achieve an improved overall system operation efficiency through closed loop control, it is most convenient to have available a mathematical simulation model of the system that permits control strategies to be implemented, experimentally tested, and evaluated relative to the significant payoff functions. To assess the extent of potential benefits in minimizing energy waste, the simulation model may treat the power plant as a supplier of power, and performance parameters, such as acceleration and deceleration rates, cruise

speed, load carrying capability, vehicle weight, etc., may be varied to find the tradeoffs in required power to achieve the desired effects.

This paper gives an overview of the vehicle parameters that have primary impact on vehicle energy requirements. Algorithms for the time rate of change of these parameters and the steady state energy requirements as a function of vehicle design parameters are illuminated. Further, a typical vehicle operational mission is cursorily defined. This mission provides the framework for evaluation of various control strategies for the achievement of desired performance and the expense of energy usage that results. Finally, two control strategies are implemented (basic ON/OFF control and proportional control) with the developed model, and the initial results of the effect of control parameters on the global parameters of fuel usage and vehicle response to customer requirements are quantified.

Vehicle Control Structure: State Of the Art

The personal transportation vehicle in recent years has increasingly incorporated numerous sensing and actuating elements to allow improved performance and efficiency. The advent of electrification of numerous functions (steering, independent wheel control, automatic (non-skid) braking systems, adjustable transmission switch points, cruise control, etc.) provides the promise of permitting expanded topics for improvement and optimization. The traditional approach of “man-in-the-loop” control of the vehicle has provided acceptable acceleration rates, steady state velocity, steering, obstacle avoidance and safe distance control, traffic merging, braking, etc. The human controlled effectors have been engine delivered power, steering wheel rotation, brake pedal actuation, and others.

Consider the automobile in the broader context of a vehicle system. The vehicle system has numerous (8–12) primary variables to manipulate and numerous (6–10) main output variables, which characterizes it as a complex multiple-input, multiple-output system. In addition, the environmental conditions that influence the desired outputs of the control block diagram vary with time throughout the mission of the vehicle usage. Further, because some of the desired requirements contradict one another, suitable compromises have to be made. To allow in-depth study of the effects of these compromises on global parameter realization, such as total time for the mission, overall fuel usage, etc., representative models of the vehicle system are needed. The fidelity of these models must be adequate to include the effects of vehicle weight, aerodynamic drag (styling), propulsion system definition, incline and decline of roads (grades), surface/wheel friction (i.e., black top versus concrete versus gravel), and other parameters to be defined over time with characterization of their influence parameters.

Development of the Mathematical Model for the Vehicle

To minimize computational requirements, the mathematical model needs to characterize the important aspects of the vehicle behavior with respect to the global cost parameters as simply and compactly as possible. This leads to an approach of describing the vehicle

operation from an overall “black box” perspective. That is, the goal of the mathematical representation of the vehicle is to define accurately the cause and effect relationships between the inputs to the model (human or automatic control interface) and the global parameters of merit (fuel usage, vehicle response, etc.). The importance of dynamic effects must be preserved superseding the temptation to model only steady state conditions. Time dependency will likely prove to be extremely important. Therefore, initial steps were aimed at defining the relevant physical principles contributing to vehicle behavior. For these initial steps, the engine, power train, vehicle suspension, and general configuration of the vehicle were assumed to be like those found in the typical existing personal vehicle used by the general populace throughout the world. The first order assumption was that the power plant will deliver the requested power when called upon to do so, as requested by the control (whether human or automatic). The validity of this assumption will be evaluated in later studies after testing the model performance against empirical data and confirming the potential rewards from focusing on a system design approach.

The development of the vehicle model emanates from the following simplifying assumptions.

Energy required (steady state): a function of (weight, friction, drag, road grade, etc.)

Drag: a function of velocity, drag coefficient, frontal area, etc.

Friction: a function of weight and friction coefficient (tire/road)

Road grade: a function of elevation change per distance

Energy (acceleration): a function of mass, rate of acceleration, drag, and friction

Energy (deceleration): a function of inertia, rate of deceleration, drag, friction, and braking force

Fuel usage: a function of total energy, braking regeneration, efficiency of the power plant, energy content of the fuel, etc.

The model for the personal transportation vehicle was conceptualized as a time dependent mathematical description of the assumptions that characterizes the response of the vehicle to the effected manipulations of the power plant delivered energy. (See the closed loop block diagram, Figure 1.) Simply put, the operator (man-in-the-loop) defines what he wishes to occur (setpoint) and compares that to what is presently happening as perceived via the sensors. This creates a calculated error. This error is processed by the human (controller), and action is applied to the output actuators, often referred to as effectors (power plant, brake, steering wheel, etc.). This action produces a change in energy that results in a change to the process over a period of time, limited by the mechanical inertia and other time dependent variables that consume the energy. The resulting change to the vehicle parameters (i.e., speed) are perceived by the sensing elements and fed back to the summing junction for comparison with the desired condition. A measure of the global cost of achieving the desired outcome (time to achieve the change, fuel expended to achieve the change) is determined by integrating the actual fuel usage per instant, summed for the time duration of the process to achieve the desired outcome.

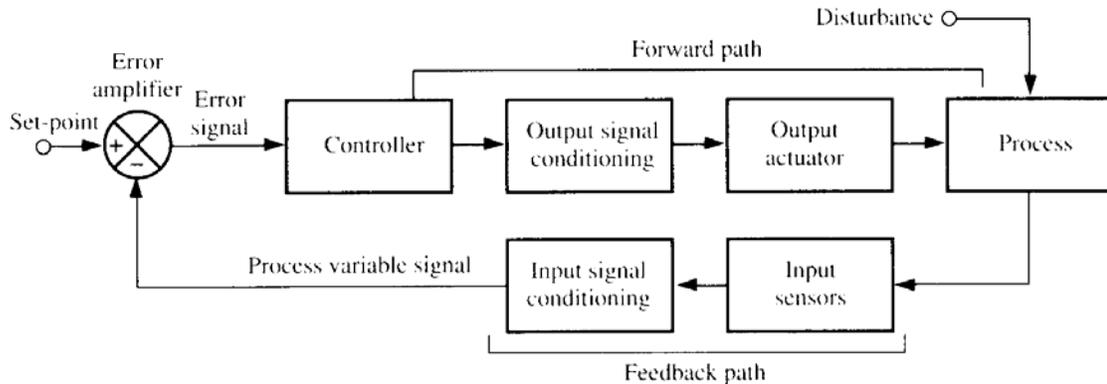


Figure 1: Block Diagram for Closed Loop Vehicle Control

The energy required for steady state (constant velocity) is:

$$E_{ss} = \int [(k_1 \times C_f \times W_{veh} \times dx/dt)dt + (k_2 \times C_d \times A_{frontal} \times (1/2 \rho) (dx/dt)^2)dt + (W_{veh} \times (dy/dx) \times (dx/dt))dt]$$

-- friction term -- -- drag term -- -- grade term --

The energy required for acceleration is:

$$E_{accel} = \int [1/2 \times (W_{veh} / g) ((dv/dt))^2 dt + (k_1 \times C_f \times W_{veh} \times dx/dt)dt + (k_2 \times C_d \times A_{frontal} \times (1/2 \rho) (dx/dt)^2)dt + (W_{veh} \times (dy/dx) \times (dx/dt))dt]$$

-- inertia term -- -- friction term -- -- drag term --
-- grade term --

The energy required for deceleration is:

$$E_{decel} = \int [1/2 \times (W_{veh} / g) ((dv/dt))^2 dt - (k_1 \times C_f \times W_{veh} \times dx/dt)dt + (k_2 \times C_d \times A_{frontal} \times (1/2 \rho) (dx/dt)^2)dt + (W_{veh} \times (dy/dx) \times (dx/dt))dt - (\text{Braking energy})]$$

-- inertia term -- -- friction term -- -- drag term --
-- grade term -- -- braking term --

(Note: In this equation, the value of dv/dt will be the opposite sense and tend to maintain vehicle speed, hence the need for external braking.)

Fuel must provide the energies consumed. Fuel energy is:

$$FuelEnergy_{required} = \int [(E_{ss} + E_{accel} + E_{decel})dt]$$

(Note: Evaluated over the time period of the vehicle usage.)

An investigation was conducted to identify the amount of energy typically required for propelling a personal vehicle at constant velocity on essentially flat terrain. As a first approximation, the data provided by automobile manufacturers for automobiles sold in the United States was consulted. This data is reported in the form of miles per gallon city and highway. The guidelines for quoting the highway miles per gallon, as specified by the U.S. Environmental Protection Agency, is, "The 'highway' program is created to

emulate rural and interstate freeway driving with a warmed-up engine, making no stops (both of which ensure maximum fuel economy.) The vehicle is driven for 10 miles over a period of 12.5 minutes, with an average speed of 48 mph and a top speed of 60 mph. Both tests are performed with the vehicle's air conditioning and other accessories off."^[1] The auto manufacturers are required by law to quote the highway MPG on the window sticker, consistent with this testing procedure. With this information, a number of 2008 automobiles were investigated, all of which were sedans, and for which delivered curb weight could be determined, along with the EPA city/highway MPG information. The data was acquired and summarized.

The data for the automobiles investigated was tabulated and plotted for analysis. The data acquired included, but was not limited to, Chevrolet, Ford, Honda, and Toyota. Figure 2 shows the results of a plot of MPG highway versus vehicle curb weight for comparable vehicles, with respect to passenger capacity and vehicle shape (inferring comparable drag coefficients). As a first approximation, the conclusion was reached that the required vehicle energy for steady state (constant velocity) operation at a given velocity on a level road bed is highly proportional to vehicle weight. The linear equation for MPG versus weight based on a number of vehicles for sale in the public market was $MPG = [-0.00714(W_{veh}) + 52.14]$. (See Figure 2.)

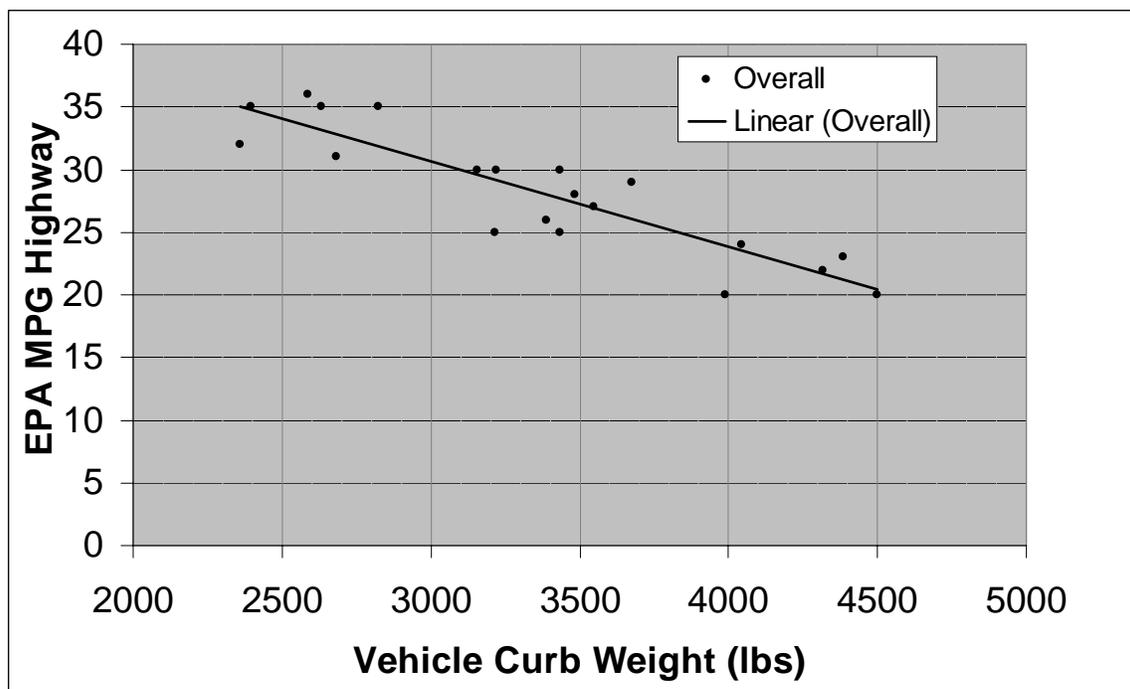


Figure 2: Vehicle EPA MPG versus Curb Weight

Further analyzing the data, an attempt was made to identify the effect of vehicle frontal area upon EPA MPG. First, the influence of vehicle weight was removed by subtracting the linearized estimate of MPG variation with weight. Then, a plot was made of the

variation of MPG with the secondary parameter frontal area. Figure 3 shows the resulting drag effect, which revealed a strong linear relationship to frontal area when assuming a consistent vehicle drag coefficient. Based on one manufacturer's data, a typical value for drag coefficient for a sedan or coupe-type vehicle is reported to be approximately 0.28, and, essentially, the same for all model shapes for this type of vehicle body. The resulting linear equation is $MPG_{\text{correction-for-drag}} = [(-0.5)A_{\text{frontal}} + 15]$. Therefore, for any vehicle weight and frontal area assuming a sedan body style with drag coefficient of 0.28, the total MPG for the vehicle can be estimated as MPG_{total} at a speed is the $MPG + MPG_{\text{correction}}$.

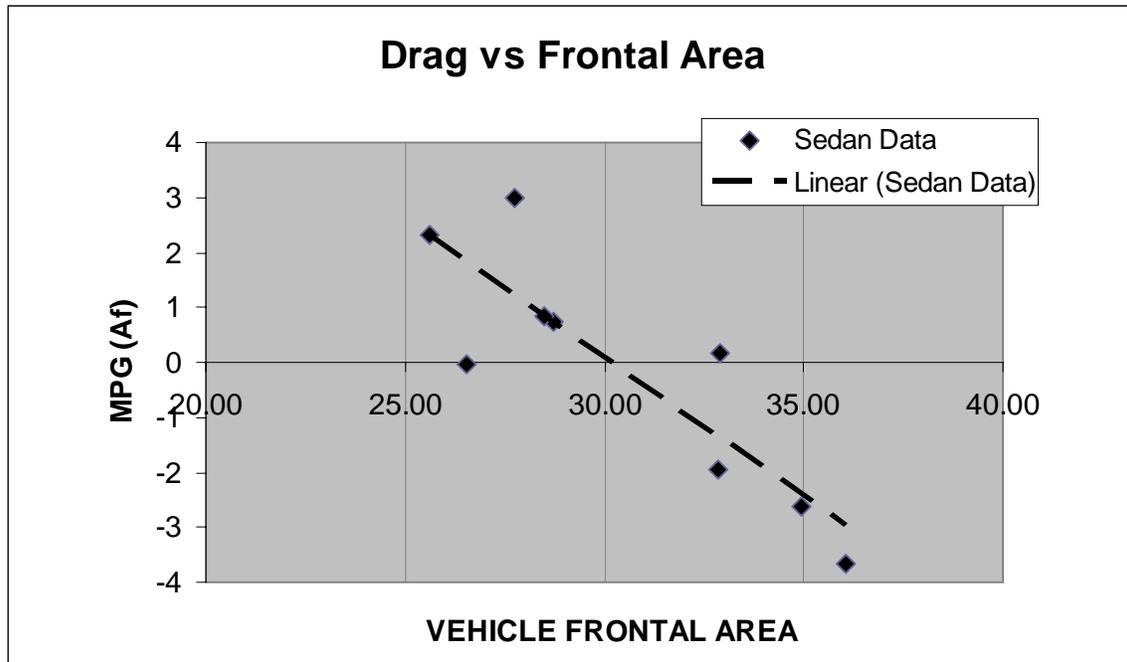


Figure 3: MPG Versus Frontal Area

To quantify the constant coefficients of the friction and drag energy equations (See Section 3.1), an assumption was made that the EPA estimate corresponds to a constant vehicle velocity of 55 mph. This permitted back calculation of the multiplication factors, $(k_1 \times C_f)$ and $(k_2 \times C_d)$, and k_2 .

$$(k_1 \times C_f) = 0.0587 \qquad (k_2 \times C_d) = 0.2152 \qquad k_2 = 0.768 \text{ (at } C_d = 0.28)$$

With the above coefficients defined, and the equations described in Section 3.1, it was possible to develop the mathematical finite difference model for the vehicle. The time step selected for implementation was one second, and initial settling initialization time was included to establish initial conditions before commencing the mission defined time dependent schedule of desired vehicle performance.

As a first step, verification and inspection of the model was accomplished by forcing the calculation of steady state operation of the vehicle at several steady state conditions, three vehicle weights, and two frontal areas. (See Table 1.) The required energy to drive the

vehicle and the corresponding calculated fuel usage are summarized in Figure 4. The assumed efficiency of conversion of fuel energy to output energy was 32 percent^[5].

Vehicle steady state velocities – 10 to 90 mph
 Vehicle curb weight – 1500, 3000, 4500 lbs
 Vehicle frontal area – 30 ft², 15 ft²

Table 1: Steady State Model Data

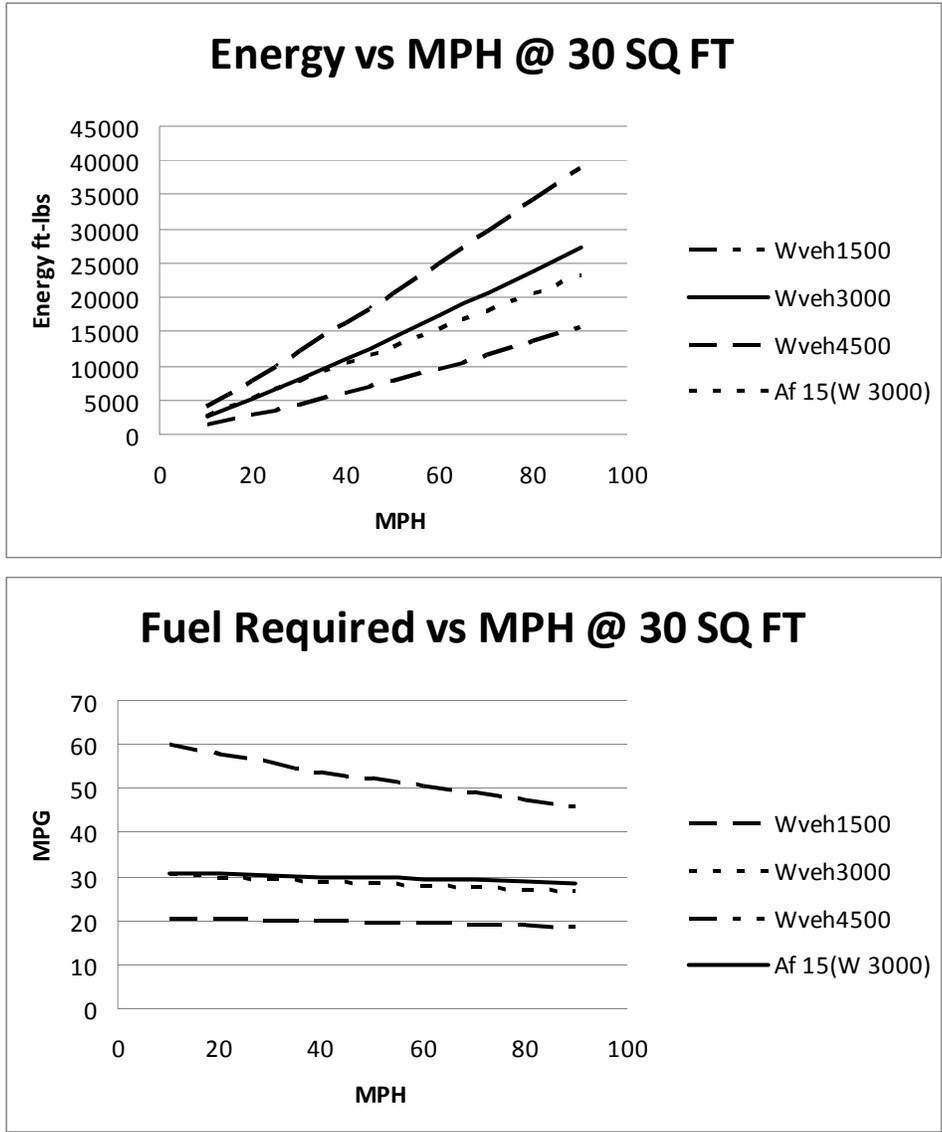


Figure 4: Energy Required for Steady State Vehicle Model

Calculations at steady state revealed the following conclusions. Starting with a vehicle curb weight of 3,000 lbs (an approximate average for the U.S. market of sedans), having a vehicle weight of 1,500 lbs would decrease energy requirements by approximately 40 percent and improve fuel efficiency from approximately 30 MPG to 50 MPG (at 60

mph). Further, the effect of halving frontal area from 30 ft² (typical of US market sedans) to 15 ft² would save approximately 10 percent of energy and improve fuel efficiency marginally by perhaps 2 MPG (quoted at 60 mph.) It should be noted that frontal area manufacturers' data had a variable range from approximately 25 to 35 ft².

As a second step, the model was exercised to define a baseline mission to allow coupling of the vehicle model (energy absorption) with an engine (power delivery) model. The mission is illustrated graphically in Figure 5 (see dashed line). Desired mph

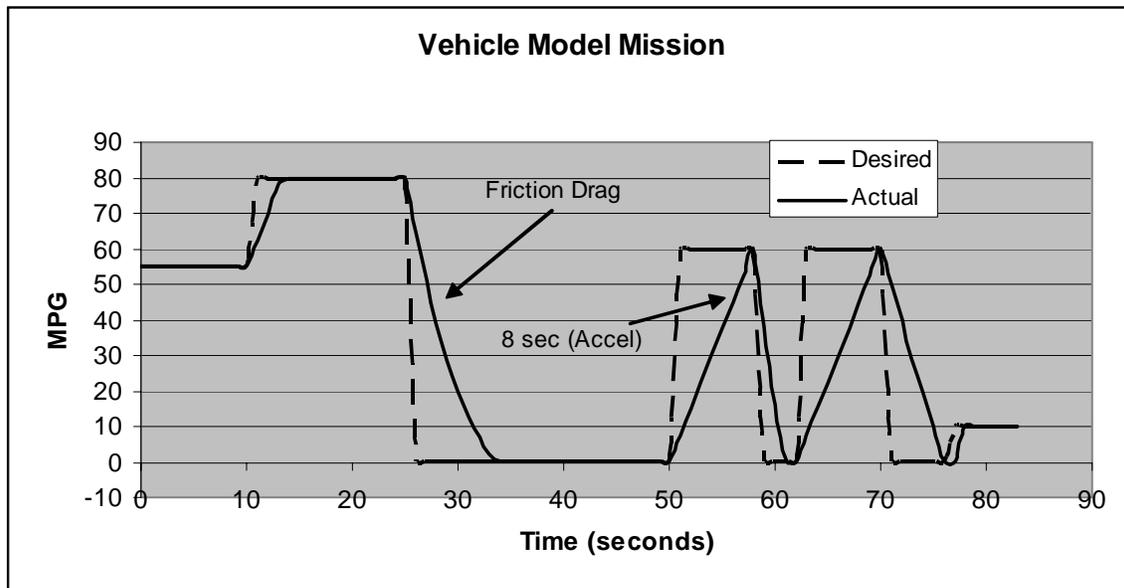


Figure 5: Graphical Description of the Vehicle Mission

is plotted against time in seconds. First, the vehicle is assumed to be operating at a steady state, 55 mph. Although this is somewhat impractical from the perspective of a real application, it must be recognized that the preponderance of the data used to establish the model coefficients and equations was acquired at the steady state operating condition of EPA highway driving. In later studies, the conditions of EPA city driving will be included for comparison. After establishing steady state operation at 55 mph, the vehicle was accelerated to 80 mph and held for 15 seconds to allow the speed to stabilize. The solid line of Figure 5 provides a characterization of the model time dependent response to the desired mission shown as a dashed line. The vehicle model was then decelerated to 0.5 mph and held until speed stabilized. The slight vehicle speed of 0.5 mph was chosen to avoid the numerical problem of dealing with a 0 mph case. This deceleration was modeled without using braking energy and, therefore, due only to friction and drag terms. The inertia of the vehicle is being consumed by the drag and friction. Then, the vehicle was accelerated with a rate such that 60 mph was achieved in eight seconds. This was accomplished by applying a ramp of supplied energy (simulating the power plant) that would overcome the inertia, friction, and drag terms so that vehicle velocity would increase linearly from 0.5 to 60 mph in precisely eight seconds. This rate was chosen because 0 to 60 mph in eight seconds is regarded as the de-facto design requirement for U.S. automobiles. Next, the vehicle was decelerated with braking energy to result in a

deceleration to 0.5 mph in a distance of 130 feet (published road breaking performance tests by manufacturers), which corresponds to a uniform deceleration rate of 30 ft/sec^2 . As with the acceleration, the deceleration was accomplished using a ramp of energy extraction simulating braking to overcome the inertia and supplemental friction, as well as drag terms to achieve the desired rate of deceleration. It is worth noting that the deceleration rate of 30 ft/sec^2 is described in the literature as unrealistically large, with 15 ft/sec^2 typically stated as a rationale estimate of braking deceleration. Therefore, a second deceleration was modeled with braking energy extraction at 15 ft/sec rate for comparison.

The next step was to couple the vehicle mathematical time dependent model to a closed loop negative feedback power plant model to provide an effector in the form of delivered power so that benefits of various power control schemes and parameters of the vehicle (weight, frontal area, friction, etc.) could be investigated. Two approaches to control, ON/OFF and proportional control, were implemented. The coupled model functioned by properly interrelating the controller, power plant, and vehicle models, including the closed loop feedback, the set point, and the error determining summing junction.

Results from Exercising the Mathematical Model

An ON/OFF control achieves the desired mission by driving the effector (in this instance, power plant) from upper limit saturation to lower limit saturation, dependent upon a feedback parameter compared to thresholds in the controller. As shown in Figure 6, a

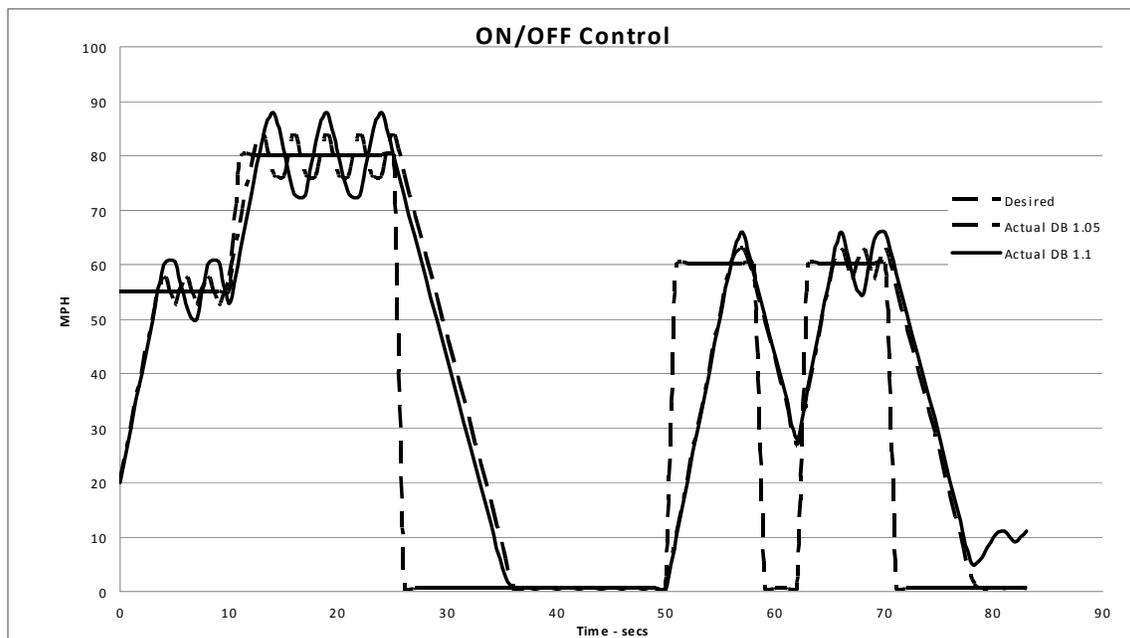


Figure 6: Graphical results for the ON/OFF Control Approach

typical saw tooth pattern results. When the actual condition is below the upper threshold, the effector is commanded to maximum deliverable energy and system response rate is set by energy absorption devices, namely inertia, friction, and drag. Similarly, after achieving the upper limit, the effector is altered to the minimum energy level, and vehicle

system performance erodes at a rate determined by the consumption parameters of drag and friction but slowed by the available inertia energy being reduced. Notice that the slope of the acceleration is greater than the absolute value of the slope of deceleration.

The system transient model was operated at two values of deadband, having thresholds of ± 5 percent and ± 10 percent of desired values for all times of the mission. A larger deadband produces a larger saw tooth. The decelerations after the 60-second time are not in agreement, since no braking power extraction was provided. Therefore, the deceleration for the transient model is due solely to energy balancing.

Proportional control uses feedback in comparison with the desired condition to proportionally control the effector authority based on the magnitude of error. Simplistically, a large error would produce twice the response of an error half as large. The characterization of a proportional control is a convergence of actual to desired value in a manner similar to a model of diminishing returns. The vehicle system transient model results are shown in Figure 7. Three proportional gains are illustrated. With a gain (K_p) of 0.3, a slower change in actual value results. With the 0.9 gain, a quick and stable solution results. With a gain of 1.8, a marginally stable result is evident based on the “ringing” (oscillation) at the point of desired value achievement.

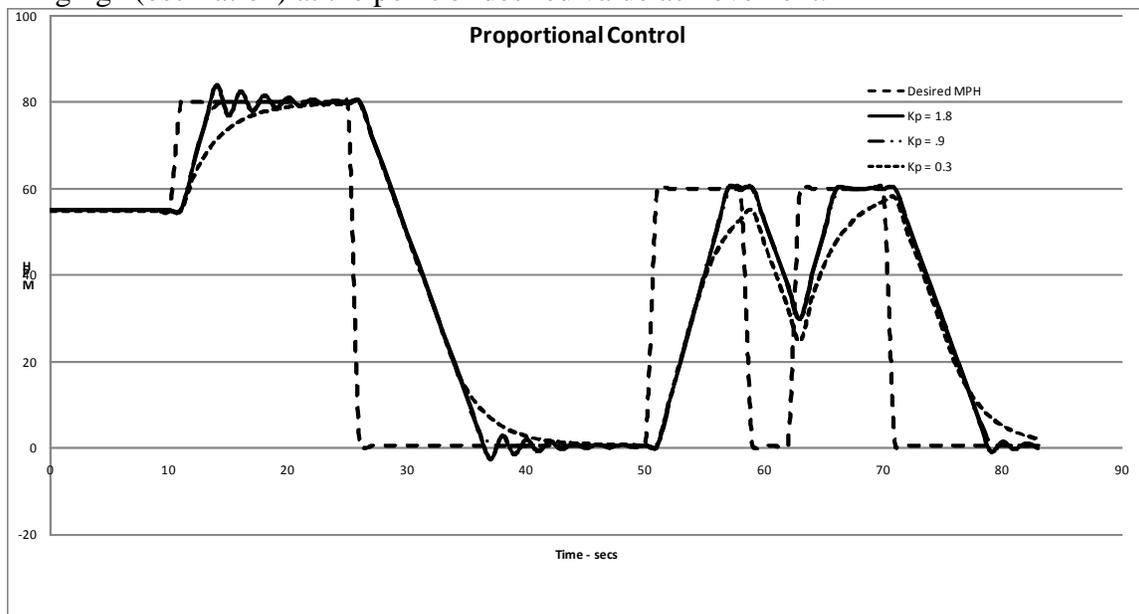


Figure 7: Graphical Results for the Proportional Control Approach

The operation of the transient vehicle system model with alternative control systems provides a platform for comparison of performance based on global parameters of merit. Table 2 summarizes the results of the present study for two global parameters, namely fuel efficiency (MPG) and customer satisfaction (time to achieve desired results).

Comparison of control system response is somewhat subjective. The parameter displayed in Table 2 is the time required for the actual value to achieve the desired value. For example, with the base model (refer to Figure 5), four seconds are required for the first acceleration from 55 mph to 80 mph. Comparatively, the 5 percent deadband required 2.5

seconds (Figure 6), and the proportional $K_P=1.3$ case required 3 seconds (Figure 7). For each of the mission events, comparison is provided for the various control strategies. This particular response characteristic is provided as an example measure that might quantify customer satisfaction. Further studies will more clearly define suitable comparative parameters.

The fuel efficiency parameter (MPG) was acquired by evaluating the average fuel required, as quoted in MPGs, to achieve each of the mission events and for each of the various control strategies. For example, notice that the 55 to 80 mph acceleration, using the K_p value of 0.3 and proportional control, requires approximately 20 percent worse MPG (21.6 versus 25.42) than the deadband control approach. Using this type of comparative analysis, the relative merits of various control strategies can be evaluated. Perhaps different strategies for different types of mission events might be suggested from the comparative studies.

Conclusions

A time dependent simulation model for a vehicle system was developed based upon fundamental equations. These equations were derived through analysis of the absorption mechanisms of the vehicle as a propulsion system. The power plant was treated as a black box provider of required energy to offset the energy absorption elements of inertia, friction, and drag. Data available from vehicle manufacturers was analyzed to provide the needed empirically influential constants to assure validity of the theoretical model.

The equations were modeled using finite difference techniques to create a time dependent model that mimics expected steady state and transient characteristics of a vehicle system. Trending analysis provided first order representation of the effects of vehicle weight (friction and inertia), as well as vehicle frontal area (drag), upon fuel usage parameters and the rate of acceleration and deceleration of the time dependent model.

The simulation model was coupled with a closed loop power plant model to allow evaluation of various control strategies and their influence on vehicle system performance. To provide a basis for comparison of the effects of the control strategies, a mission was defined for the vehicle system that included steady state, acceleration, and deceleration events typical of those expected in everyday engine use. The mission developed was provided as an example of approach and not meant to be inclusive of an entire typical mission for a vehicle.

Two control strategies were implemented, an ON/OFF control and a proportional control. Two different deadband magnitudes were executed for the ON/OFF control, and three proportional gains were executed for the proportional control.

A summary of results was prepared to illustrate the potential for using the simulation model with control strategies to seek out approaches for optimizing global performance parameters with respect to comparing and contrasting the competing goals of achieving customer performance desires (acceleration rate, large vehicle size, wide comfortable

vehicles, etc.) and energy conservation imperative (high MPG and minimal power plant size).

Many questions have been left unanswered in this study. The development of the vehicle system approach offers the potential for providing insight to aid in achieving beneficial trade-offs and the best overall systems. Future activity will address refining and applying the model to better understand vehicle system optimization.

References

- [1] Environmental Protection Agency, "Light-Duty Automotive Technology and Fuel Economy Trends through 1996," EPA/AA/TDSG/96-01.
- [2] Heisler, Heinz, "Advanced Engine Technology," SAE International, 1995.
- [3] Hanselmann H. "Automotive Control: From Concept to Experiment to Product," IEEE International Symposium on Computer-Aided Control System Design, 1996.
- [4] Rakopoulos, C. D., Giakoumis, E. G., and Hountalas, D. I., "Experimental and Simulation Analysis of the Transient Operation of a Turbocharged Multi-cylinder IDI Diesel Engine," *International Journal of Energy Research*, Vol. 22, Issue 4, 25 March 1998, pp. 317–331.
- [5] Gilles, Tim. *Automotive Engines*, Delmar Thomson Learning, 4th Edition, 2002.
- [6] Isermann, R. and Muller, N., "Design of Computer Controlled Combustion Engines," *Mechatronics*, Vol. 13, 2003, pp. 1067–1089.
- [7] White, C. M., Steeper, R. R., and Lutz, A. E., "The Hydrogen-fueled Internal Combustion Engine: A Technical Review," *International Journal of Hydrogen Energy*, Vol. 31, 2006, pp. 1292–1305.
- [8] Onovwiona, H., Ugursal, V., and Fung, A., "Modeling of Internal Combustion Engine Based Cogeneration System for Residential Applications," *Applied Thermal Engineering*, Vol. 27, 2007, pp. 848–861.
- [9] Franco, J., Franchek, M., and Grigoriadis, K., "Real-time Brake Torque Estimation for Internal Combustion Engines," *Mechanical Systems and Signal Processing*, Vol. 22, 2008, pp. 338–361.

Biography

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PAUL DEERING is currently an Assistant Professor in the Industrial Technology Department in the Russ College of Engineering at Ohio University. He has worked in the area of computational techniques and provided helpful collaboration in the construction of the time dependent mathematical model.