PERIODIC OPERATION OF A DIESEL LOCOMOTIVE FOR FUEL OPTIMIZATION

by

Barry L. Pendegrass

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APPROVED:

R. G. Leonard, Chairman

R. H. Fries

C. J. Hurst

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Barry Lloyd Pendegrass

Committee Chairman: Robert G. Leonard
Mechanical Engineering

(ABSTRACT)

An attempt was made to reduce fuel costs of a diesel-electric locomotive by operating the locomotive in a periodic manner, as opposed to operating at a constant velocity. The periodic operation consisted of accelerating the locomotive in a high throttle position and then deccelerating at a low throttle position.

An SD40 Locomotive was modeled to test the periodic operation. The periodic operation was actually found to offer no improvement in fuel performance over that of constant velocity operation. A modification to the diesel engine that takes advantage of the periodic operation is suggested that will give a better fuel performance. The modification to the engine would not be possible with constant velocity operation. With the modification, the periodic operation was found to save fuel over the constant velocity operation.

A controller was then designed to implement the periodic operation. The key component of the controller is

an observer to determine unknown hill forces. The controller was found to work successfully.

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LIST OF SYMBOLS

c_0, c_1, c_2, c_3	Coefficients of non-dimensional train model
c_4, c_5, c_6	Coefficients of observer model
d_1	Constant resistance coefficient
d_2	Linear damping resistance coefficient
d_3	Square-law damping resistance coefficient
E	Energy
E_0	Energy for train 0 of simple model
E_1	Energy for train 1 of simple model
F_0	Force for train 0 of simple model (constant velocity force)
F_1	First component of time-varying force
F_2	Second component of time-varying force
dF	Time-varying force minus F_0
F_h	Hill Force
H	Non-dimensional hill force
M	Total train mass
n	Efficiency
n_0	Efficiency of train 0 for simple model
n_1	Efficiency of train 1 for simple model
n_d	Efficiency of generator and tractor motors
p	Power
P	Dimensionless power
P_m	Maximum power

Q	Fuel consumed
R	Train resistance
t	Time, seconds
t_o	Cycle length for simple model
t_1	Length of time of application of F_1
t_2	Length of time of application of F_2
T	Dimensionless time
T_r	Reference time value
v	Velocity
v_o	Velocity of train 0 for simple model
v_1	Velocity of train 1 for simple model
V	Dimensionless velocity
V_m	Maximum velocity
V_1	Velocity tolerance limit
V_{des}	Desired velocity

1. INTRODUCTION

Background and Literature Review

Prior to the 1970's, little work was done on fuel optimization of diesel-electric locomotives. Before the mid 1970's fuel costs were less than 2% of freight revenues. There was little incentive in saving fuel, or encouraging practices which save fuel. Currently, fuel costs are approaching 15% of freight revenues. Fuel costs have now exceeded the cost of train and engine crew wages.[1]

A typical freight locomotive operating in the United States operates 17% of the time at full load, 28% at part load, 46% at idle, and 9% in the dynamic braking mode. A one per cent fuel savings on a 3000 hp locomotive operating on the above duty cycle will save $3,700 per locomtive per year.[2] Certainly, there is incentive to reduce fuel costs.

Surprisingly, not much work on fuel optimization of locomotives has been done to date. Most of the current effort in reducing fuel costs consists of eliminating fuel-inefficient train handling practices. Some of the

inefficient practices arise from the difficulty of maintaining a constant speed with a diesel-electric locomotive. To control the speed of the train, the locomotive operator has to select one of only eight throttle positions. In addition to only having eight thottle settings, each throttle setting corresponds to a constant power output from the engine. This means that, given a constant throttle setting, at different velocities, the force applied to the train is different and therefore the acceleration of the train is different.

One inefficient practice of train operation is power braking. "This method consists of applying the train brakes while continuing to use power [1]." Thus, to get a more accurate speed control, the train is operated at a higher throttle setting, with braking being applied to achieve the desired speed.

To overcome the use of power braking, "throttle modulation" is used. This method consists of varying the throttle postion to achieve the desired speed, rather than using braking while power is being applied. It is difficult in practice for the operator to apply this method. This difficulty is an additional incentive for a more effective speed controller.

With efforts being spent reducing such obviously inefficient practices, it is easy to see how more refined

methods of minimizing fuel costs have not yet been investigated. Besides eliminating wasteful practices, only a few other areas have been investigated.

One promising area is the development of MUTH, or Multiple Unit THrottle control. This method controls the locomotives of the train configuration, or consist, separately rather than as one unit. A typical consist contains either four or six locomotives. This enables most of the locomotives to operate at higher, more efficient throttle positions, as opposed to the entire consist operating in a lower, less efficient throttle position. While this method looks promising, it is still being evaluated, and is not in widespread use [1].

Despite the tremendous advancement in the knowledge of optimal control theory, optimal control theory has not proven to be effective in minimizing fuel costs for the diesel-electric locomotive. Previous papers have applied optimal control techniques to the optimum fuel control problem. The optimum control techniques applied included dynamic programming, the optimum principle, and energy tables. All of these methods resulted in large calculations, being too difficult to implement in an actual locomotive [3].

There is an additional problem in applying optimum control theory to a diesel-electric locomotive. There is

no accurate way to measure the instantaneous fuel flow rate. This is the result of a complicated engine fuel path. Thus, the fuel flow rate cannot be used as a control variable.

The paper by Kimura Y., and Koga S. [3], used a simpler approach. This paper minimized the kinetic energy of a train. Two different methods of train operation were compared: constant speed, and non-constant speed. The non-constant case consisted of a cycle of powering and coasting. Both cases had the same average velocity. The constant speed case was proven to have the lowest total kinetic energy. However, this method did not directly minimize actual fuel costs. In addition, it did not consider the potential savings in optimizing the method of applying power. Another method may yield the possibility of a higher fuel savings.

Topic of research

Since optimum control theory cannot easily be applied directly to the fuel optimization problem of the diesel-electric locomotive, this research concentrated on a trail and error approach. This was accomplished by running simulations using a train model. Different operation strategies were tested in the simulations to see which strategies resulted in the lowest fuel consumption.

The research considered only the problem of maintaining a constant average speed over a period of time. No attempts were made to save fuel while bringing the train to the desired operating speed. Similarly, no attempts were made to save fuel by optimizing braking strategy. In fact, it was assumed that braking was not used at any time in the simulations, since braking dissipates the kinetic energy, obtained by burning fuel, of the train. Thus, with this strategy, fuel savings will only be realized during the 28% of the duty cycle where the locomotive is operating at part loads.

The normal method of train operation consists of maintaining the constant speed by using a constant throttle setting. If it is not possible to maintain the speed with a constant throttle setting, than the throttle is varied between two adjacent throttle settings.

The method of train operation that was explored for potential fuel savings was of a general periodic nature. Instead of varying the throttle between two adjacent positions, the throttle was set at some high (and efficient) position, allowing the train to accelerate, and then setting the throttle at a low position, allowing the train to coast. The average speed over the cycle of acceleration and deceleration was equal to the desired constant speed. The high throttle position, the length of

the period of acceleration, and the length of the complete cycle were to be chosen to minimize fuel consumption. It was expected that the minimum fuel consumption by the periodic method would be less than the fuel consumed by the normal method of train operation.

This periodic method may, however, be an undesirable method of operating a train. An important factor in train operation is the amount of slack in the train. When the train accelerates or deccelerates, the amount of slack in the train changes. If the slack in the train changes too quickly, the equipment and car lading could be damaged. The length of the cycle needs to be examined to see if there is sufficient time between acceleration and deceleration for the slack to completely run-in or run-out.

The periodic method was first examined with a simplified model. The simplified model consisted of a model for a typical train and an assumed simple efficiency characteristic for the locomotive. This preliminary model was used only to explore some of the performance characteristics produced by the periodic method. It was not intended for any practical applications.

The preliminary model did show fuel savings while operating at certain velocities. With the promise of fuel savings with the periodic method of operation, a more

realistic model was then examined. This model used data from the E.M.D. (Electro-Motive Division of General Motors) SD40 locomotive. The same train model was used as in the previous case.

Unfortunately, the periodic method did not show any fuel savings for the more realistic model using the periodic method of operation. No particular selection of the parameters of the periodic cycle resulted in a lower fuel consumption than the normal method of operating a train.

However, there is still potential for fuel savings using the periodic method. The way that the diesel engine in the locomotive is designed does not take full advantage of periodic operation. It may be possible to modify the diesel engine to obtain fuel savings using the periodic operation that would not be possible with normal train operation.

An engine modification is suggested that improves only the efficiency of the high throttle position. With this modification, the periodic method of operation was shown to show a fuel savings over normal train operation.

A controller was then designed to implement the periodic operation. The controller was designed with several important features in mind. First, it was designed with the idea of using a small digital computer aboard the

locomotive. Microprocessors are already replacing analog circuits in locomotives [4], so the addition of a digital computer should not be too difficult. Second, the controller will accept the desired speed as the reference input, not a desired power level. This feature alone should save fuel since it will eliminate the inefficient practices that arise from not having an effective speed control. Third, the controller will automatically compensate for the level of grade on the track. This was accomplished using an observer. Last, the controller will be able to estimate important information that is difficult to measure, such as the tractive effort and instantaneous fuel flow rate.

All simulations were done with the Advanced Continous Simulation Language (ACSL) [5]. This simulation language consists of FORTRAN statements, with integration routines accessed by simple FORTRAN-like statements. The integration routines used were fourth-order Runge-Kutta.

2. SIMPLE MODEL

Train Model

The train model, or train dynamic equation, was derived largely from the empirically developed Davis equation. The Davis equation calculates the train resistance and is given in [6] as

$$R = 1.3 + 29/w + 0.045v + 0.0005Av^2/wn, \qquad (1)$$

where

R = train resistance in lb/ton
w = average weight per axle in tons
v = train speed in mph
n = total number of axles
A = effective frontal cross sectional area of car in sq ft.

Thus, the train resistance is a non-linear function of velocity. For the purposes of the train model, we need the train resistance in units of lb (N), and the velocity in

ft/sec (m/s). The equation for the train resistance in these units is

$$R = d_1 + d_2 v + d_3 v^2, \qquad (2)$$

where

d_1 = constant resistance coefficient (for fixed w) in lb (N)

d_2 = linear damping coefficient in lb·s/ft (N·s/m)

d_3 = square-law damping coefficient in lb·s^2/ft^2 (N·s^2/m^2).

For our model, we will assume a train consisting of one locomotive and twenty loaded coal cars. A locomotive weighs approximately 500 tons (450,000 kg) and a loaded coal car weighs approximately 125 tons (112,000 kg). This would give a total train weight of 3000 tons (2,700,000 kg). Both the locomotive and the cars have four axles each (some locomotives do have six axles). This gives a total number of 84 axles for the train. The effective cross-sectional area will be assumed to be 120 sq ft (11 sq m). The resistance coefficients d_1, d_2, and d_3 can now be computed.

d_1 = 6340 lb (28,200 N).

d_2 = 76.7 lb·s/ft (1120 N·s/m).

d_3 = 0.0279 lb·s^2/ft^2 (1.33 N·s^2/m^2).

The mass of the train is 155,000 lb·s^2/ft ($2.27 \cdot 10^6$ kg). The dynamic equation of the train is given by

$$M(dv/dt) = F - R, \tag{3}$$

where

F = the force applied to the train by the locomotive

M = total train mass.

The complete train model is then given by substituting the resistance equation 2 into equation 3.

$$M(dv/dt) = F - d_1 - d_2v - d_3v^2. \tag{4}$$

Simple Locomotive Model

Now that we have a model for the train, it is now necessary to model the locomotive. For the simple model, this will consist of only of the force applied to the train and an assumption of how the fuel consumption rate is determined.

For the simple model, the efficency, n, is assumed to be as shown in Fig. 1. The maximum efficiency occurs at 60 ft/s (18.3 m/s) with a value of 100%. As the velocity increases or decreases from this value, the efficiency decreases. The equations for the efficiency are

$$n = 40+v\ (12.1+v)\ \%, \quad v < 60\ \text{ft/s}\ (18.3\ \text{m/s}) \tag{5}$$

$$n = 160-v\ (48.8-v)\ \%, \quad v > 60\ \text{ft/s}\ (18.3\ \text{m/s}) \tag{6}$$

For this simple model, we will assume that the rate at which fuel is consumed is proportional to the force applied to the train divided by the efficiency, or

$$dE/dt = F/n \tag{7}$$

where

E = the fuel (energy) used.

Fuel Optimization Strategy

Our goal is to try to find a more economical way to run a train than operating at a constant velocity. This will be done by letting the train accelerate and

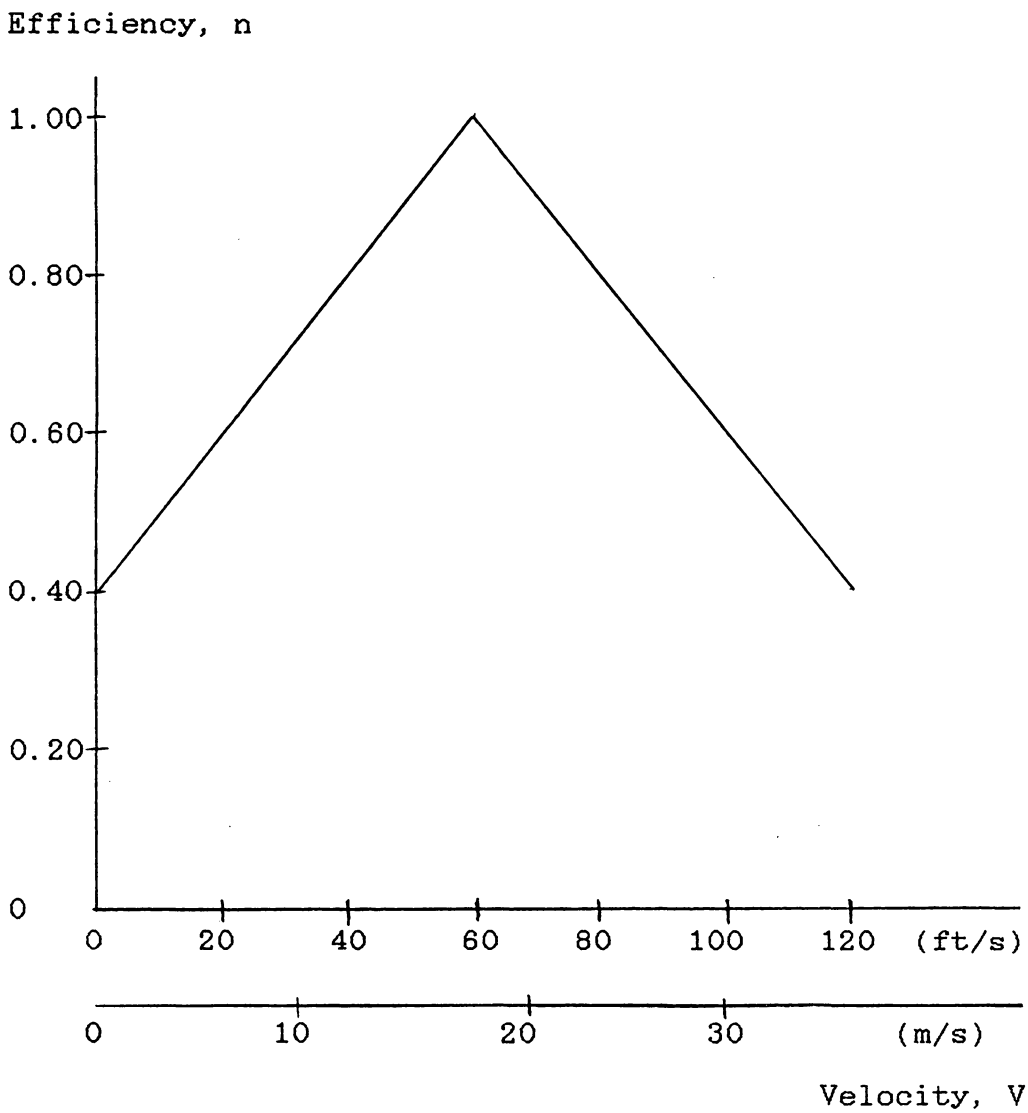

Figure 1. Efficency Curve for Simple Locomotive Model

decelerate so as to maintain the same average speed as if it were operating at a constant velocity. The cycle of acceleration and deceleration that uses the least amount of fuel will be found by trial end error. Before finding a way to operate the train in the desired periodic manner, it is necessary to first look at the operation of the constant velocity train.

The force required to keep a train moving at constant velocity can easily be computed. If the train is moving at constant velocity, the acceleration is zero. From equation 3, the force applied to the train by the locomotive is equal to the train resistance. From equation 2, the force is

$$F = d_1 + d_2 v + d_3 v^2. \qquad (8)$$

Thus, in order to run a train at a constant velocity, a constant force must be applied to the train that will sustain this constant velocity.

One alternative to constant velocity operation is the application of a time-varying force to the train. If the time-varying force has the same average force over time as the force necessary to keep the train traveling at a constant velocity, the train should have the same average velocity. Figure 2 shows the parameters, F_0, F_1, F_2, t_0,

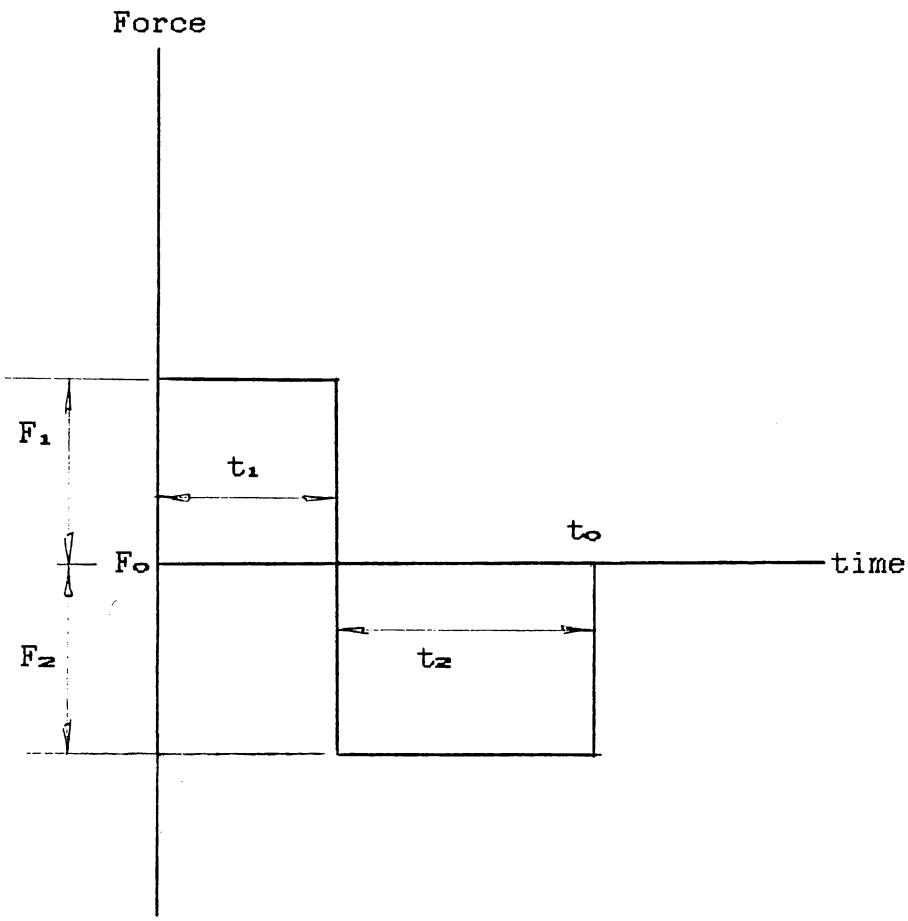

Figure 2. Parameters of the Periodic Force

t_1, and t_2 of the time-varying force that were considered for the train operation. F_o is the force necessary to keep the train at a constant velocity.

To compare the two methods, a simulation of both trains was formulated. Figure 3 shows a block diagram of this simulation. The constant force, F_o is applied to the first train. A time-varying force, dF is added to F_o to get the input force for the second train. The force dF is the value of F_1 if $t < t_1$, or F_2 if $t > t_1$. E_o and E_1 are the energies consumed by train 0 and train 1.

Results of the Simulation

The program for the simple model is given in Appendix A. The periodic train (train 1) was run for one cycle and then the two trains were compared. For an accurate comparison of the two trains, train 1 must end at the same velocity as it started. This will insure a steady-state cyclic operation. In the program, this starting velocity was found by using the ending velocity as the initial condition for the next run. By repeatedly running the train model, the steady-state starting velocity will eventually be reached.

For the first case examined, the train model was first tested at a velocity of 88 ft/sec (27 m/s). This is on the downward sloping portion of the efficiency curve.

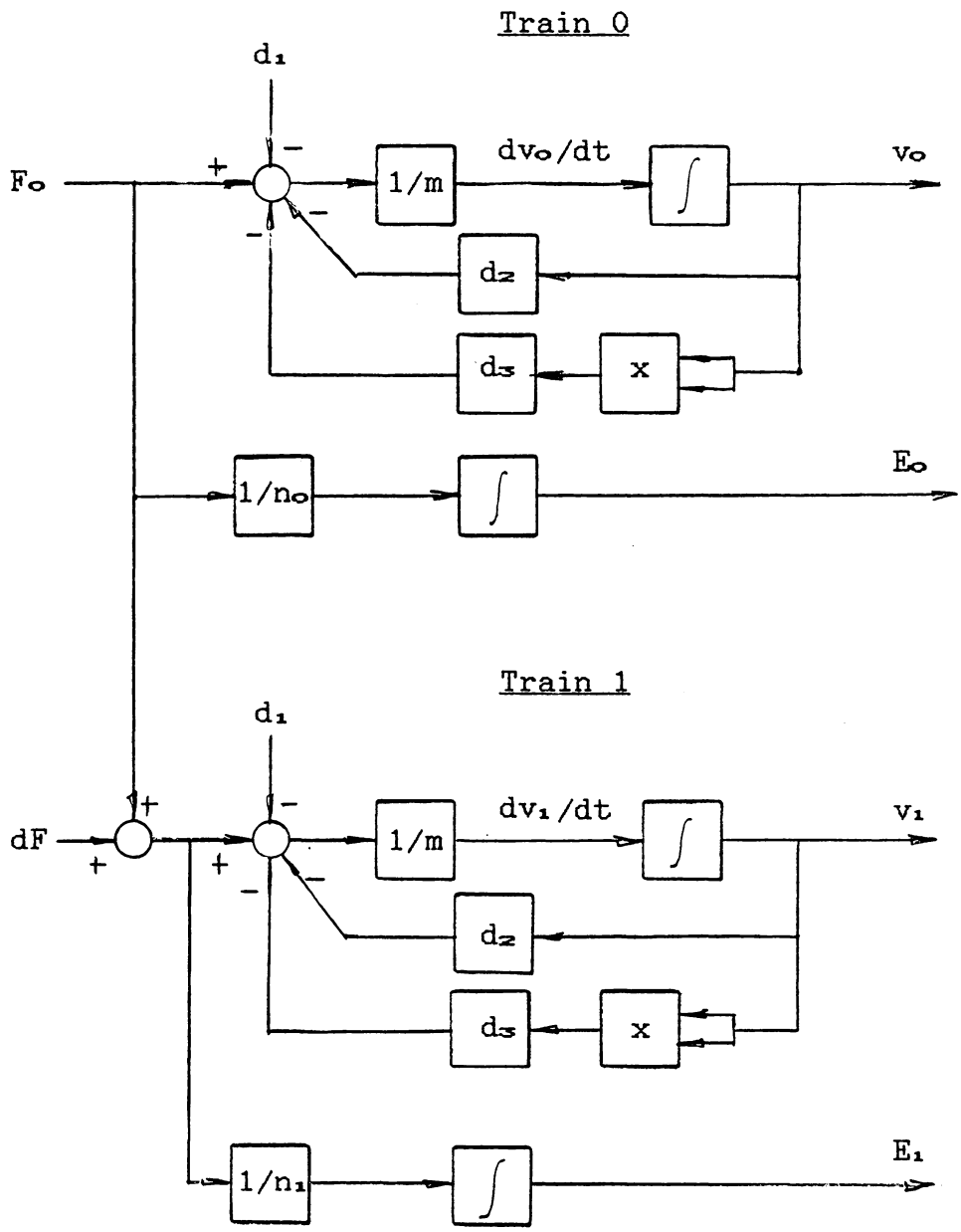

Figure 3. Block Diagram of Simple Train Model.

The length of the cycle was chosen to be 1000 s. F_1 and F_2 were both chosen to be 4000 lb (17,800 N). t_1 and t_2 are then 500 s. The velocity for the two trains is shown in Fig. 4. The energy used by both trains was found to be the same, 1.85×10^7 units. In this case, there is no advantage in operating in a periodic manner.

The second case examined had the same starting velocity and length of cycle as the previous case, but had a different time-varying force. In this case, F_1 was chosen to be 8000 lb (35,600 N), and F_2 was chosen to be 2000 lb (8900 N). F_1 was applied for 200 s, and F_2 was applied for 800 s. The velocities for the two trains for this case are shown in Fig. 5. The energy used by both trains in this case was found to be the same as the first case examined. Since the non-symmetric time-varying force did have the same energy consumption as both a symmetric time-varying force and a constant force, we can conclude that any time varying force with the same average force and average velocity will have the same energy consumption. We have only demonstrated this conclusion on the downward part of the efficiency curve.

The same conclusion was reached for the two trains operating on the upward sloping portion of the efficiency curve. The results of case 3 and case 4 tested on this portion of the efficiency curve, along with cases 1 and 2

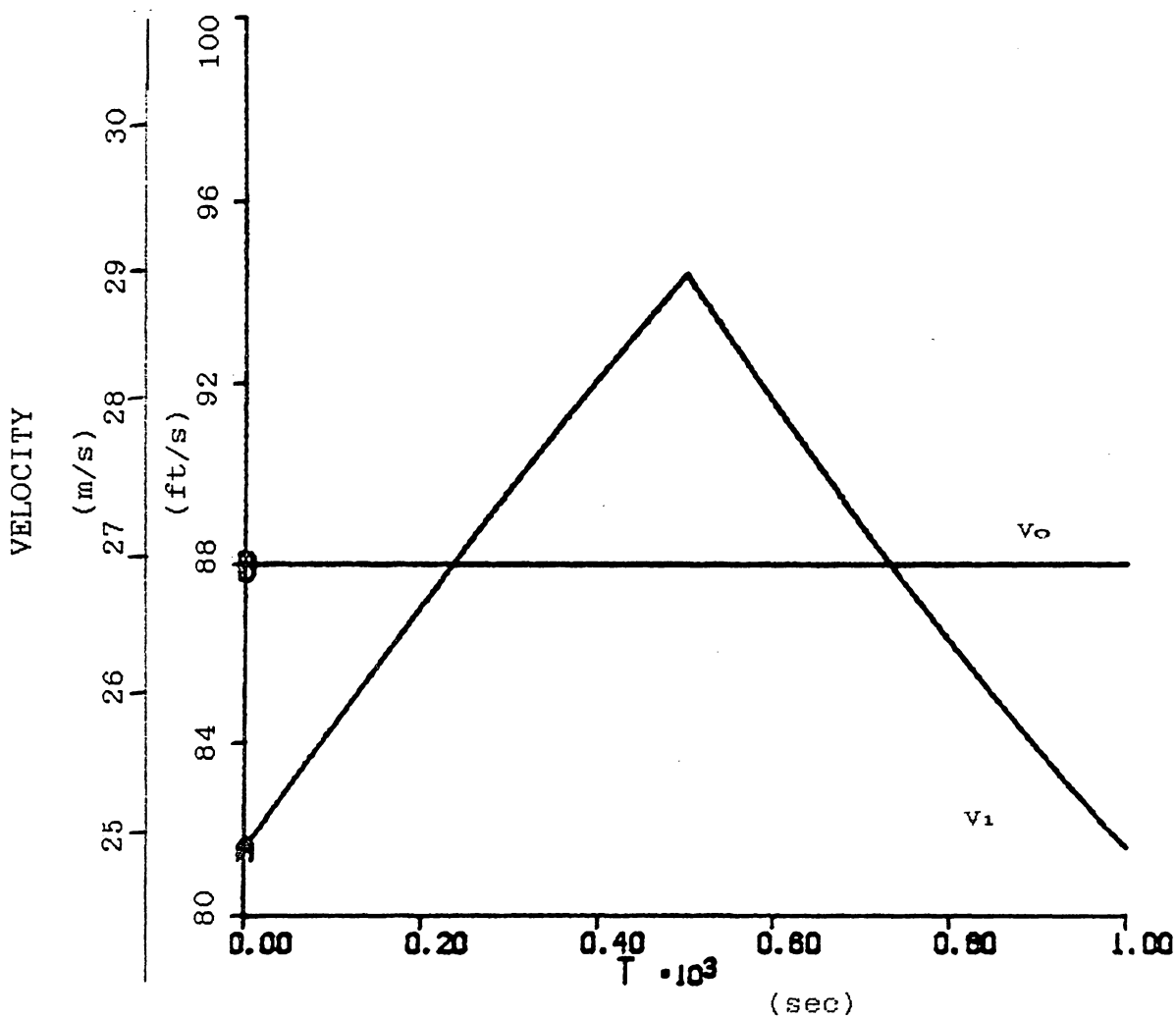

Figure 4. Velocity of Simple Train Simulation with Symmetric Time-varying Force on Downward Sloping part of Efficiency Curve

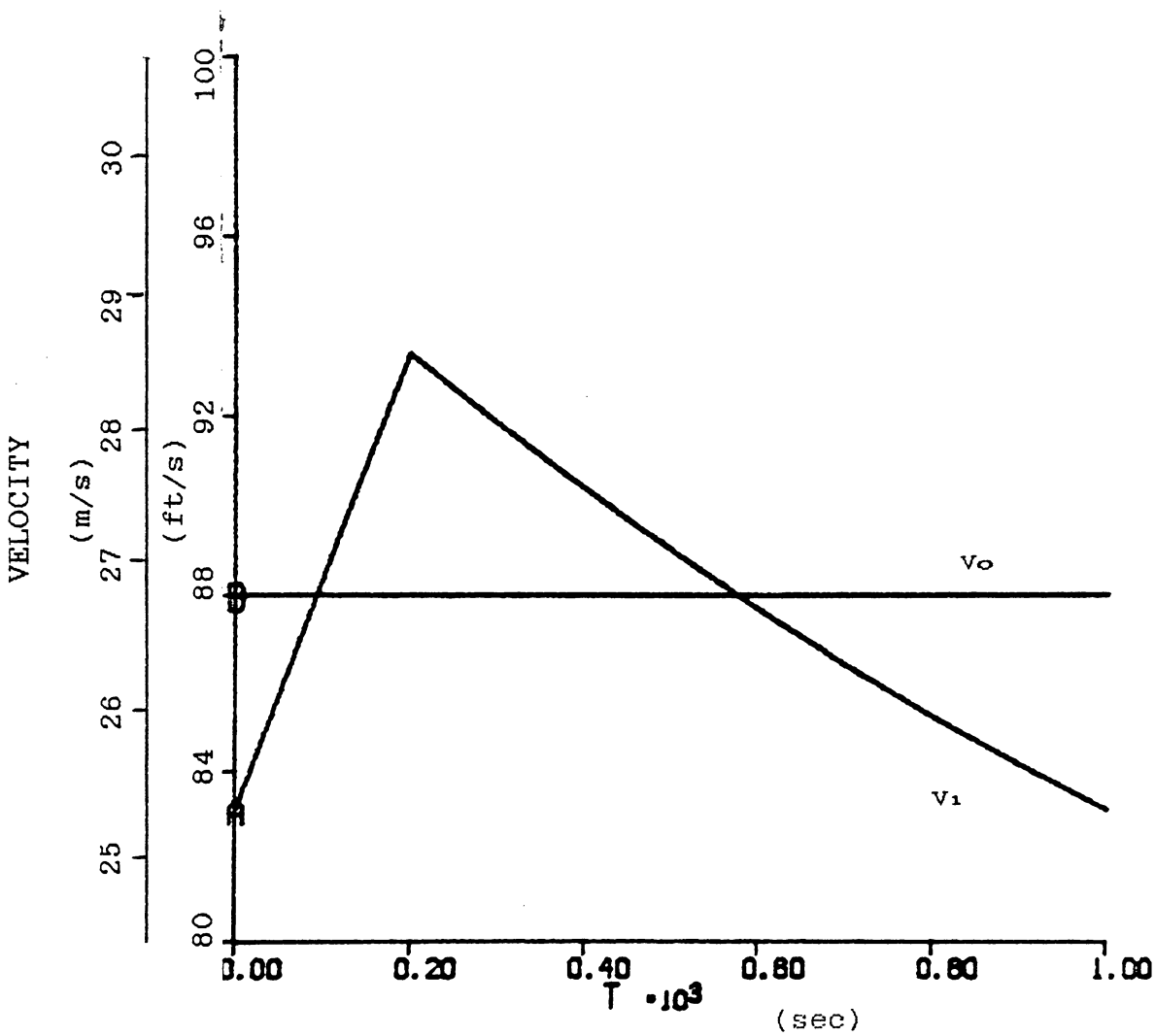

Figure 5. Velocity of Simple Train Simulation with Non-Symmetric Time-varying Force on Downward Sloping part of Efficiency Curve

are shown in Table 1.

Next, the periodic operation which included both the upward and downward sloping parts of the efficiency curve was examined. This occurs when the velocity v_o is near the peak of the efficiency curve. Cases 5, 6, and 7 explored this part of the efficiency curve. All three cases had the constant velocity, v_o, at the very peak of the curve. The results of these cases are given in Table 2.

Case 5 examined a symmetric time-varying force. The velocities of the trains for this case are shown in Fig. 6. The train with the time-varying force had a higher energy consumption than the train with the constant velocity. Therefore, the periodic operation in not more energy efficient for this case.

Case 6 examined a longer cycle time. The velocites for the two trains in this case are shown in Fig. 7. The train with the time-varying force showed an even greater difference in the energy consumed from the constant force train than did case 5, with the shorter cycle length.

Case 7 examined the effect of a non-symmetric time-varying force. The velocities of the two trains for this case are given in Fig. 8. The train with the time-varying force showed less difference in energy consumed over the constant force train than did case 5.

Table 1. Summary of Results for Simple Train Model on Upward and Downward Portions of Efficiency Curve

Case	1	2	3	4
t_o (s)	1000	1000	1000	1000
v_o (ft/s)	88	88	44	44
(m/s)	26.7	26.7	13.4	13.4
F_o (lb)	13,300	13,300	9770	9770
(N)	59,200	59,200	43,500	43,500
F_1 (lb)	4000	8000	4000	8000
(N)	17,800	35,600	17,800	35,600
F_2 (lb)	4000	2000	4000	2000
(N)	17,800	8900	17,800	8900
t_1 (s)	500	200	500	200
t_2 (s)	500	800	500	800
E_o ($\times 10^6$)	18.5	18.5	11.6	11.6
E_1 ($\times 10^6$)	18.5	18.5	11.6	11.6

Table 2. Summary of Results for Simple Train Model Operating Around the Peak of the Efficiency Curve

Case	5	6	7
t_o (s)	1000	2000	1000
v_o (ft/s)	60	60	60
(m/s)	18.3	18.3	18.3
F_o (lb)	11,000	11,000	11,000
(N)	49,100	49,100	49,100
F_1 (lb)	4000	4000	8000
(N)	17,800	17,800	36,600
F_2 (lb)	4000	4000	2000
(N)	17,800	17,800	8900
t_1 (s)	500	1000	200
t_2 (s)	500	1000	800
E_o ($\times 10^6$)	11.0	22.1	11.0
E_1 ($\times 10^6$)	11.4	23.6	11.3
Difference in E_o, E_1 (%)	4	7	3

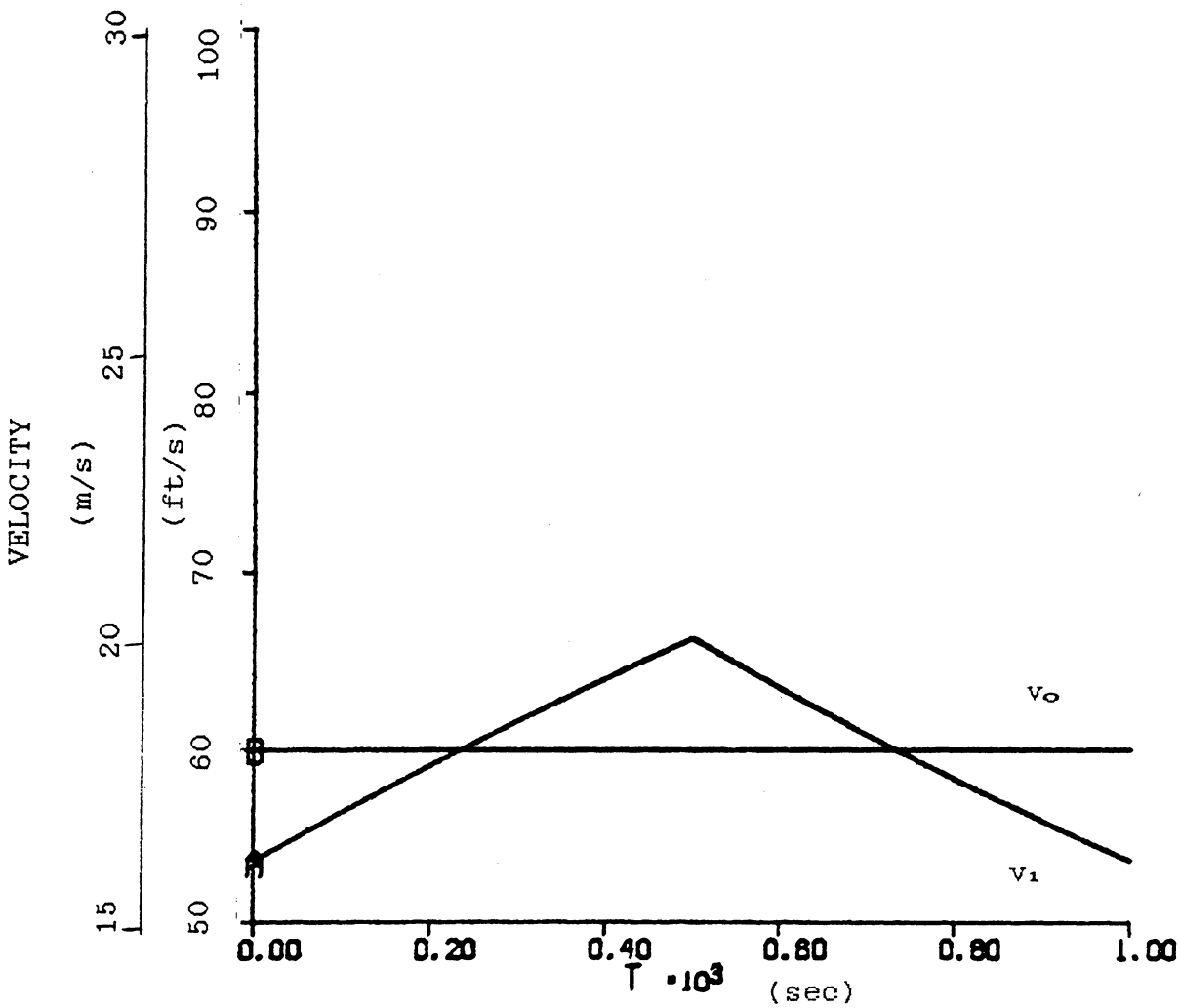

Figure 6. Velocity of Simple Train Simulation with Symmetric Time-Varying Force Around the Peak of the Efficiency Curve

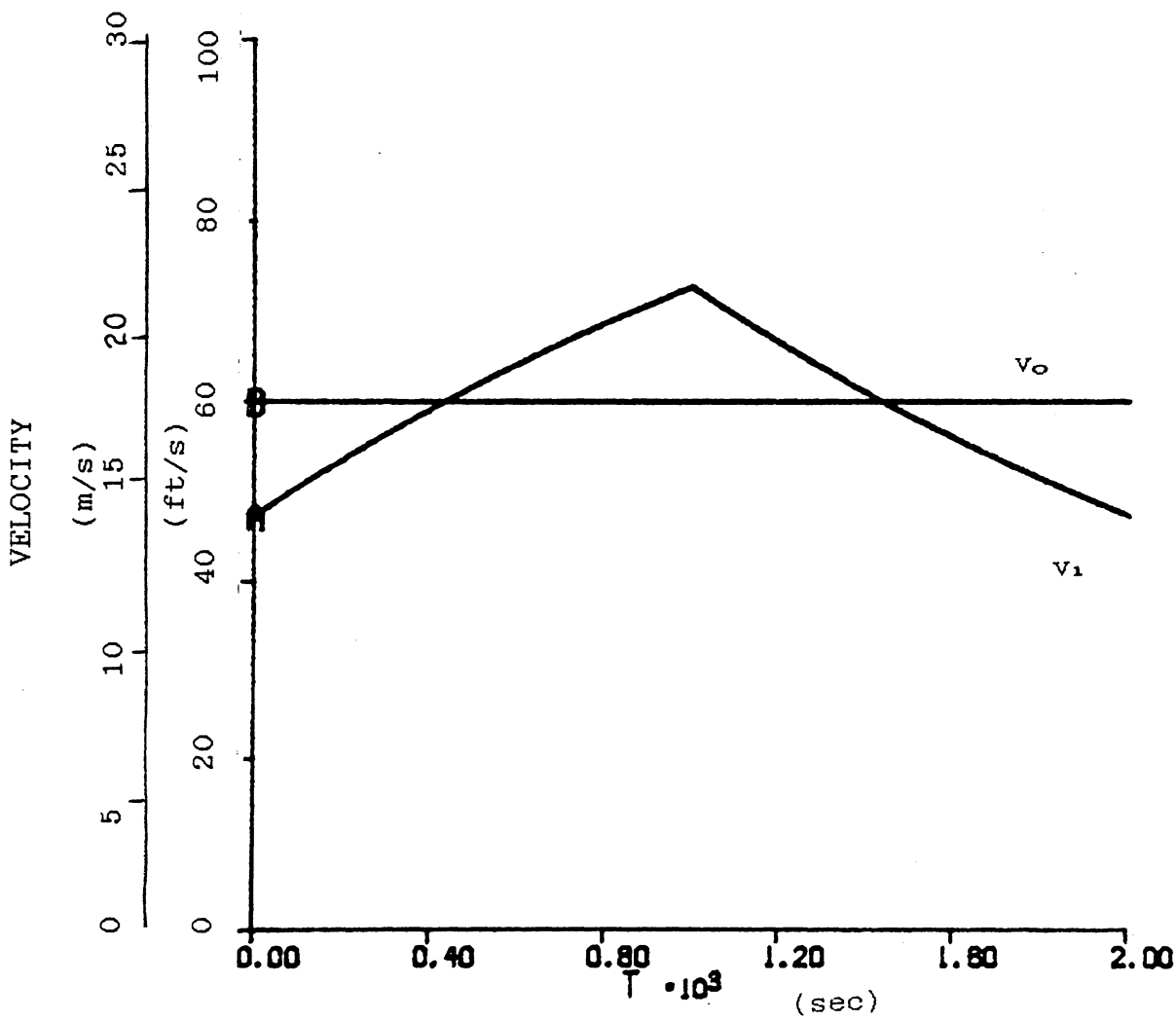

Figure 7. Velocity of Simple Train Simulation with Symmetric Time-Varying Force Around the Peak of the Efficiency Curve, with Longer Cycle

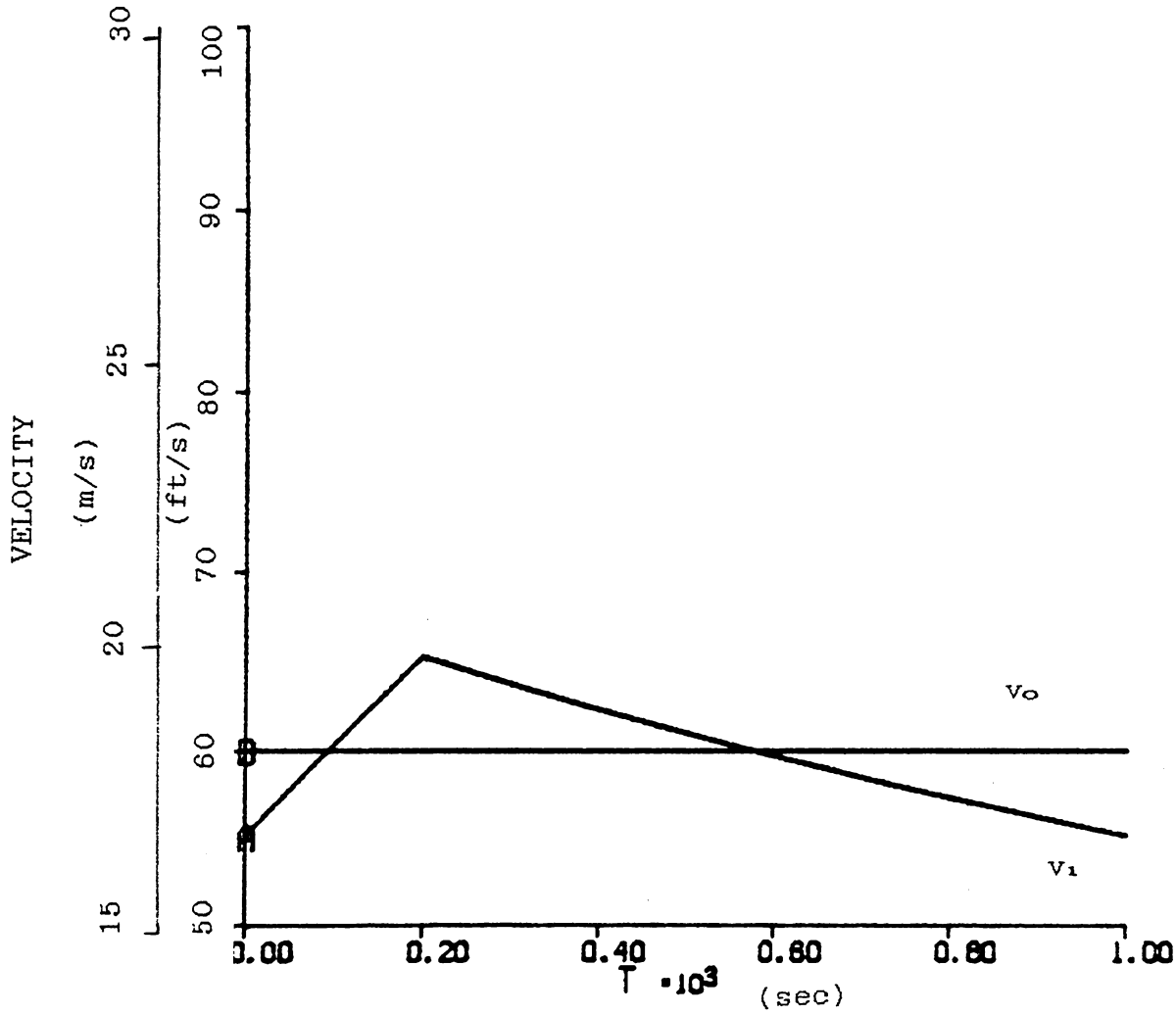

Figure 8. Velocity of Simple Train Simulation with Non-Symmetric Time-Varying Force Around the Peak of the Efficiency Curve

From these three cases, we can conclude that the periodic operation does not save energy over the constant velocity operation. For the periodic operation around the peak of the efficiency curve, more energy is consumed for a longer cycle. Also, less energy is consumed when the difference in the two values of the time-varying force, F_1 and F_2, is greatest.

As stated before, the efficiency assumption does not correspond to an actual locomotive. The model was still useful, since some insight into the fuel consumption characteristics of the locomotive was gained. The periodic operation was shown to have the same energy consumption over most velocity ranges. Perhaps a more realistic model will show fuel savings with the periodic operation.

From the results of the simple model, the effect of slack in the train can now be examined. The important consideration is how quickly the slack changes. If the slack changes too quickly, excessive slack action can result. The cycle length of 1000 seconds resulted in small changes in velocity. Since the length of time of acceleration and deceleration is as long as 500 seconds, plenty of time can be allowed to slowly change the force applied to the train so as not to allow slack action. Thus, since the cycle times are long, slack action in the train is not a problem for periodic operation.

3. E.M.D. SD40 LOCOMOTIVE MODEL

The next model is based on the SD40 locomotive, manufactured by the Electo-Motive Division of General Motors. The data used in this model is shown in Table 3 [7], and only considers the steady-state operation of the diesel engine. The diesel engine in the locomotive is designed to operate at a constant speed and torque for a constant throttle setting. Thus, the output power and specific fuel consumption are nearly constant for a given throttle setting.

The fuel flow rate can easily be calculated from the specific fuel consumption and the engine power. Values for the specific gravity of diesel fuel can range from 0.82 to 0.95. The specific gravity was assumed to be 0.90 for all calculations. The calculated fuel flow rates for the different throttle settings are shown in Table 3. An example of the calculation of the fuel flow rates is given for the first throttle setting.

$$\text{Fuel Flow Rate} = (\text{BSFC})(\text{Power})$$
$$= (0.6299\ \text{lb/hp·hr})(96\ \text{hp})$$

Table 3. Engine RPM, Power, BSFC, and Fuel Flow Rates for the SD40 Locomotive

Throttle Position	Engine Speed (RPM)	BSFC (lb/hp·hr)	Power (hp)
1	315	0.6299	96
2	392	0.4160	392
3	479	0.3894	692
4	560	0.3780	1049
5	647	0.3677	1525
6	732	0.3646	2048
7	818	0.3637	2742
8	900	0.3638	3266

Throttle	Fuel Flow Rate		
Position	(lb/hr)	(kg/hr)	(gal/hr)
1	60.5	27.4	8
2	163.1	74.0	22
3	269.5	122.2	36
4	396.5	180.0	53
5	560.7	254.3	75
6	746.7	338.7	100
7	997.3	452.4	130
8	1188	538.8	160

$$= 60.4 \text{ lb/hr}$$

$$= (60.4 \text{ lb/hr})(7.481 \text{ gal/ft}^3)/$$
$$(0.90)(62.4 \text{ lb/ft}^3)$$

$$= 8.0 \text{ gal/hr}$$

$$= 27.4 \text{ kg/hr}$$

The tractive effort of the locomotive can be computed from the engine power and train velocity. It was assumed that the efficiency, n_g, of the generator and tractor motors was 0.92. The tractive effort, F, is then

$$F = n_g p/v, \tag{9}$$

where

p = output power of the locomotive.

From equation 4, the dynamic equation for the locomotive and train is

$$M(dv/dt) = n_g p/v - d_1 - d_2 v - d_3 v^2. \tag{10}$$

This equation would be much easier to work with in a

non-dimensional form. The non-dimensional equation will serve several purposes. Each set of parameters corresponds to a family of different models. Also, each variable will always vary between zero and one.

To put equation 10 into non-dimensional form, first let

$$V = v/V_m, \text{ the dimensionless velocity} \quad (11)$$

$$P = p/n_d P_m, \text{ the dimensionless power} \quad (12)$$

$$T = t/T_r, \text{ the dimensionless time,} \quad (13)$$

where

V_m = maximum velocity

P_m = maximum power

T_r = reference time.

Then

$$dV = dv/V_m \quad (14)$$

$$dT = dt/T_r. \quad (15)$$

Substituting equations 11-15 into equation 10 gives

$$MV_m/T_r(dV/dT) = P_m P/V_m V - d_1 - d_2 V_m V - d_3 V_m^2 V^2. \quad (16)$$

Dividing equation 16 by MV_m/T_r gives

$$dV/dT = [P_m T_r/MV_m^2]P/V - [d_1 T_r/MV_m] - [d_2 T_r/M]V - [d_3 T_r V_m/M]V^2. \quad (17)$$

Now let the dimensionless coefficients be defined as

$$c_0 = P_m T_r/MV_m^2 \quad (18)$$

$$c_1 = d_1 T_r/MV_m \quad (19)$$

$$c_2 = d_2 T_r/M \quad (20)$$

$$c_3 = d_3 T_r V_m/M. \quad (21)$$

Equation 17 becomes

$$dV/dT = c_0 P/V - c_1 - c_2 V - c_3 V^2. \quad (22)$$

To simplify equations 18-21 somewhat, choose

$$T_r = MV_m^2/P_m, \quad (23)$$

So that the dimensionless coefficients become

$$c_0 = 1 \quad (24)$$

$$c_1 = d_1 V_m/P_m \quad (25)$$

$$c_2 = d_2 V_m^2 / P_m \quad (26)$$

$$c_3 = d_3 V_m^3 / P_m. \quad (27)$$

The maximum velocity, V_m, was chosen to be 125 ft/s (38.1 m/s). The maximum power was chosen to be the value at throttle position 8, multiplied by the efficiency, 0.92. Using the values of d_1, d_2, and d_3 from the simple model, the parameters c_0, c_1, c_2, and c_3 can be computed to be

$$c_0 = 1$$

$$c_1 = 0.431$$

$$c_2 = 0.726$$

$$c_3 = 0.033.$$

The reference time in equation 23 can be computed to be 1470 s. Table 4 lists the non-dimensional power and fuel flow rate for each throttle setting. The non-dimensional fuel flow rate was computed by dividing by the maximum fuel flow rate.

The model for the SD40 locomotive is now complete. The block diagram for this model is shown in Fig. 9. The amount of fuel consumed is given by Q. Note that the throttle setting is the input. Once the input is given, the engine power is known, and the dynamic equation can be

Table 4. Non-dimensional Power and Fuel Flow Rate for the SD40 Locomotive Model

Throttle Position	Power	Fuel Flow Rate
idle	0	0.026
1	0.0294	0.051
2	0.120	0.137
3	0.212	0.227
4	0.321	0.334
5	0.467	0.472
6	0.627	0.629
7	0.840	0.839
8	1.00	1.00

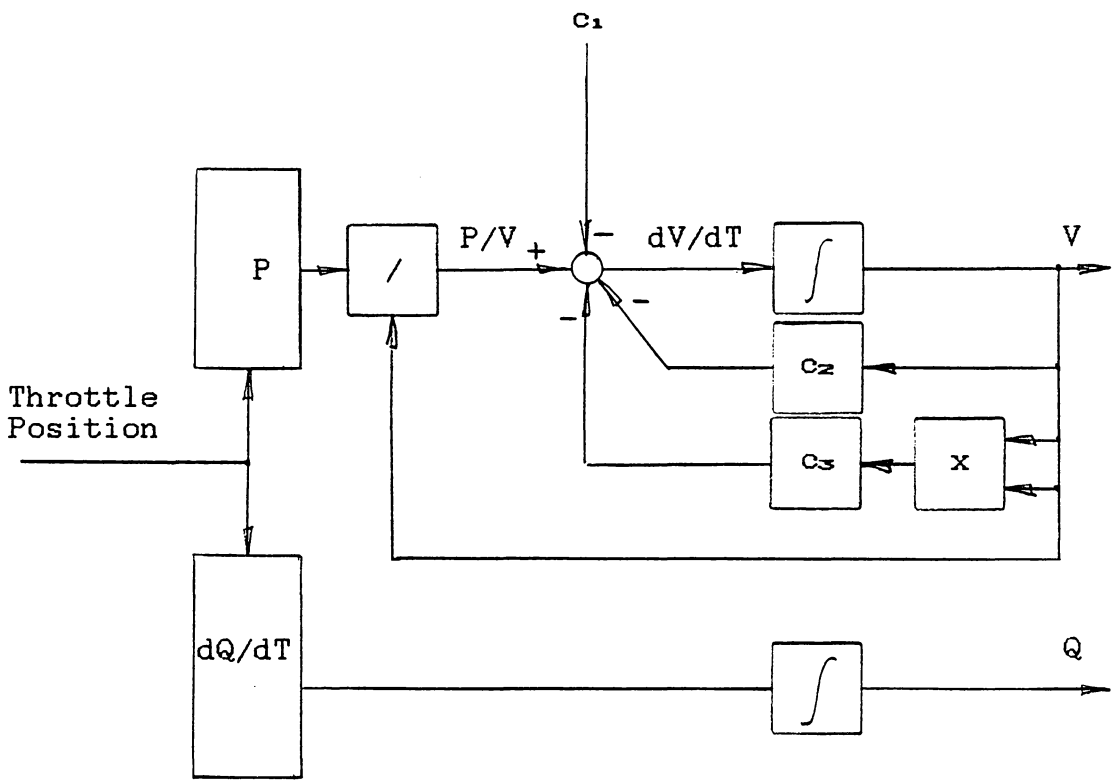

Figure 9. Block Diagram of SD40 Locomotive Model

solved. The fuel flow rate can also be determined.

This model does not consider the transient effects in the engine while switching throttle settings. From the results of the simple model, we know that a small change in velocity takes a long time to occur. Any transient effects in the engine would occupy only a small portion of the total time of the cycle. Thus, the transient effects will not have a large effect on the outcome of the simulation.

4. OPERATING STRATEGY FOR THE SD40 LOCOMOTIVE

The parameters of the periodic operation of the SD40 locomotive operation are different from those used on the simple locomotive model. Instead of choosing values for a time-varying force, high and low throttle settings must be chosen. In order to get a good idea of likely choices for the high and low throttle settings, it is helpful to look at the efficiency of the engine. The efficiency of the engine is given by

$$\eta = P_{out}/P_{in}. \tag{28}$$

The input power is given by

$$P_{in} = P_{out} \cdot BSFC \cdot HHV, \tag{29}$$

where

HHV = higher heating value.

Therefore,

$$n = 1/BSFC \cdot HHV \tag{30}$$

The range of higher heating values (HHV) for diesel fuel is between 18,500 (42,900 kJ/kg) and 20,000 Btu/lb (46,400 kJ/kg). For all calculations, the HHV is assumed to be 19,000 Btu/lb (44,100 kJ/kg). An example of the calculation of the efficiency is given for the first throttle setting

$$\begin{aligned} n &= (1/BSFC)/HHV \\ &= (1/0.6299 \text{ lb/hp·hr})/(19{,}000 \text{ Btu/lb}) \\ &\quad \times (2545 \text{ Btu/hp·hr}) \\ &= 0.213 \end{aligned}$$

Table 5 shows the efficiency for the different throttle settings and the efficiency characteristics are given in Fig. 10.

In looking at the efficiency for the SD40 locomotive, the efficiency does not depend on velocity, as did the simple model. This means that the locomotive should be operated at the highest efficiency, independent of the velocity of the train. Looking at Table 5, the efficiency is highest at throttle position 7 or 8, and then decreases with decreasing throttle position. This means that the

Table 5. SD40 Engine Efficiency

Throttle Possition	Efficiency
1	0.213
2	0.322
3	0.344
4	0.354
5	0.364
6	0.367
7	0.368
8	0.368

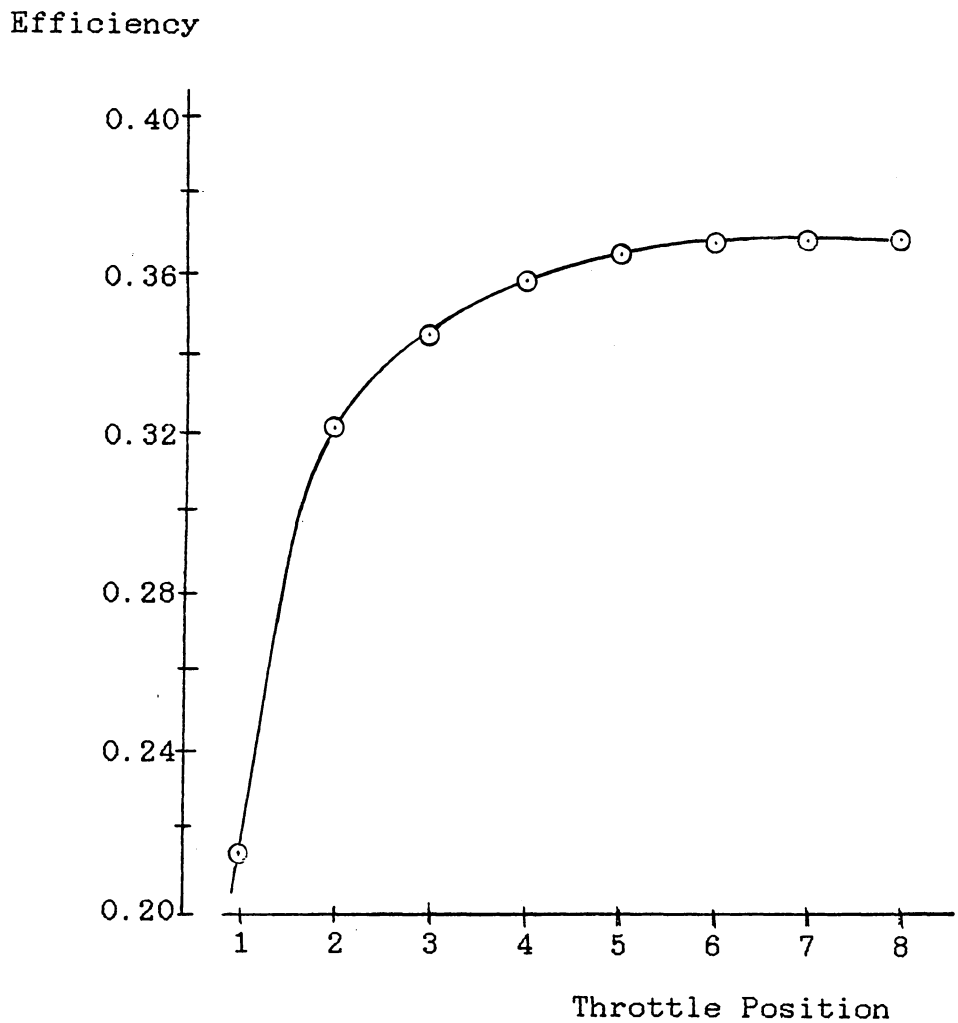

Figure 10. SD40 Locomotive Efficiency Characteristics

locomotive should be operated at throttle position 7 or 8 as often as possible.

The following strategy was selected to operate the train in a periodic manner. First, a velocity tolerance limit, V_t, is chosen, and also a desired velocity, V_{des}. Then if

$V > V_{des} + V_t$, select a low throttle position

$V < V_{des} - V_t$, select throttle position 7 or 8.

The program given in Appendix B was used to simulate the train in either the constant velocity mode or the periodic mode. The particular mode depends on the logical variable CV.

The periodic operation was first compared to the normal operation at the velocites corresponding to constant throttle settings. These velocities can easily be obtained. They were calculated by selecting a throttle setting, and letting the train simulation run until a constant velocity was reached. These values are given in Table 6.

There is some problem in comparing the periodic operation with the constant velocity operation. The problem is that even though the train is operating with a velocity limit above and below the desired velocity, the

Table 6. Velocites at Constant Throttle Settings for the SD40 Locomotive Model

Throttle Possition	Velocity
1	0.0564
2	0.193
3	0.302
4	0.410
5	0.533
6	0.649
7	0.785
8	0.876

desired velocity is not necessarily the average velocity. If the average velocities are not the same, the fuel consumption cannot be compared.

Some of the problem is due to the starting transient which results from choosing the wrong initial velocity. Choosing the desired velocity minus the velocity limit for the initial value will help eliminate transient behavior.

The solution to the problem is to run the simulation for a long period of time to further reduce the transient behavior, and then to check the average velocity. To make this easier, the program was modified to stop the simulation at a certain distance travelled, rather than at a certain time elapsed. Then the elapsed time of the simulation can be used to determine the average velocity. The average velocities were found to be accurate to three decimal places, with the exception of very small velocities. An accurate comparison was not obtainable for the velocity corresponding to the constant throttle position one. There was no problem for the velocities corresponding to other constant throttle postions.

The high throttle position was first chosen to be at 7. The low throttle position was chosen to be at idle. On the SD40 locomotive, there are two idle settings. For the simulation, it was assumed that the low idle setting was used. The velocity limit was chosen to be 0.02. The

nature of the periodic behavior can be seen from the desired velocity corresponding to to the constant throttle position 5, in Fig. 11. As can be seen in Table 7, the periodic operation has a worse fuel performance than operating at a constant velocity. The periodic operation used as much as 4% more fuel and no less than 1% more fuel than the constant velocity operation.

Next, the low throttle position was chosen to be at 1. This gives some performance advantages over operating at idle in that wheel slip protection is maintained [6]. It take slightly more time for the train to decelerate than when the low throttle setting was at idle. The desired velocity corresponding to the constant throttle position at 5 is shown in Fig. 12. The fuel performance is still worse than the constant velocity operation, as seen in Table 7. The fuel performance is slightly better than when the low throttle postion was chosen to be at idle. The difference between the periodic operation and the constant velocity operation was slight, with no more than a 1% difference in the fuel consumed by the periodic operation as opposed to the constant velocity operation.

Other combinations of low and high throttle settings were examined. None of the combinations had a better fuel performance than the two combinations of throttle settings of 1 and 7, and idle and 7. If a higher throttle postion

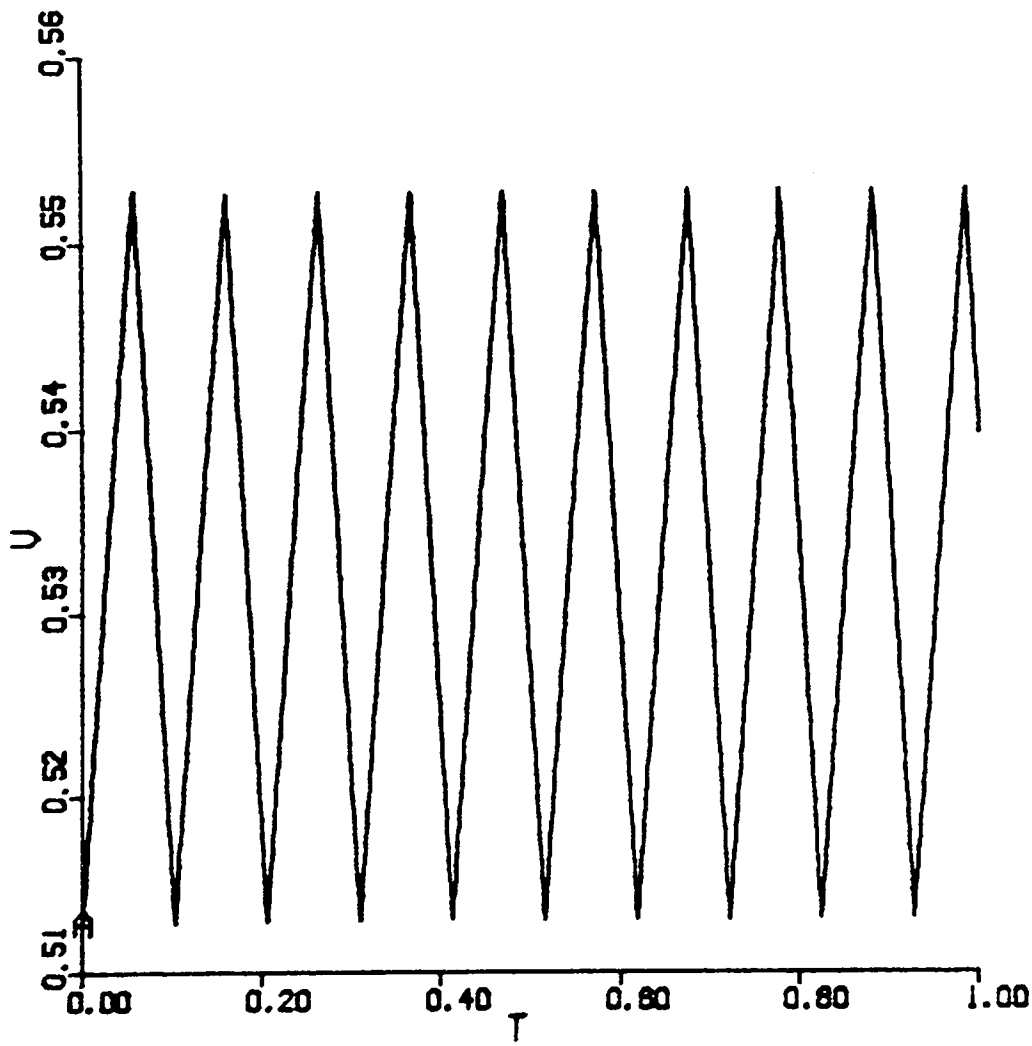

Figure 11. Velocity of Periodic Cycle, with Low Throttle Setting at Idle, Desired Velocity at 0.533

Table 7. Fuel Consumption Comparison of the Periodic Operation and Constant Velocity Operation

Switching From Idle to Throttle Position 7

Throttle Position	Periodic	Constant Velocity	Savings (%)
1	0.05	0.051	*[1]
2	0.142	0.137	-4
3	0.231	0.227	-2
4	0.338	0.334	-1
5	0.478	0.472	-1
6	0.634	0.629	-1

Switching From Throttle Position 1 to Position 7

Throttle Position	Periodic	Constant Velocity	Savings (%)
2	0.139	0.137	-1
3	0.230	0.227	-1
4	0.335	0.334	-0.3
5	0.478	0.472	-1
6	0.633	0.629	-0.6

1. The fuel consumed was not accurate enough to make a comparison.

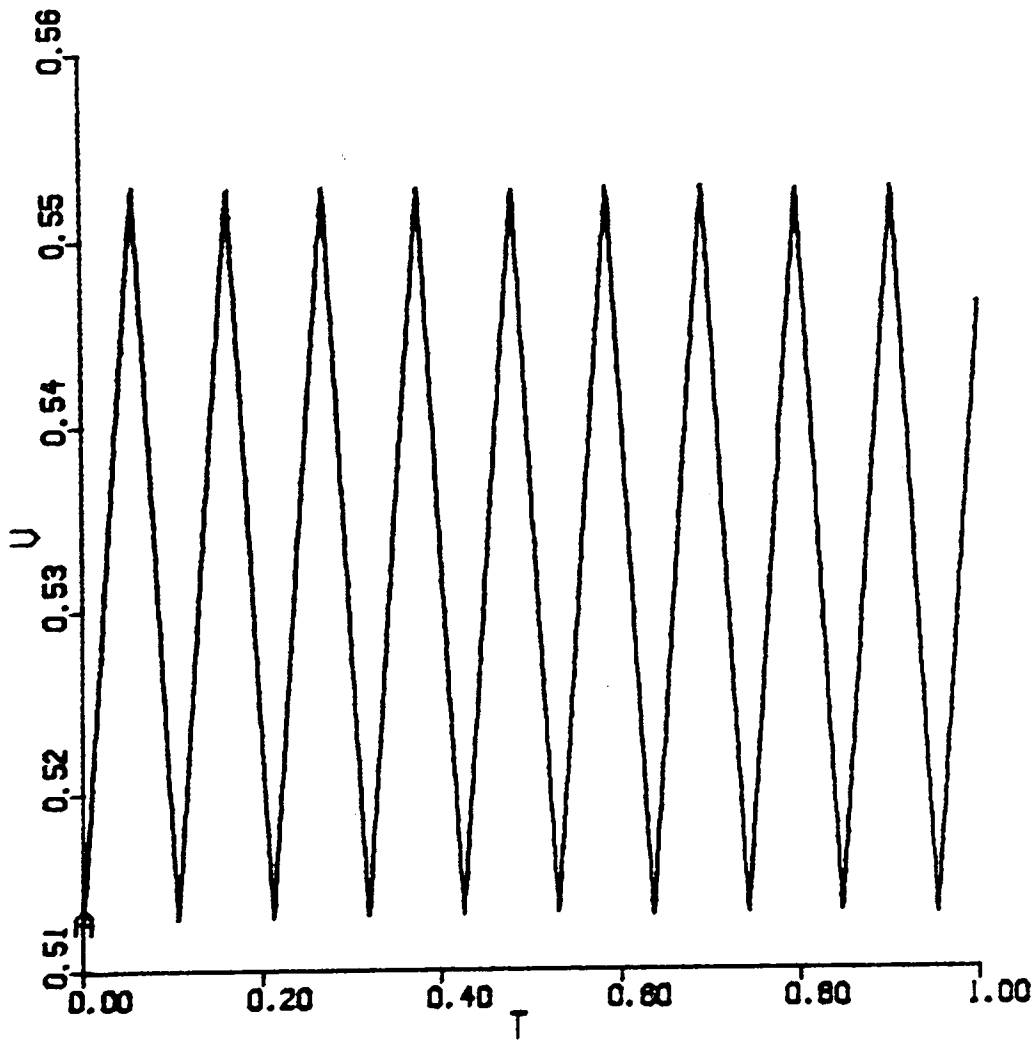

Figure 12. Velocity of Periodic Cycle, with Low Throttle Setting at 1, Desired Velocity at 0.533

than 1 is chosen for the low throttle setting, than it takes longer for the train to decelerate. Even though higher throttle settings are more efficient, the amount of time it takes to decelerate is long enough that fuel performance is worse. This occurs because more time is spent at the low throttle setting, with a lower efficiency than the throttle setting for normal operation. Similarly, if position 8 is chosen for the high throttle setting, the time to accelerate is shorter. This means that more of the time in the cycle is at a low efficiency. If lower settings are chosen than 7 for the high throttle position, than the efficiency decreases, and the fuel perfomance is worse.

Of the two switching schemes presented, the one with the low throttle position at 1 is more desirable than the one at idle, since wheel slip protection is maintained and the fuel consumption is lower.

The periodic operation has only been compared to operating at a constant velocity. Frequently during normal operation, the throttle must be varied between adjacent positions to maintain the desired speed. The possibility exists that fuel can be saved by switching between throttle position 1 and 7, rather than switching between adjacent throttle positions. To check this possibility, four velocities between the velocities corresponding to the

constant throttle positions at 3 and 4 were chosen. The fuel consumed by both switching methods was compared. It was found that the periodic operation used more fuel than the normal operation as seen in Table 8. The results show that the same loss in fuel consumption occured when the periodic operation was compared to both maintaining a constant throttle setting and switching between adjacent throttle positions.

Next, the effect of varying the velocity limit was examined. The throttle positions of 1 and 7 were used as the values for the periodic cycle. The velocity tolerance limit values of 0.01 and 0.04 were compared to the value previously used of 0.02. As can be seen in Table 9, the velocity limit value of 0.01 is better at throttle position 3, but worse at throttle position 6 than the limit value of 0.02. The limit value of 0.04 is worse at throttle position 3, but better at position 6 than the limit value of 0.02. There is no clear advantage to using any of the velocity limit values. Since the limit value of 0.04 has a higher difference at throttle position 6, it may be possible that the more fuel is consumed when operating at high velocity limits.

Since there is no clear difference for the different velocity limit, and since the velocity limit affects the length of the cycle, the velocity limit can be chosen so

Table 8. Fuel Consumption Comparison of Periodic Operation and the Normal Operation of Switching Between Adjacent Throttle Settings[1]

Velocity	Periodic	Normal	Savings, %
0.32	0.246	0.244	-1
0.34	0.265	0.263	-1
0.36	0.284	0.283	-0.3
0.38	0.304	0.303	-0.3

1. Periodic operation consists of switching from throttle position 1 to position 7. Normal operation consists of switching form throttle position 3 to position 4.

Table 9. Fuel Consumption Comparison for Varying Velocity Tolerance Limits

Throttle Position	Velocity Tolerance Limit 0.01	0.02	0.04
2	0.139	0.130	0.139
3	0.229	0.230	0.231
4	0.335	0.335	0.335
5	0.478	0.478	0.477
6	0.634	0.633	0.636

that plenty of time can be allowed to change the engine between the values of the high and low throttle settings.

From the previous results, the periodic operation is not the optimum method for operating the SD40 locomotive. Why is the periodic operation worse than constant velocity operation when the high throttle position is at a higher efficiency than the intermediate throttle positons? The answer is that there is a penalty for operating at a the low throttle setting, since the efficiency is very low. The efficiency curve for the throttle settings must be steep enough that the penalty for operating at idle or at a low throttle positon must be overcome.

Large diesel engines are characterized by a flat efficiency curve. Looking at the values in Table 7, the periodic operation is not that much worse than the constant velocity operation. For the case where the low setting is throttle position 1, the periodic operation is no worse than 1% of the constant velocity operation. It could well be that a locomotive other than the SD40, with different efficiency characteristics, would result in a periodic operation using less fuel than the constant velocity operation.

There is also the possibility of modifying the diesel engine to take advantage of operating in a periodic manner. A key component in both the power output and efficiency of

a diesel engine is the turbocharger. Turbochargers have a problem with only working well over a narrow range of operating conditions [8,9]. An article by Gunther [10], suggests using sequential turbochargers to improve engine performance. The turbochargers are switched on as exhaust gas from the engine increases. For an engine used for periodic operation, an additional turbocharger can be added that has a sharp efficiency that peaks at the operating point corresponding to throttle position 7.

With the extra turbocharger efficiency, the specific fuel consumption at throttle position 7 could be improved. For normal engine operation, this improvement would have little effect on overall fuel performance, since fuel would be saved only when operating at throttle position 7. However, for the periodic operation, the savings would exist for throttle settings 2 through 7.

To test this idea, assume the specific fuel consumption at throttle position 7 is improved from 0.3637 to 0.3453, or a difference of 5%. This is a large increase, but it may be possible that a smaller increase will still yield fuel savings.

With this modification, periodic operation was compared to operating at a constant velocity. Both high and low throttle settings of idle and 7, and 1 and 7 were compared. As can be seen in Table 10, the periodic

Table 10. Fuel Consumption Comparison of Periodic Operation and Constant Velocity Operation for Modified Engine

Switching From Idle to Throttle Position 7

Throttle Position	Periodic	Constant Velocity	Savings (%)
1	0.05	0.051	*[1]
2	0.136	0.137	1
3	0.221	0.227	3
4	0.322	0.334	3.6
5	0.455	0.472	3.6
6	0.603	0.629	4.1

Switching From Throttle Position 1 to Position 7

Throttle Position	Periodic	Constant Velocity	Savings (%)
2	0.135	0.137	1
3	0.220	0.227	3
4	0.320	0.334	4.2
5	0.455	0.472	3.6
6	0.602	0.629	4.3

1. The fuel consumed was not accurate enough to make a comparison.

operation showed a definite fuel savings. For throttle settings 3 through 6, the savings was greater than 3%. Again, the periodic cycle with a low throttle setting at 1 showed slightly better performance than the cycle with idle as the low setting.

The periodic operation was also compared to the normal operation when switching between throttle positions 3 and 4, as was done with the unmodified engine. For the four velocities at which the comparison was made, the periodic operation showed a fuel savings of 3 to 4%, as seen in Table 11.

The increase of 5% on the specific fuel consumption at throttle position 7 could be reduced and there would still be a fuel savings. A more realistic increase of 2 to 3% is still likely to yield fuel savings.

Table 11. Fuel Consumption Comparison of Periodic Operation and the Normal Operation of Switching Between Adjacent Throttle Settings for Modified Engine[1]

Velocity	Periodic	Normal	Savings, %
0.32	0.235	0.244	3.7
0.34	0.253	0.263	3.8
0.36	0.271	0.283	4.2
0.38	0.290	0.303	4.3

1. Periodic operation consists of switching from throttle position 1 to position 7. Normal operation consists of switching form throttle position 3 to position 4.

5. CONTROLLER FOR PERIODIC OPERATION

Controller Design

Now that the operating strategy that optimizes the fuel consumption has been determined, the controller can now be designed. It was assumed the modified engine was used in the remaining simulations.

Before the controller could be designed, the train model had to be revised. The previous model assumed that the train was operating on level, straight track. To include the effects of hill forces and resistance forces due to curved track, an extra term must be added to the dynamic equation. From equation 10,

$$M(dv/dt) = p/v - d_1 - d_2v - d_3v^2 - F_h. \qquad (31)$$

where

F_h = hill and curvature forces

Some important facts should be noted. The Davis equation is not valid on a non-level, tangent track. Also, no

attempt is made to model the resistance forces due to curved track. The forces due to curved track are assumed to be incuded in the hill forces. This model will not accurately simulate an actual track. However, the model will be adequate for testing the controller design, since the hill forces will only be used to see if the controller can accurately maintain the desired speed. The fact that the unknown resistances forces do not accurately represent actual track conditions is not important for the present study.

The non-dimensional model is treated the same as before, with

$$H = F_h V_m / P_m, \tag{32}$$

where

H = non-dimensional hill and curvature forces.

The new non-dimensional model is

$$dV/dT = c_0 P/V - c_1 - c_2 V - c_3 V^2 - H \tag{33}$$

From the results of the previous chapter it was found

that for the modified engine, the optimum periodic operation was switching from throttle position 1 to throttle position 7. Nothing was said about operating at power levels greater than that provided by throttle position 7. If throttle position 7 does not provide enough power to maintain the desired velocity, then the throttle should be varied between postions 7 and 8. This means that there are two separate operating regions for the locomotive. The first is switching from throttle position 1 to 7. The second is switching from throttle position 7 to 8.

To control the speed of the train, one of the two operating regions must be chosen. The choice depends on the amount of power needed to drive the train at the desired velocity. On level, straight track, the required power can be determined from the desired velocity. The power needed to operate the train cannot be determined if the train is not on a level, straight track unless the additional forces are known. Therefore, to design a speed controller, the unknown forces must be determined. This can be done with an observer.

With a digital controller, the inputs are sampled at regular intervals. If the velocity is sampled at regular intervals, the acceleration can be approximated. From a second order Taylor series,

$$V_{t+h} = V_t + h(dV/dT)_t + h^2/2(dV^2/d^2T)_t, \quad (34)$$

where

h = the sampling interval

V_t = velocity at time t

V_{t+h} = velocity at time t+h

$(dV/dT)_t$ = the first derivative of the velocity (acceleration), evaluated at time t

$(dV^2/d^2T)_t$ = the second derivative of velocity evaluated at time t.

Equation 33 can be differentiated to give

$$dV^2/d^2T = [-P/V^2 - c_2 - 2c_3V](dV/dT). \quad (35)$$

Substituting equation 35 into equation 34 gives

$$V_{t+h} = V_t + h(dV/dT)_t - h^2/2[P_t/V_t^2 + c_2 + 2c_3V_t](dV/dT)_t. \quad (36)$$

Now, solving for the acceleration gives

$$(dV/dT)_t = (V_{t+h}-V_t)/[h - h^2/2(P_tV_t^2+c_2+2c_3V_t)]. \quad (37)$$

From equation 33, the estimated hill force, H_{est}, can be calculated.

$$H_{est} = P_t/V_t - c_1 - c_2V_t - c_3V_t^2 - (dV/dT)_t. \qquad (38)$$

Now, the power level needed for the train operation can be computed.

$$P = V_{des}(c_1+c_2V_{des}+c_3V_{des}^2+H_{est}), \qquad (39)$$

where

V_{des} = desired velocity.

Equations 37-39 comprise the observer and controller design.

In operation, the controller estimates the hill forces, computes the power needed, and then chooses the correct operating region. This is done by comparing the power needed to the power of throttle position 7. This value is 0.840, as given in Table 4.

It may first appear that the comparison of the estimated power to the power corresponding to throttle

position is critical. If the comparison is in error, the train will be operating in the wrong region. When this happens, the throttle will stay in position 7, since the controller will try to maintain the desired velocity by using the limiting throttle position. If the error is not too large, the velocity will still be within the velocity tolerance, V_1, of the desired velocity. Thus, the accuracy of the comparison of the power values depends on the velocity limit chosen.

Test of the Controller design

The program of the train model and the controller is given in Appendix C. The controller is simulated in the discrete section. ACSL automatically takes care of the discrete sampling.

The controller was first examined with a very simple case. The train simulation started at an initial velocity of 0.2, and a desired velocity of 0.60. There were no hill forces. The train velocity is compared with the desired velocity in Fig. 13. The observed hill forces should be zero. The observed hill forces were zero with the exception of some "spikes" as shown in Fig. 14. These spikes occur whenever there is a discontinuous acceleration, or when the throttle position is changed. These spikes could cause some problems when changing

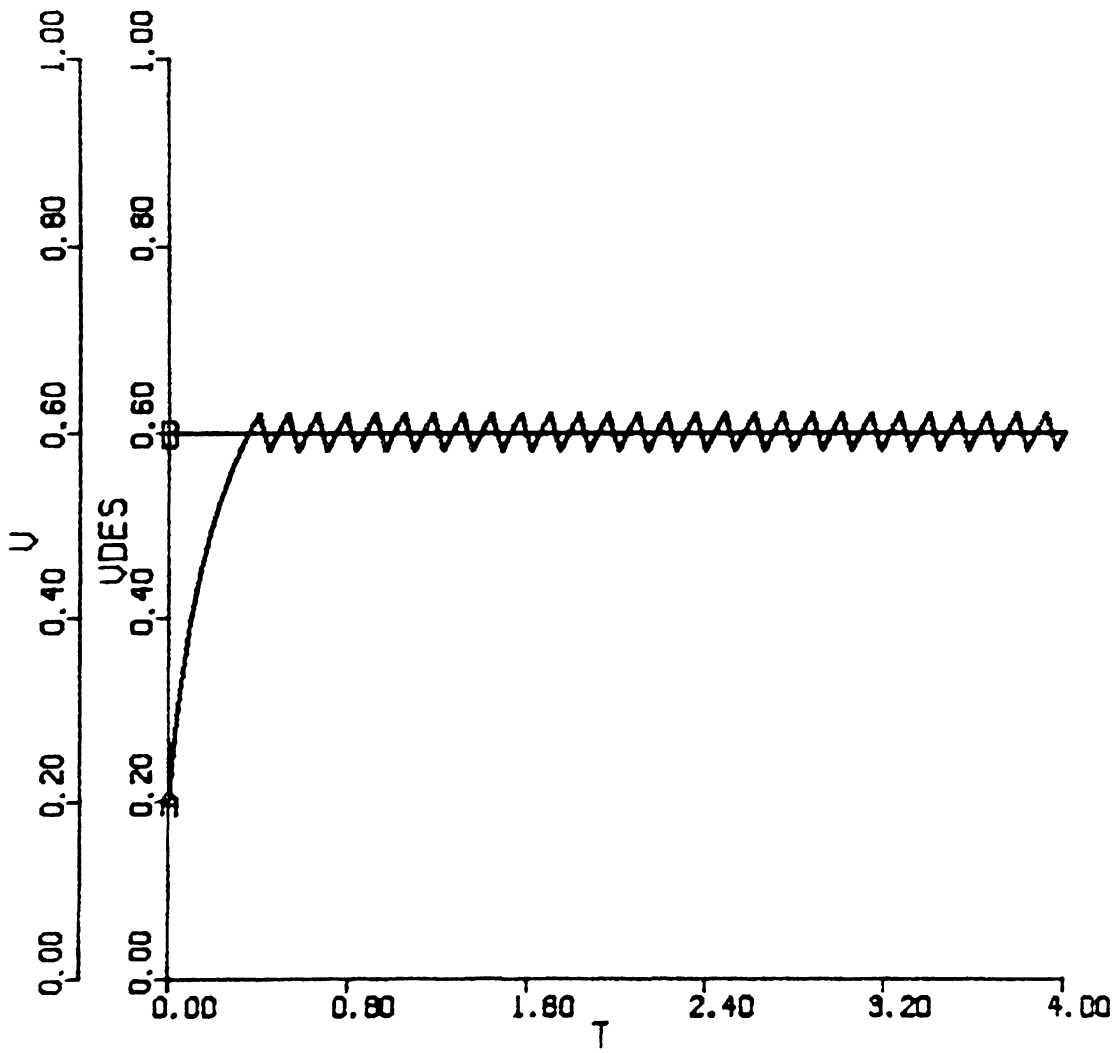

Figure 13. Train Velocity for a Desired Velocity Different than the Initial Velocity

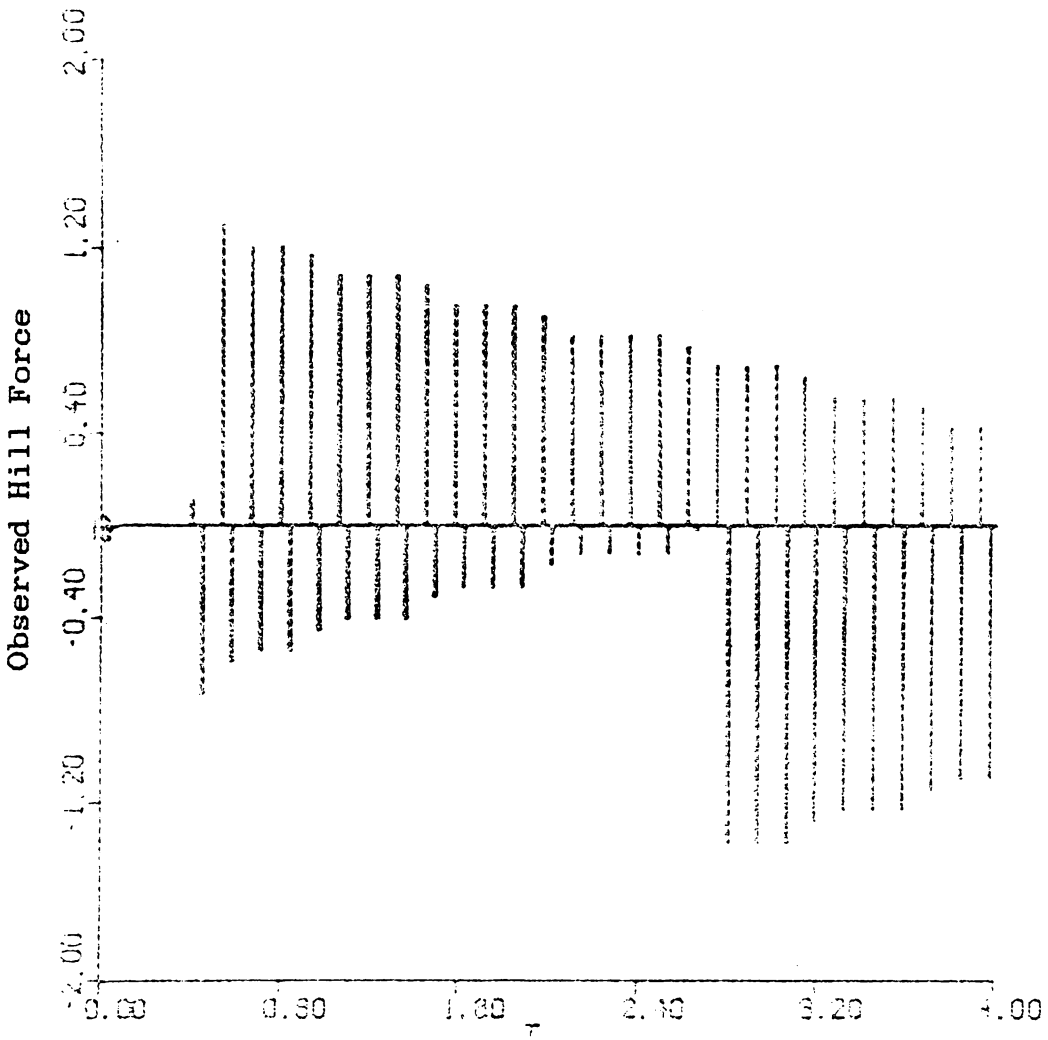

Figure 14. Observed Hill Force for a Desired Velocity Different than the Initial Velocity

desired velocity.

The solution to this problem is simple. The discrete controller needs to check to see if the throttle position has changed. If it has, then the current high and low throttle settings should not be changed. In effect, the observer is ignoring the information given by the spikes.

There was another problem with the simulation. If the initial velocity started in the region corresponding to the constant velocity given by throttle postion 7, there was a large error in the observed hill force. Thus, the train was immediately put in the incorrect operating region. This problem occurs by not having the proper initial conditions for the observer variables. This problem was avoided by not starting the initial velocity near the problem area. In actual operation, the train must be started at low power levels, so the observer routine would never be started with a desired velocity corresponding to corresponding to the constant velocity given by throttle position 7.

Next, the effect of a change in velocity was tested. The initial velocity and desired velocity were started at 0.83. At time 2.0, the desired velocity was changed to 0.70. No hill forces were applied. The controller has no problem following the desired velocity as shown in Fig. 15. The observer correctly estimated the hill force as shown

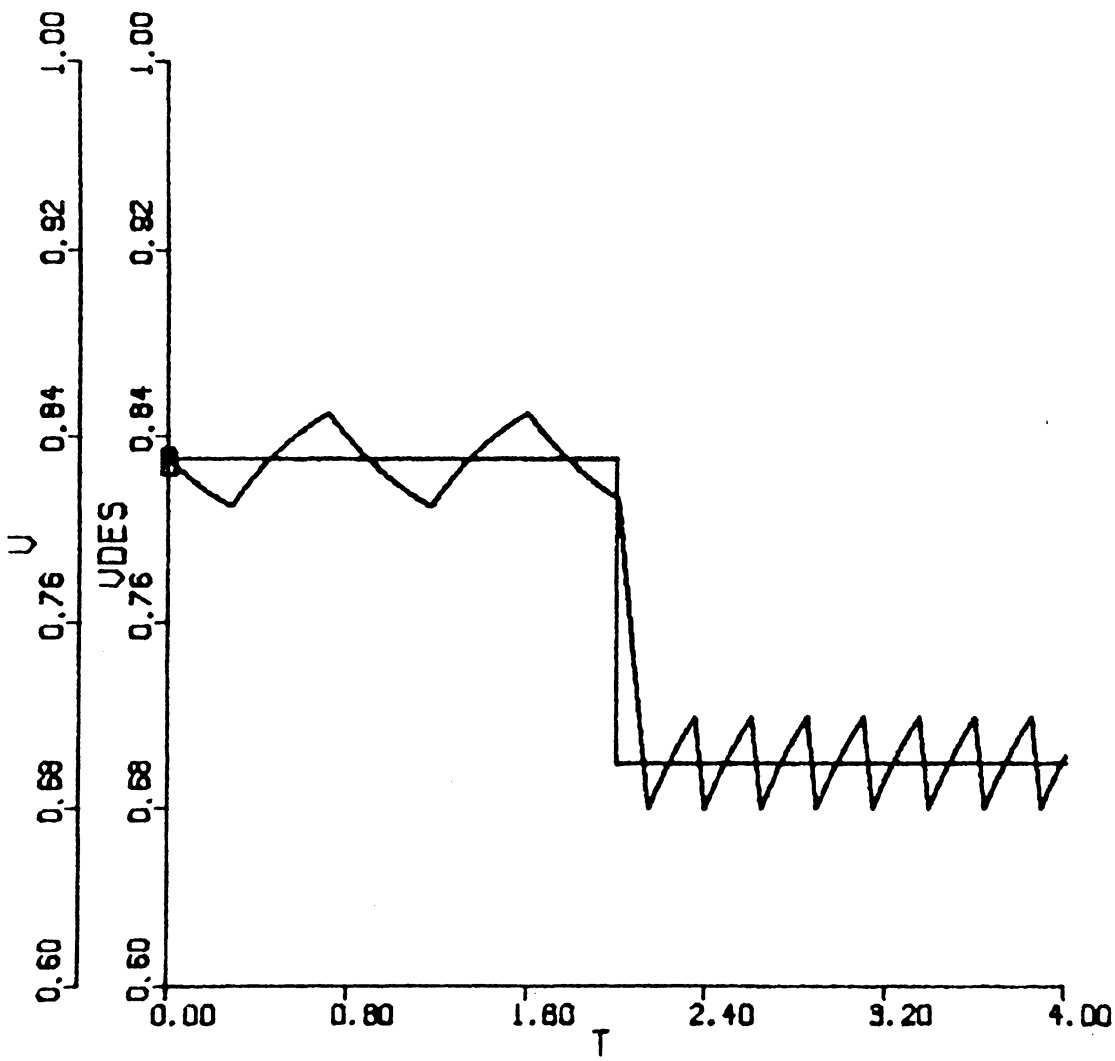

Figure 15. Train Velocity for a Change in Desired Velocity to 0.70

in Fig. 16. There is also no problem with the spikes affecting the correct operating region. The throttle is changed at the proper times to the correct positions as shown in Fig. 17.

A more important test of the observer is when the desired velocity is changed to the value corresponding to the constant velocity given by throttle position 7. The next simulation was set up as the previous one, with the exception that the desired velocity was changed to 0.79 at time 2.0. This is slightly more than the constant velocity value at throttle position 7 of 0.785 as given in Table 6. The simulation showed that when the desired velocity was changed, the velocity of the train followed the desired velocity, but did not end in the periodic cycle, but with a constant error. This result can be seen in Fig. 18. While the velocity is at a constant error, the throttle position remained constant, as shown in Fig. 19. This error is still less than the velocity tolerance, V_1. Had the desired velocity been changed to 0.785, there would have been no error at all. The observer still correctly estimated the hill force, as seen in Fig. 20.

Finally, the effect of a change in the hill force was examined. The initial velocity and desired velocity were started out at 0.75. The desired velocity remained constant. A hill force of 0.2 was applied at time 1.0.

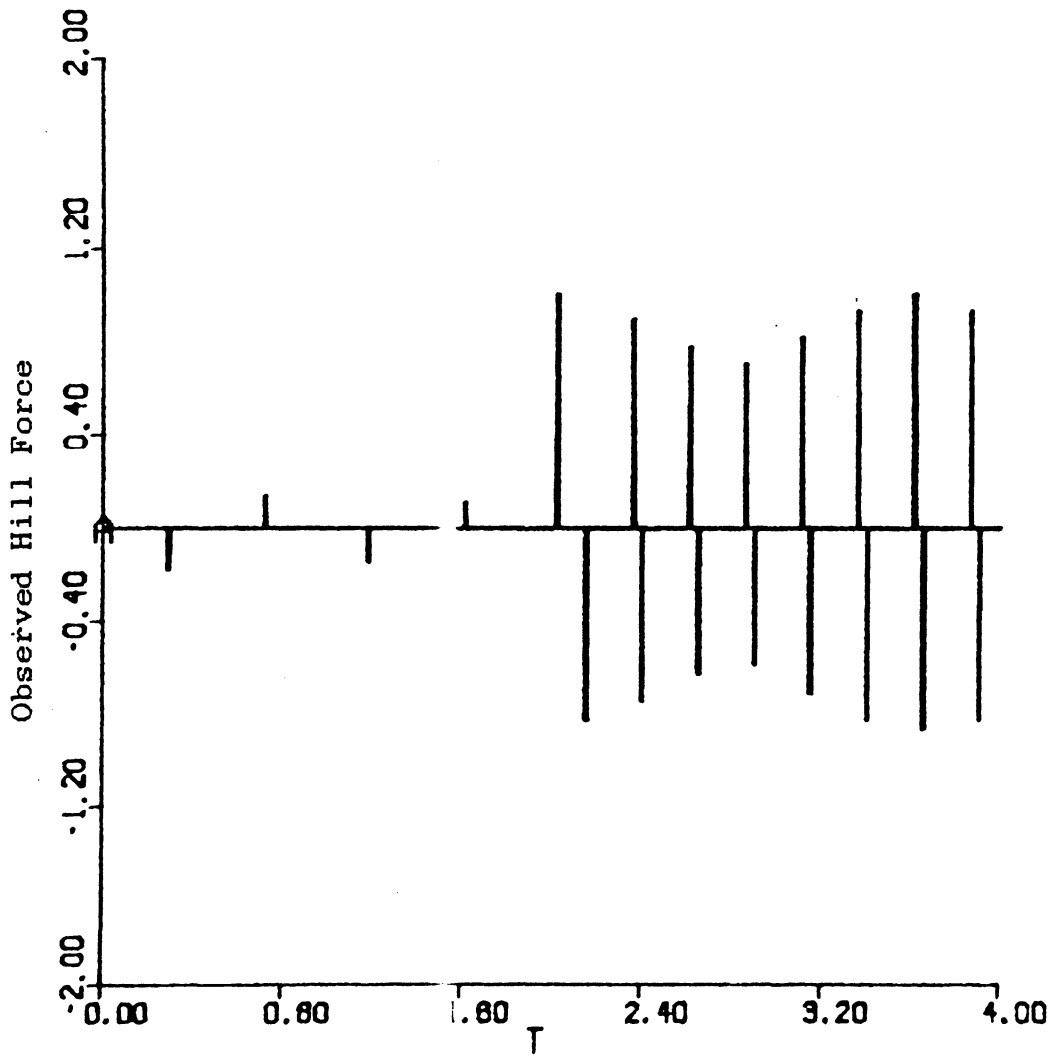

Figure 16. Observed ill Force for a Change in Desired Velocity to 0.70

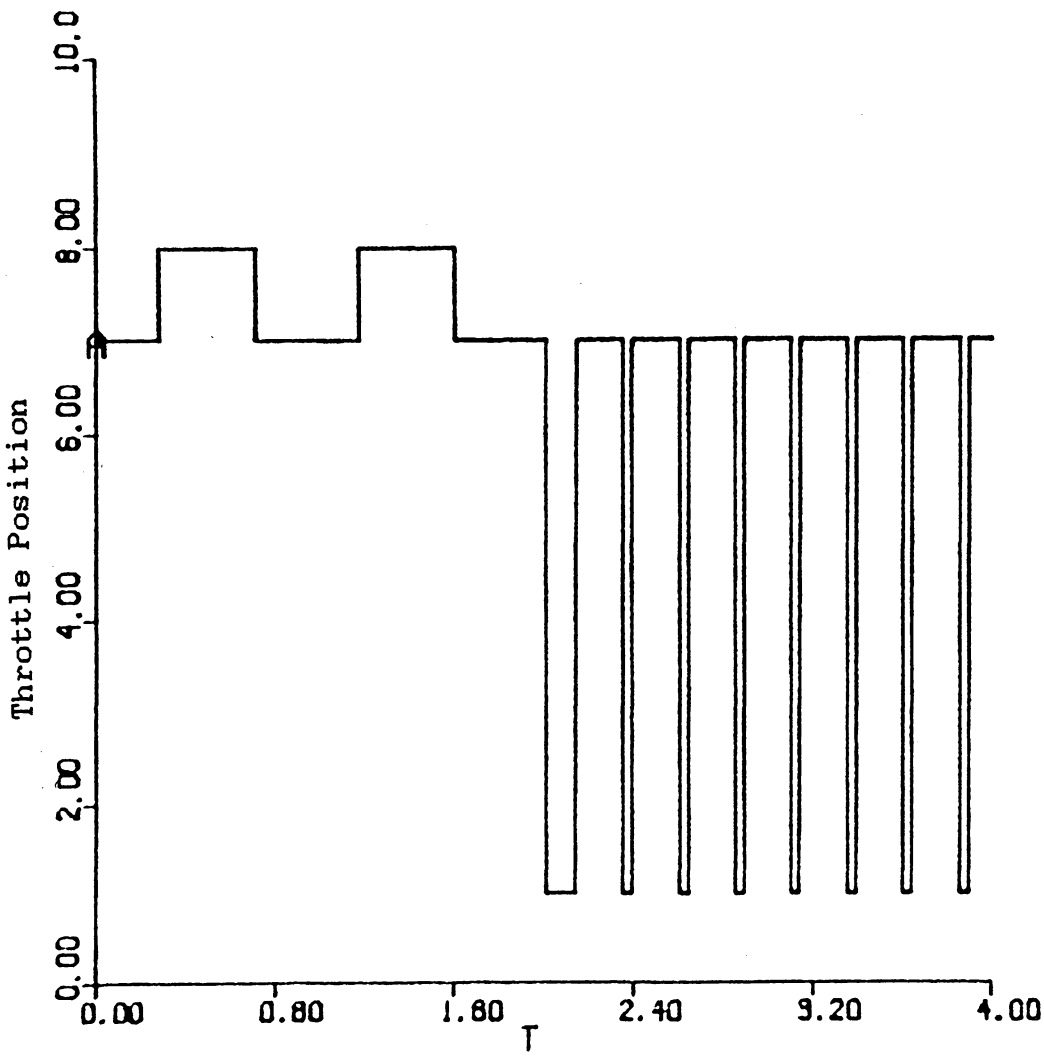

Figure 17. Throttle Position for a Change in Desired Velocity to 0.70

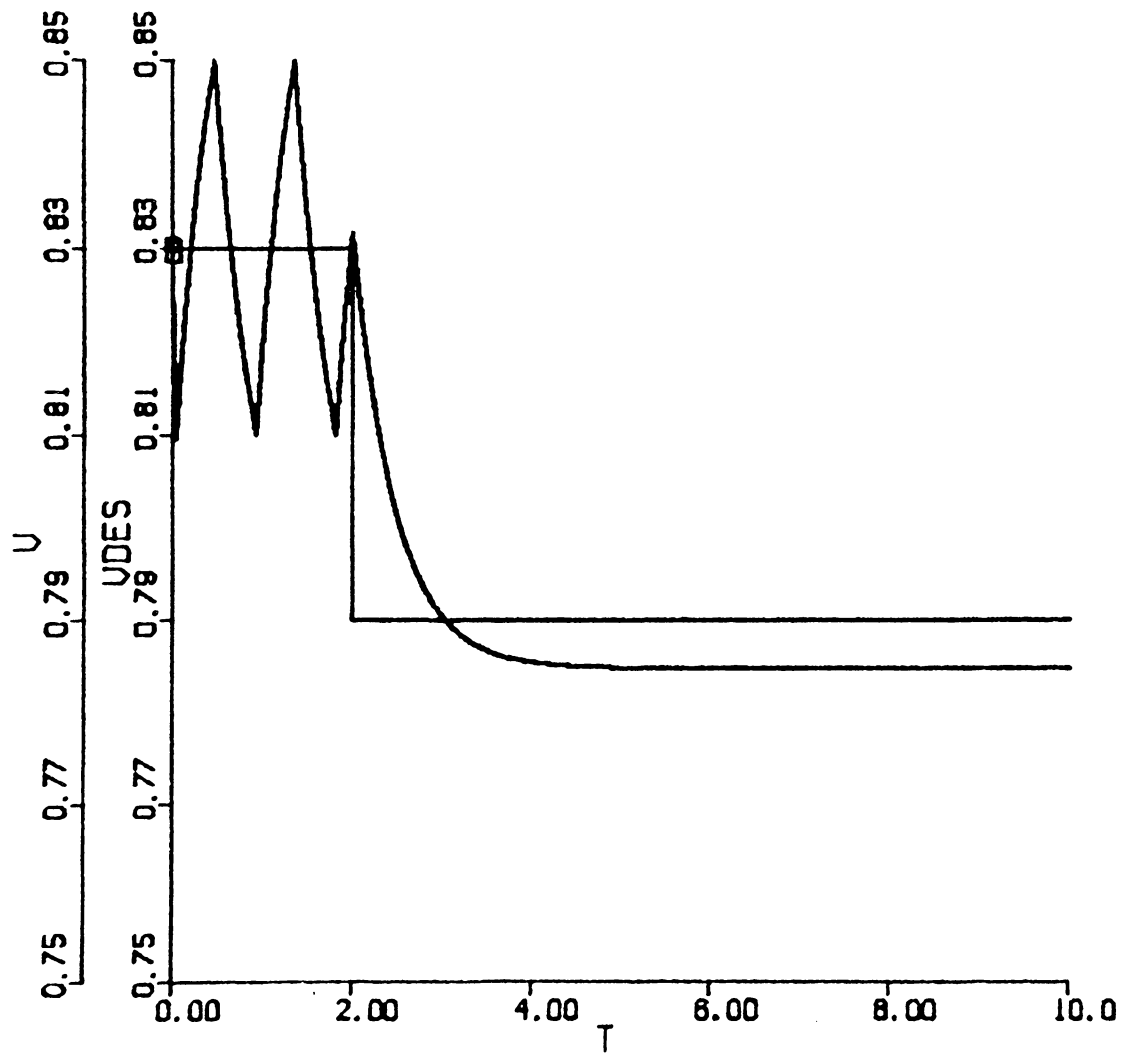

Figure 18. Train Velocity for a Change in Desired Velocity to 0.79

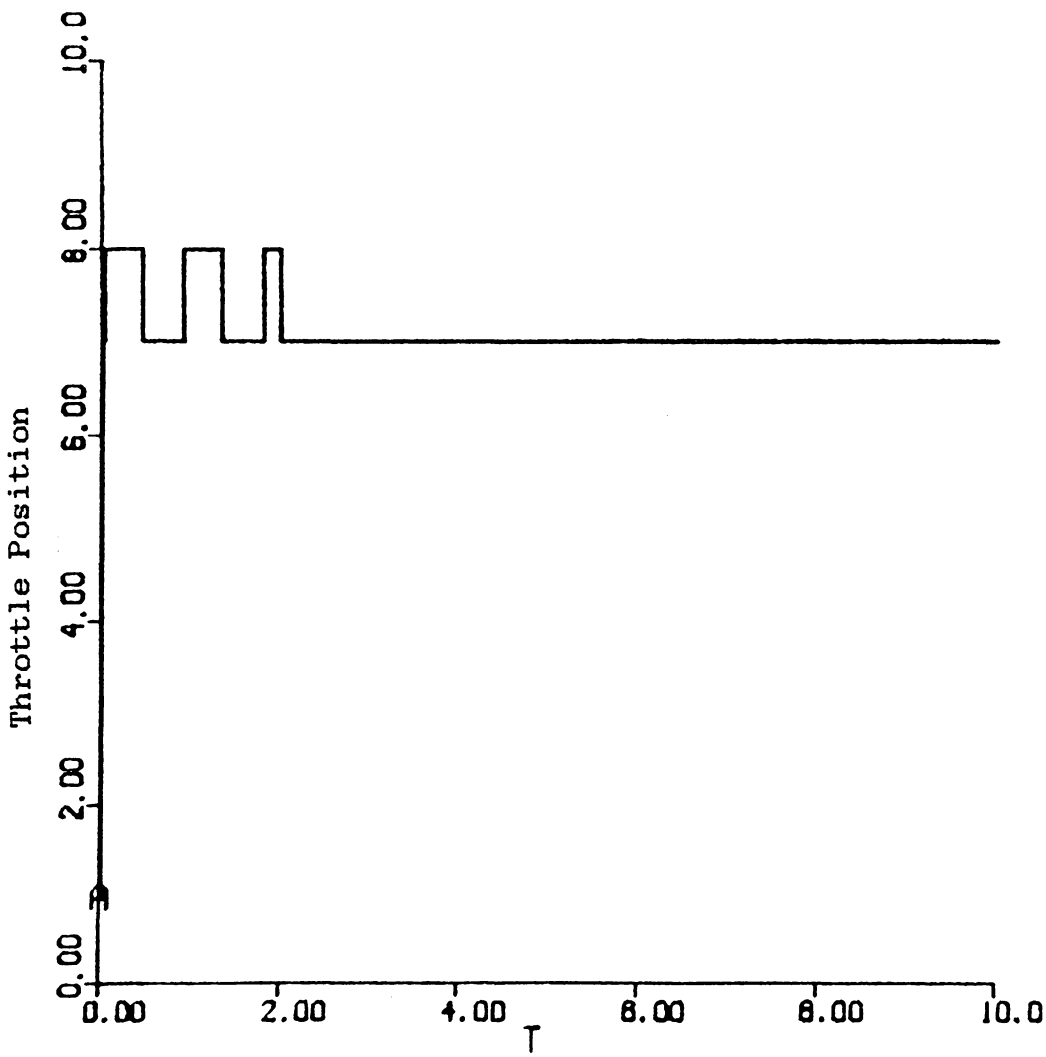

Figure 19. Throttle Position for a Change in Desired Velocity to 0.79

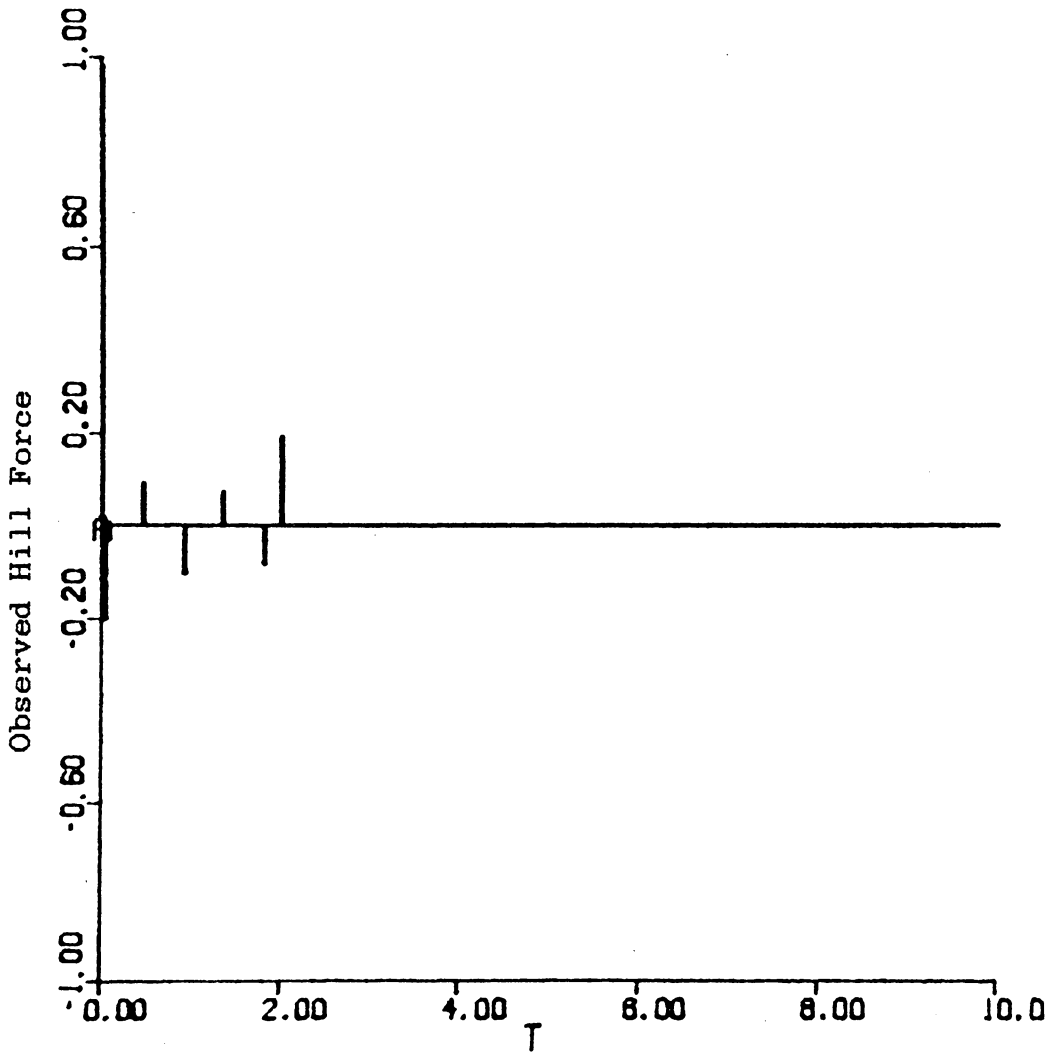

Figure 20. Observed Hill Force for a Change in Desired Velocity to 0.79

The controller again had no problem following the desired velocity as shown in Fig. 21. Notice that with the exception of the spikes, the observer correctly follows the actual hill force, as seen in Fig. 22. The throttle is again changed at the proper times as seen in Fig. 23.

The observer has been shown to work as designed. What will happen if the parameters in the train model are incorrect? Throughout the simulations, a non-dimensional model has been used. Imbedded in the model are such values as the train weight and the number of cars. While it would be easy to count the number of cars in the train, and enter this information into the control computer before the trip was started, it would be impossible to measure the exact train weight.

By looking at equations 37-39, it may be possible to predict what would happen if the parameters in the train model were in error. The parameters of the train model are given by c_1, c_2, and c_3. If the these values are incorrect, from equations 37 and 38 it can be seen that the hill forces are incorrectly estimated. Assume that the values for c_1, c_2, and c_3 are all lower than they should be. From equation 38, the hill force will be estimated to be higher than it should be. But, from equation 37, the computed power should be near the correct value since the low values for c_1, c_2, and c_3 will offset the high

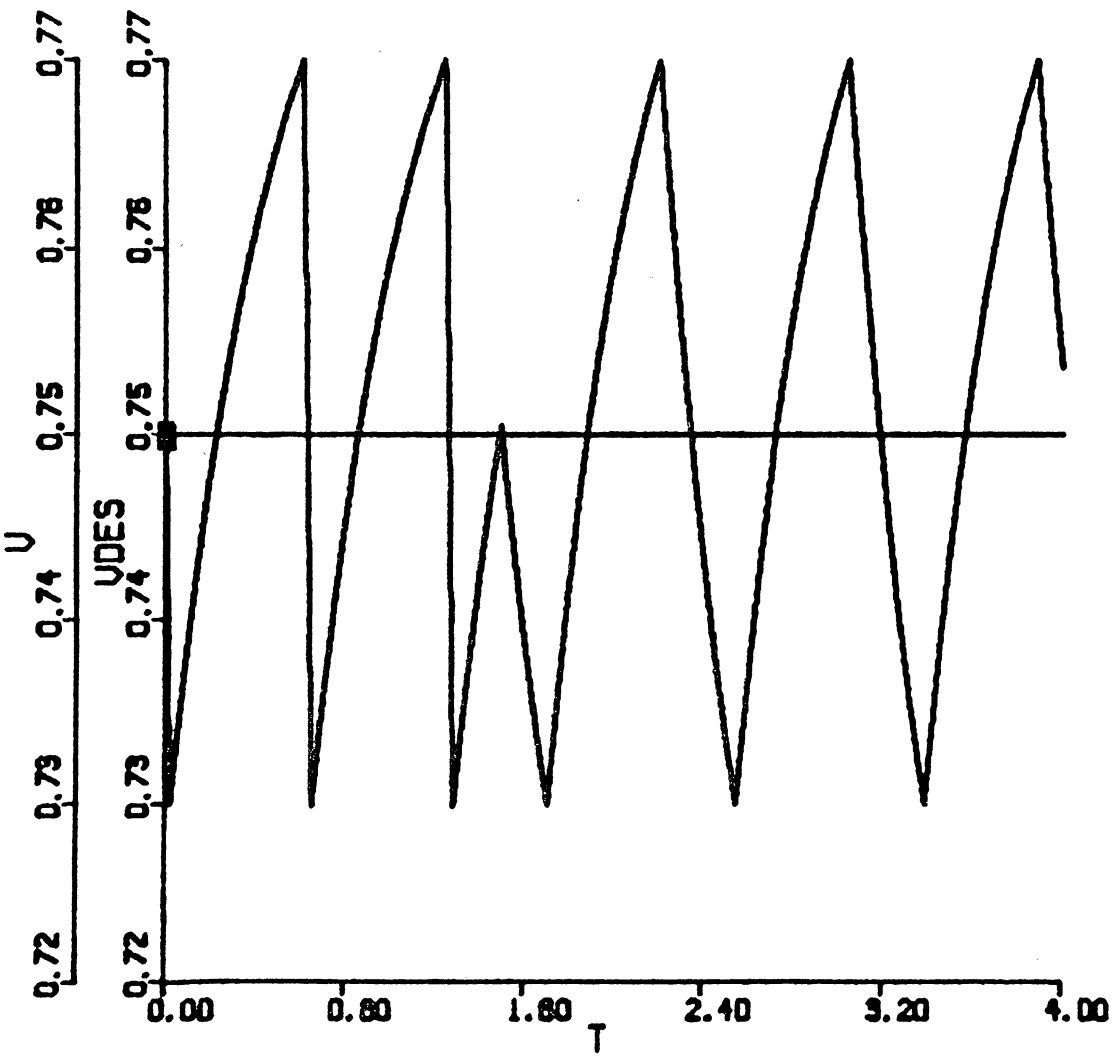

Figure 21. Train Velocity for a Change in Hill Force

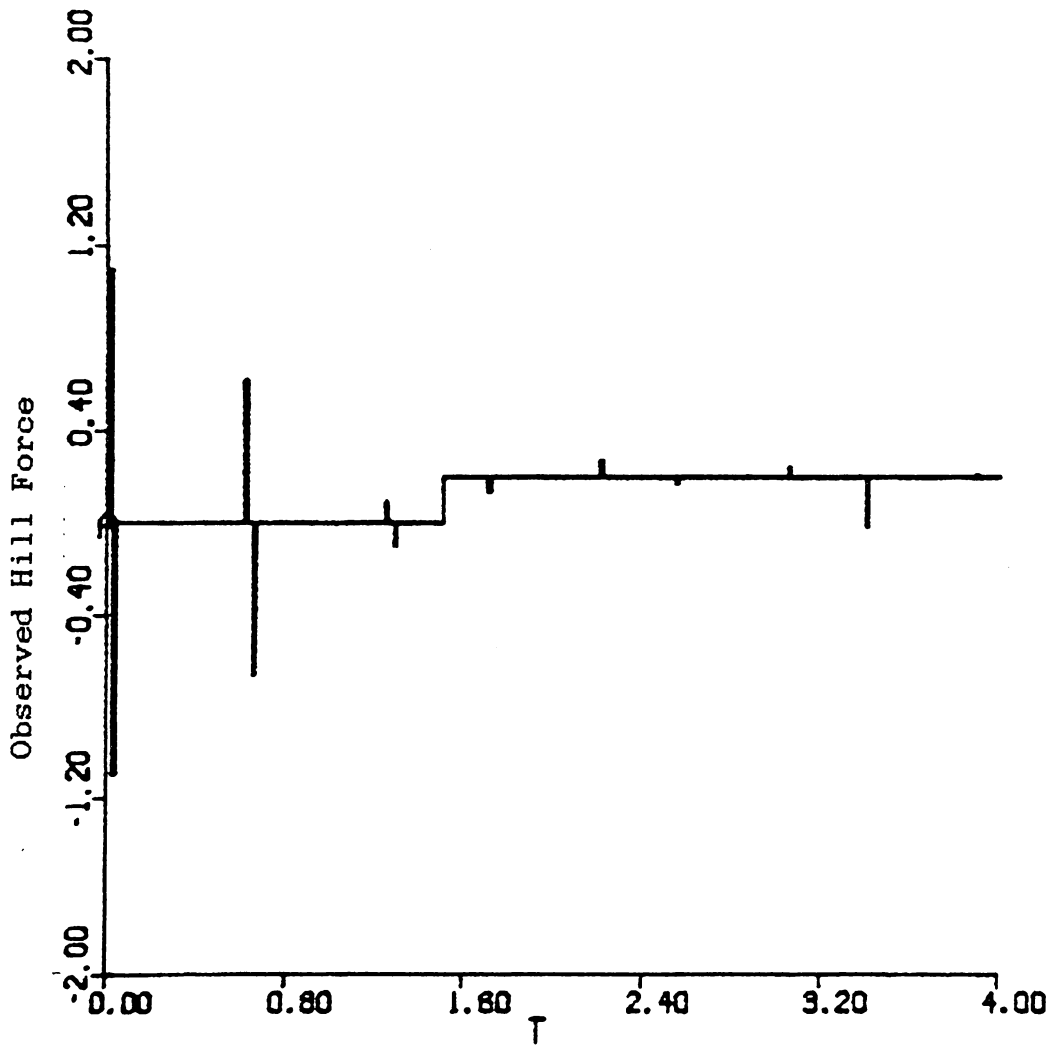

Figure 22. Observed Hill Force for a Change in Hill Force

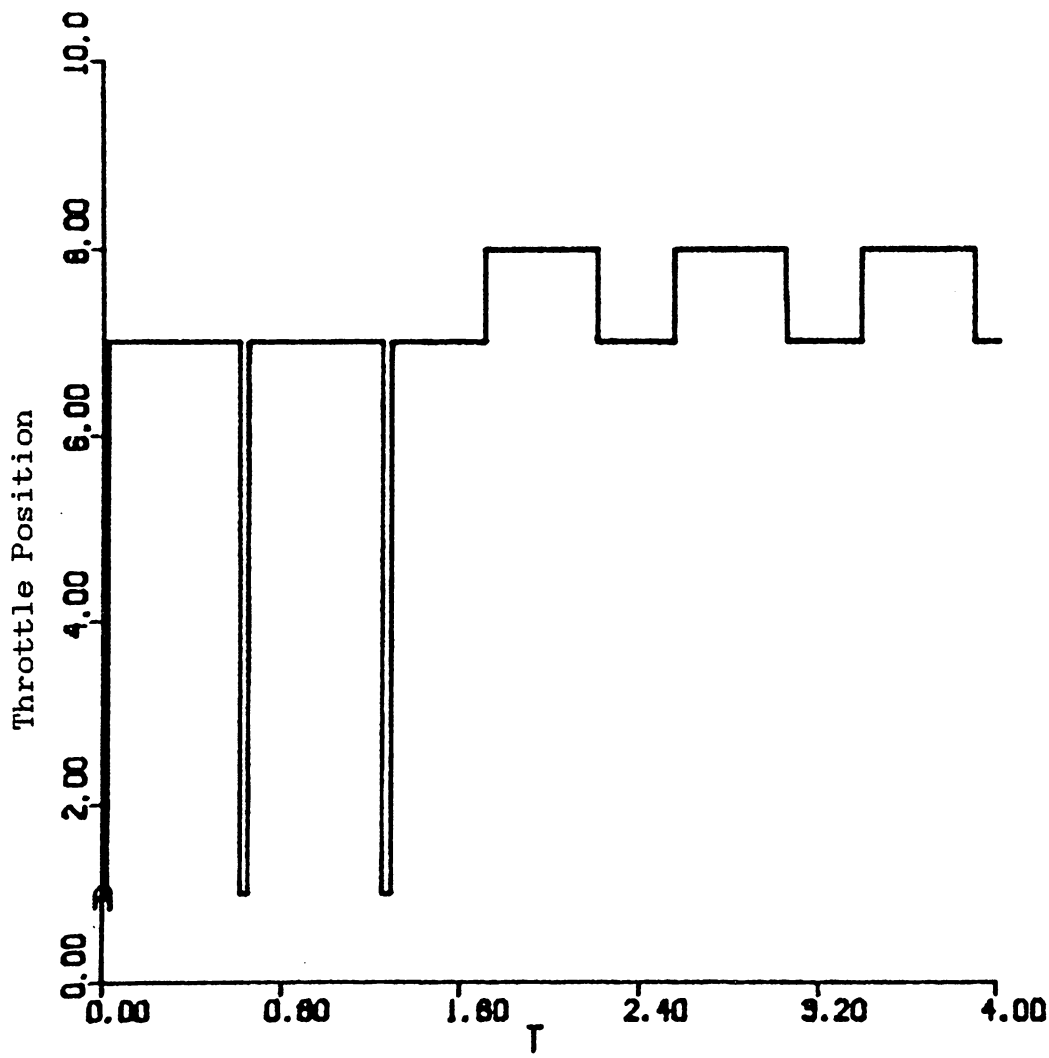

Figure 23. Throttle Position for a Change in Hill Force

estimated hill force. The power level needed is actually the quantity needed by the controller, not the estimated hill force.

To test this prediction, the program was modified so that the observer used the model parameters c_4, c_5, and c_6, corresponding to the train parameters of c_1, c_2, and c_3. The value of c_4 was set equal to 0.240 and the value of c_5 was set equal to 0.363. These values are half of the values for c_1 and c_2. This would roughly correspond to the observer train model having half of the weight of the actual train.

The first simulation to test the prediction is the same as the one given by Fig. 15-17. The initial velocity and starting desired velocity were 0.83. At time 0.2, the desired velocity was changed to 0.70. There were no hill forces. The velocity and throttle postion as given in Fig. 24 and 25 appear identical to those in Fig. 15 and 17. However, the hill force as seen in Fig. 26 was observed to be approximately 0.5, even though no hill forces were applied. Even though the hill force had a large error, the controller automatically compensated for it when it computed the power required. There is still some small variation in the observed force. This variation could cause some problems if it is large in magnitude compared to the velocity tolerance.

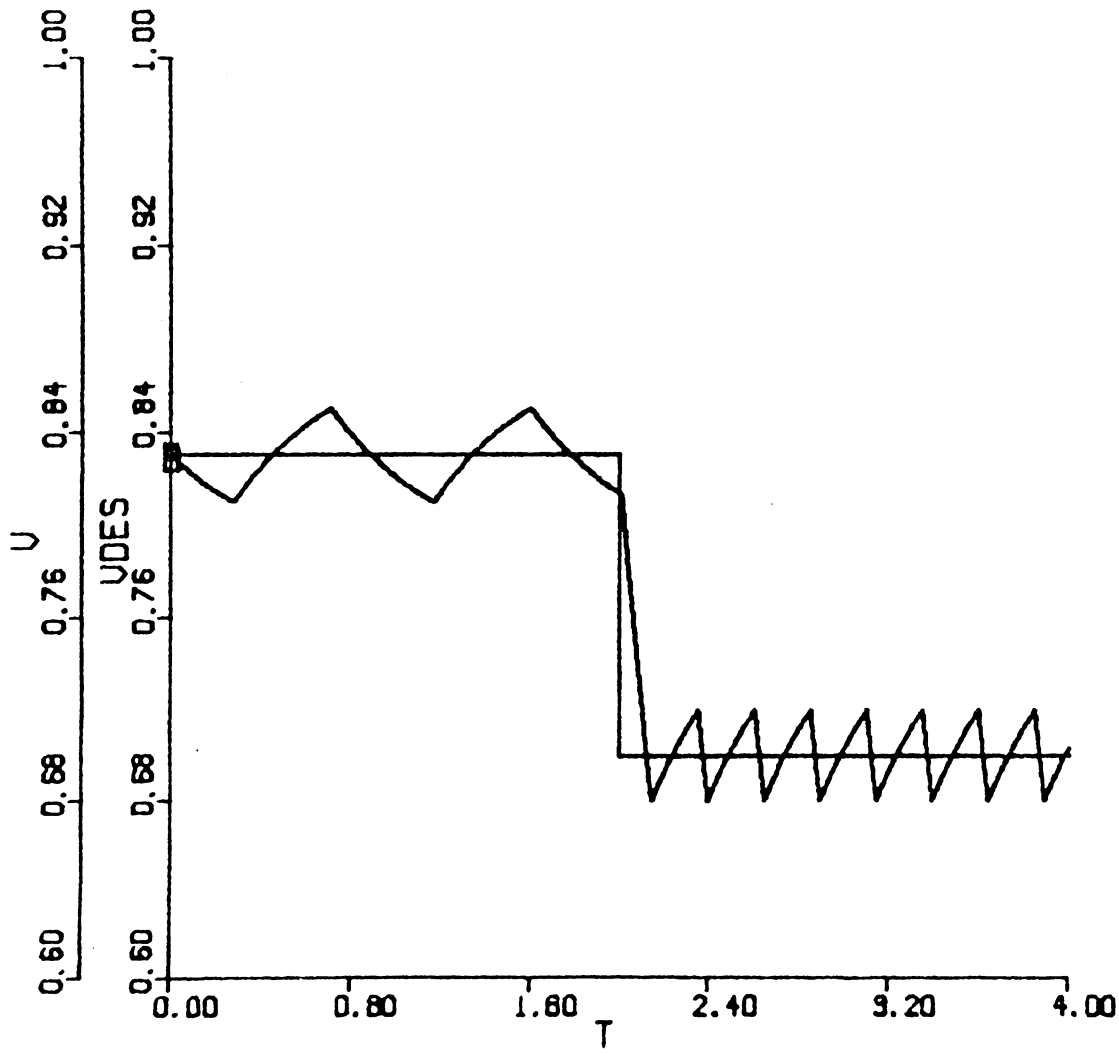

Figure 24. Train Velocity for a Change in Desired Velocity to 0.70, with Error in Train Model

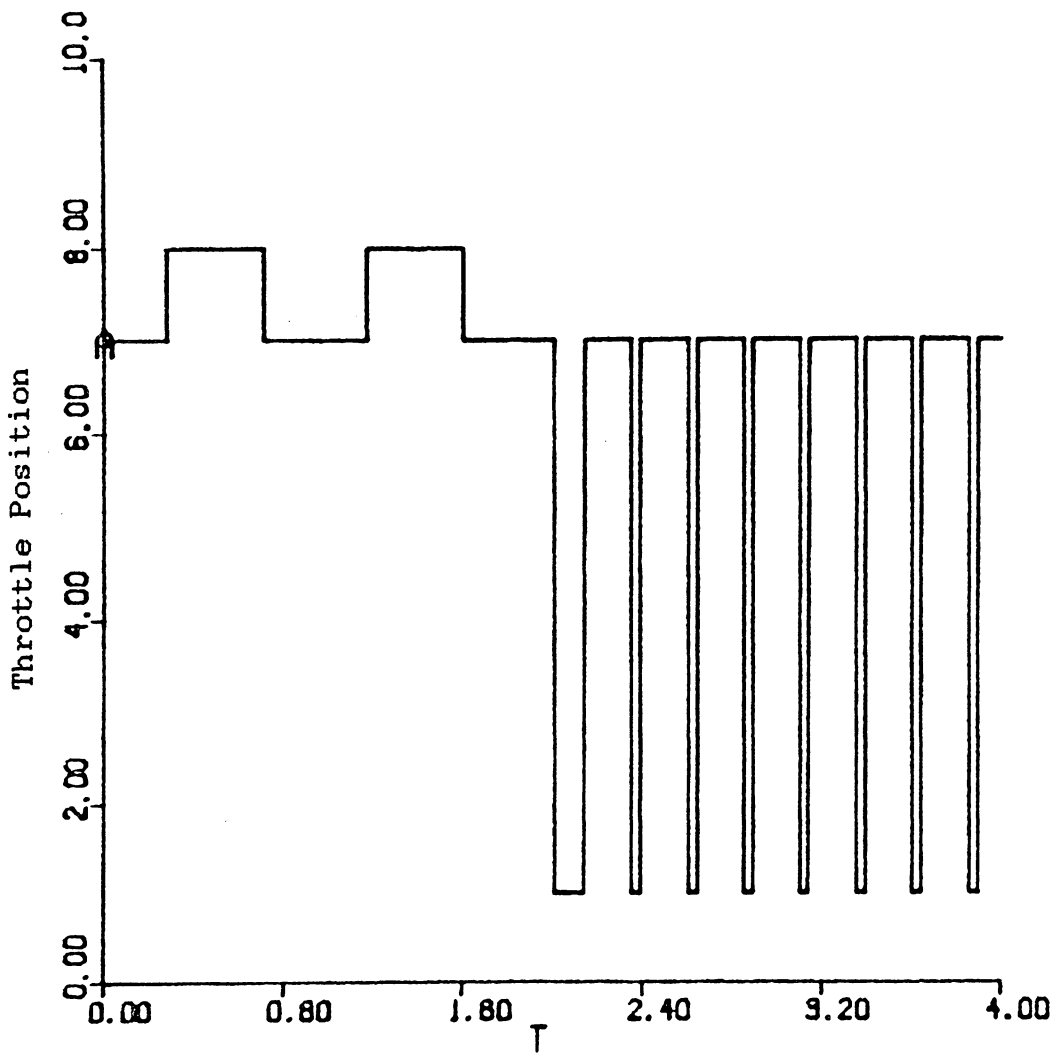

Figure 25. Throttle Position for a Change in Desired Velocity to 0.70, with Error in Train Model

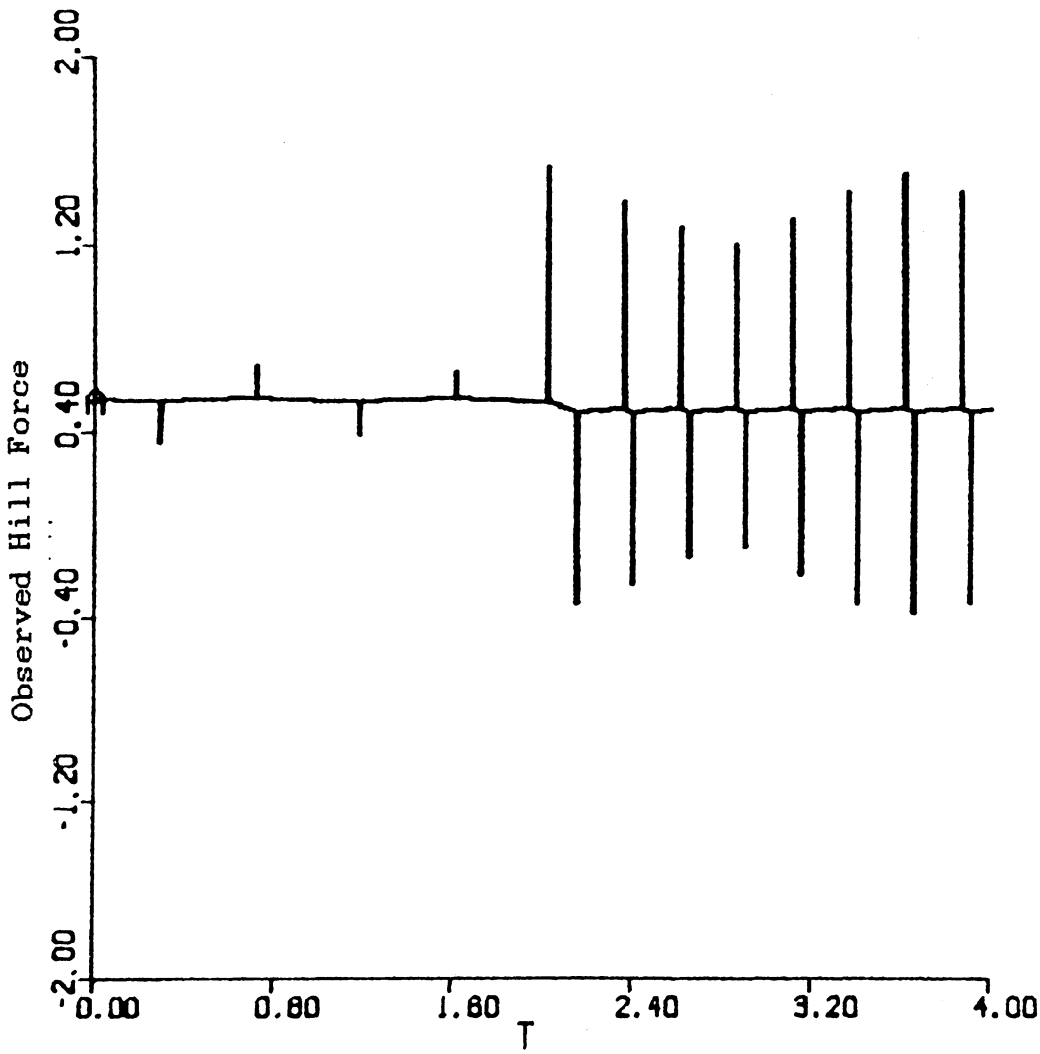

Figure 26. Observed Hill Force for a Change in Desired Velocity to 0.70, with Error in Train Model

Next, the set-up of the simulation given by Fig. 18-20 was examined. In this simulation, the initial and starting desired velocities were the same as the previous case. Instead of changing the desired velocity to 0.70 at time 2.0, it was changed to 0.79. Again, the velocity and throttle position as seen in Fig. 27 and 28 appear identical to the plots in Fig. 18 and 19. The observer still showed a large error in the hill forces as shown in Fig. 29. Again the error was roughly constant, with some small variations.

Finally, the case were the hill force of 0.20 was applied at time 1.5 was examined. This is the same set-up as given by the simulation with the results shown in Fig. 21-23. Like the previous two cases, the velocity and throttle position as given by Fig. 30 and 31 appear identical to Fig. 21 and 23. The observed hill force as shown in Fig. 32 correctly follows the pattern of the actual hill forces, but with a large, roughly constant error.

We have seen the observer has a very robust design. Even though the model parameters were in error by 50%, the controller still maintained the desired velocity pattern. The only information the controlling computer would need as far as the train weight is concerned would be the number of empty cars and the number of loaded cars. This would give

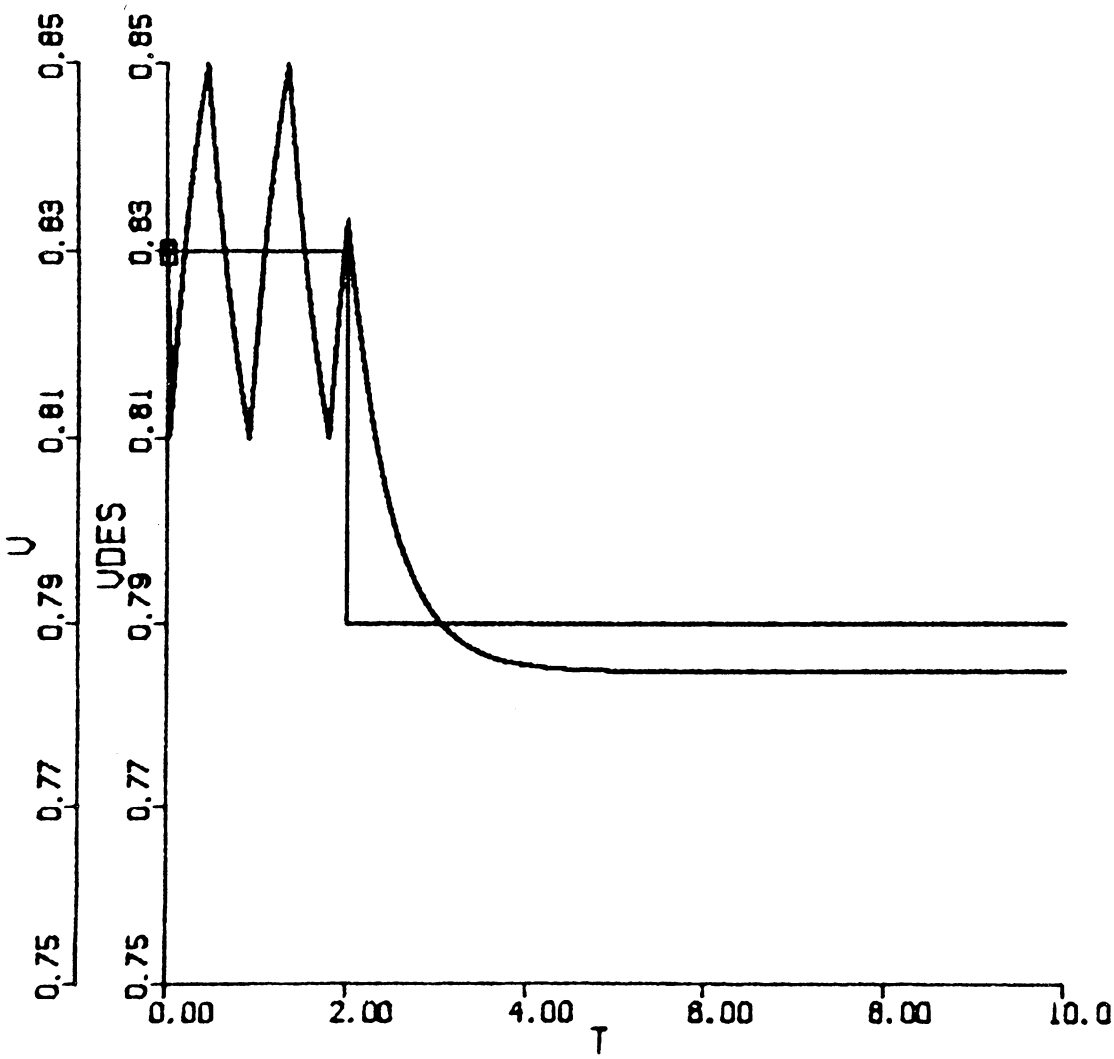

Figure 27. Train Velocity for a Change in Desired Velocity to 0.79, with Error in Train Model

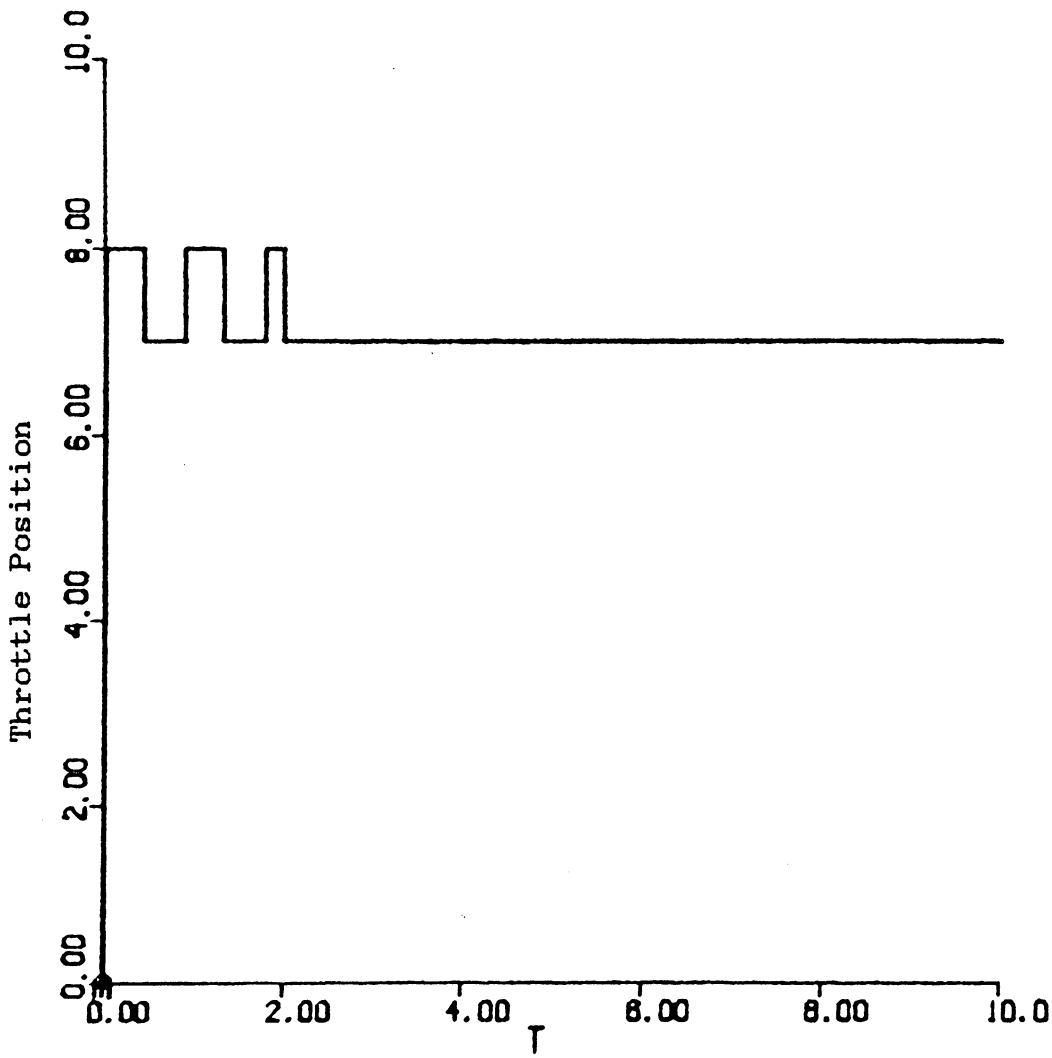

Figure 28. Throttle Position for a Change in Desired Velocity to 0.79, with Error in Train Model

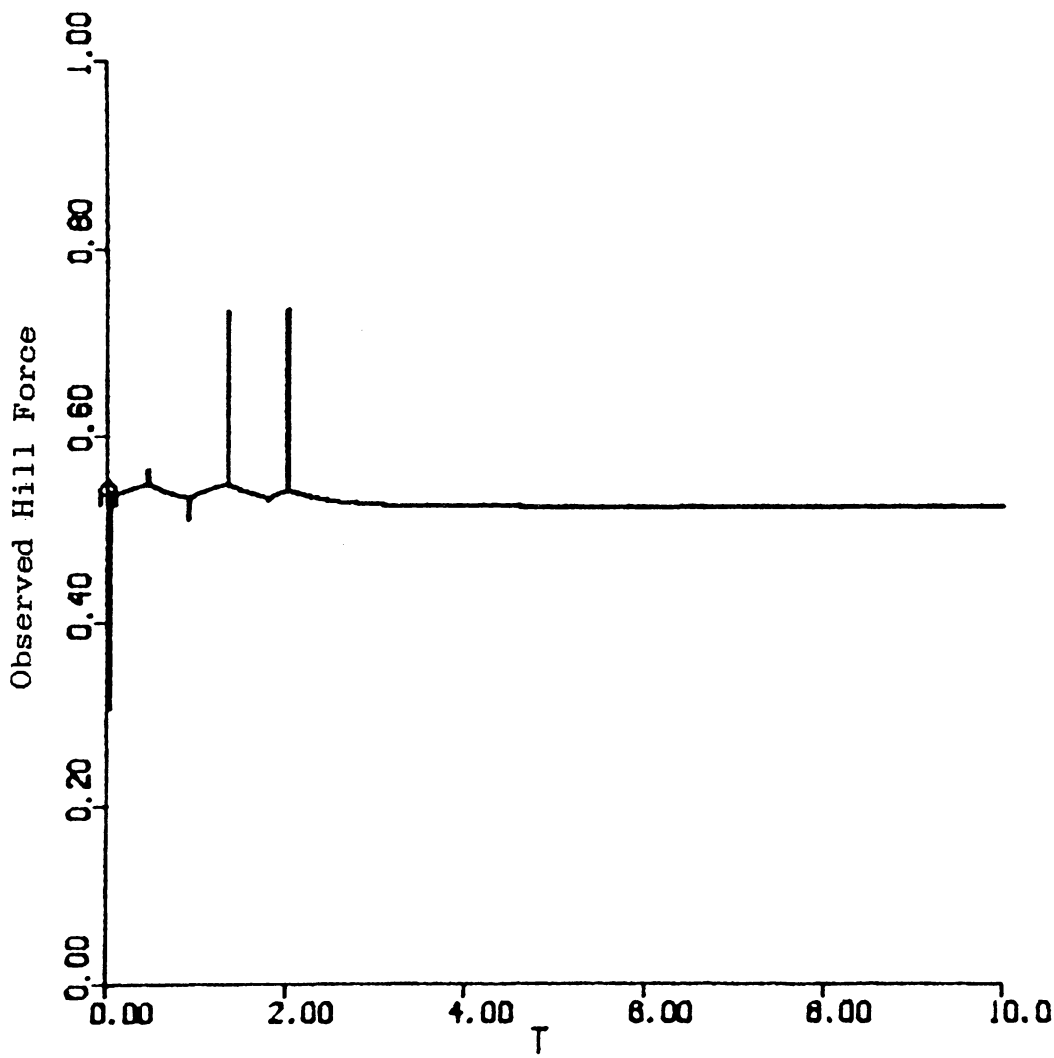

Figure 29. Observed Hill Force for a Change in Desired Velocity to 0.79, with Error in Train Model

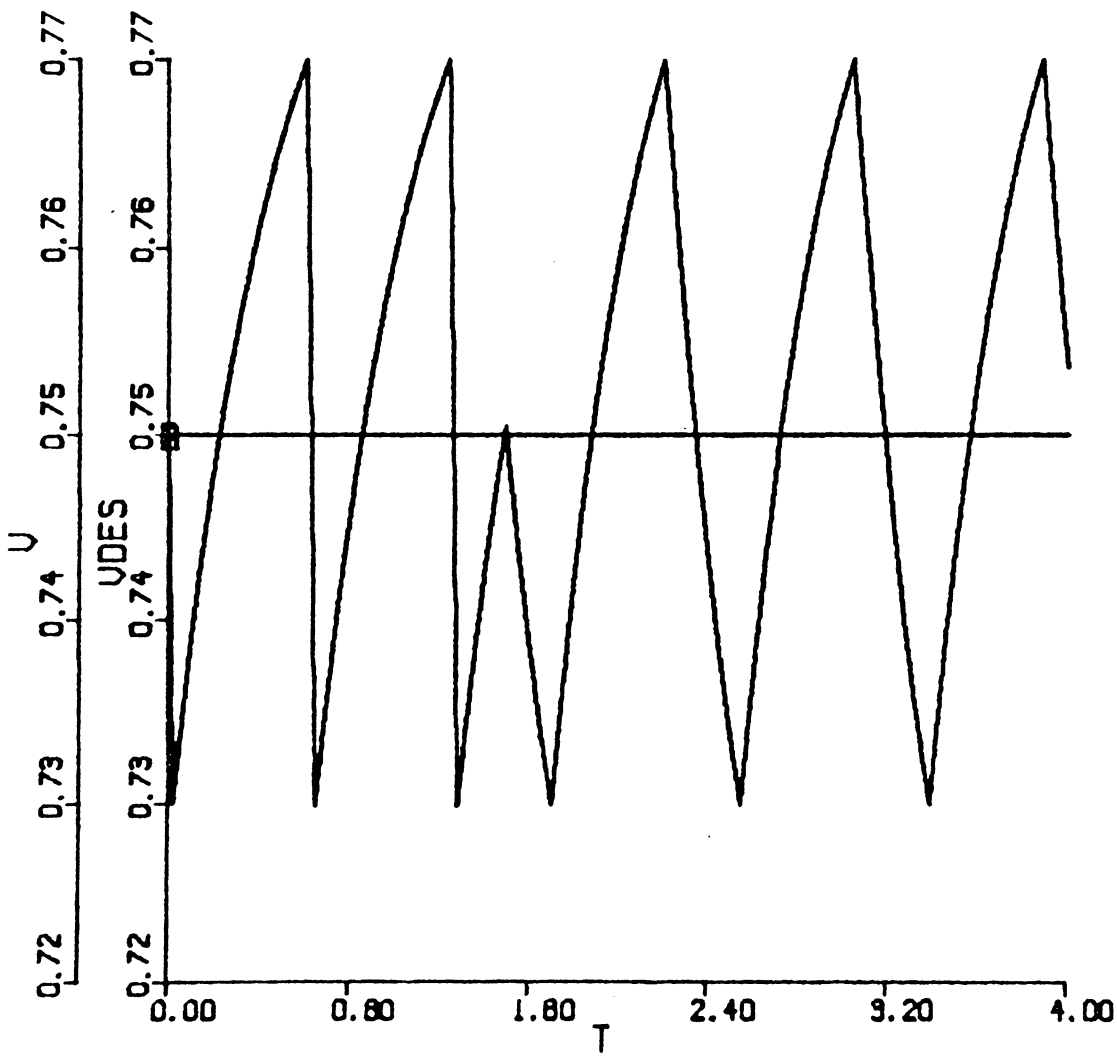

Figure 30. Train Velocity for a Change in Hill Force, with Error in Train Model

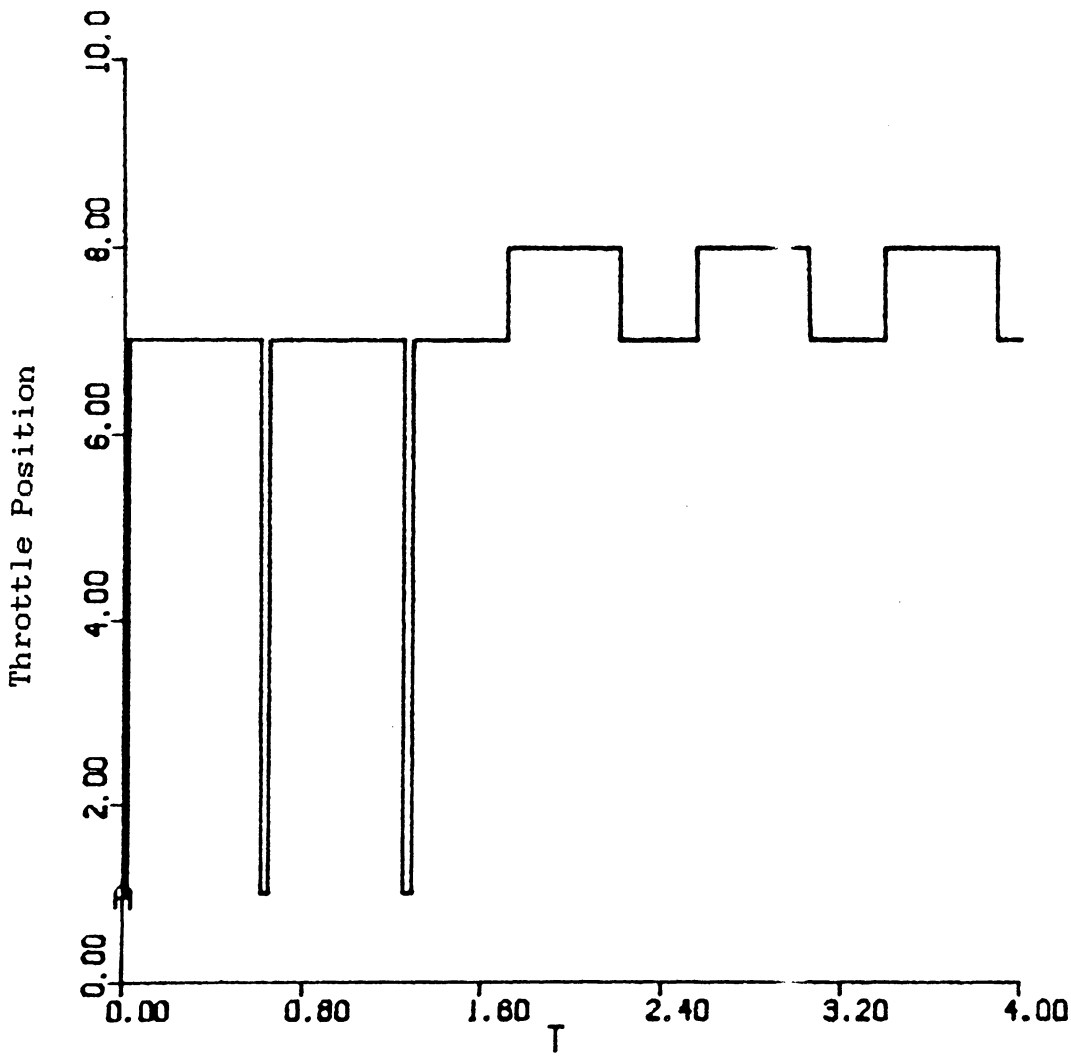

Figure 31. Throttle Position for a Change in Hill Force, with Error in Train Model

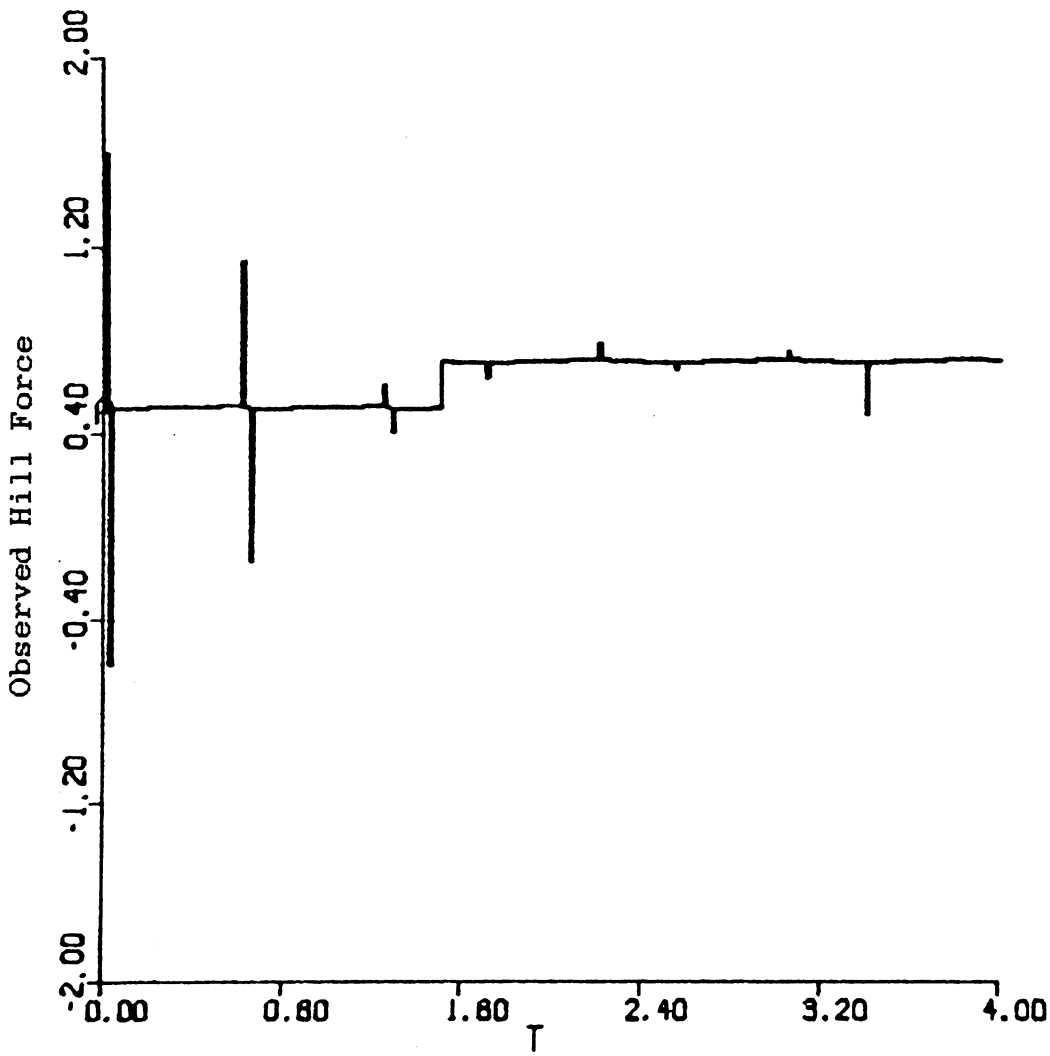

Figure 32. Observed Hill Force for a Change in Hill Force, with Error in Train Model

an estimate of the train weight that would be close enough for the controller to work properly.

This observer design would be suitable for a speed controller for the normal operation of a train. For the normal operation, the throttle should be switched between two adjacent throttle postions. Instead of having two operating regions, there would be eight different operating regions. This means that the power needed would have to be compared to 7 different values.

Some additional features could be added to the controller as well. The velocity limit might be dependent on the desired velocity. This could be used to lengthen the cycle for low velocities, where the velocity changes very quickly. A feature could be incorporated to allow faster acceleration when desired. This would be accomplished by using postion 8 as the high throttle position. Of course, this would use more fuel.

In summary, the controller design is well suited to the periodic operation of the train. The controller has a very robust design, and will tolerate errors in the train model. In addition it may be used as a speed controller for a conventional locomotive.

6. CONCLUSION

The periodic method of operation was found to cause no problems with train slack. Due to the large time constant, there is sufficient time to prevent slack action in the train. Also, the length of the transient period of operation of the engine is small in comparison with the total length of the cycle.

For a simple locomotive model, the periodic method of operation was found to show some fuel savings over the normal method of operation. Unfortunately, the periodic operation was found not to show fuel savings for a model of the SD40 locomotive.

The diesel engine in the locomotive can be modified by adding an additional turbocharger. The turbocharger would increase the efficiency of one throttle position. This modification would probably not be cost-effective for normal train operation. However, for periodic train operation, this modification will enable a fuel savings over a range of throttle settings. An increase of 5% in the efficiency of throttle position 7 showed a fuel savings of 3 to 4% for throttle positions 3 through 6 for the periodic operation.

The controller to implement the periodic operation was found to work for a variety of desired velocites and hill forces. The observer was able to accurately determine changes in hill forces. The observer has a very robust design, and will work well even with a large error in the train model.

7. RECOMMENDATIONS

The periodic method of operation should be examined for locomotives other than the SD40. The information from the locomotive needed for use in the simulations is easy to obtain. It is possible that this method may show fuel savings for other locomotives without modifying the diesel engine.

Further computer simulation should be performed with a mored detailed model. Since the model used in this report considered only steady-state data, the transient engine effects should be included in the new simulation. Perhaps with transient data included in the study, the periodic method may show more fuel savings.

If the more detailed model shows the possibility for fuel savings, the periodic method should be tested on an actual train, rather than a simulation. Such factors as the forces between cars, wheel traction on the rails, and the effect of switching rapidly from low power levels to high power levels on the engine should be carefully examined. The effect of these factors on reliablity should be carefully examined also.

If the periodic method is still found to be

acceptable, than the amount of possible increase in specific fuel consumption for throttle position 7 by adding another turbocharger should then be investigated. If this increase is as high as 2-3%, than further testing on an actual locomotive should be performed.

Some further work can be performed on the controller to implement the periodic operation. The velocity tolerance limit can be varied depending on the desired velocity. A higher acceleration mode can be added to improve train performance. These features can easily be added due to the nature of the digital computer.

The controller given by this report should be considered for use as a speed controller for normal train operation. This would at least eliminate current inefficient operator practices. The design is perfectly suitable for this application.

A study similar to this one should be performed to optimize dynamic braking. The braking strategy developed from this study should be implemented by adding to the controller design, using similar techniques given here. The power level needed can be computed by the controller, and then used to set the braking level as well as the throttle position.

8. REFERENCES

1. Association of American Railroads, Fuel Conservation in Train Operation, 1981, p. 1, pp. 19-24.

2. Kotlin, J. J., et al., The GM/EMD Model F3A Diesel Engine for Rail Application, The Next Generation of Diesel Engines for Rail Traction, 1982, p. 69.

3. Kimura, Y., Koga, S., An Energy Minimum Control in Train Operation, 1984 Joint ASME/IEEE Railroad Conference, pp. 36-41.

4. Morris, H. M., Microcomputers Put Trains Back on the Track, Control Engineering, July 1985, pp. 50-57

5. ACSL User Guide/Reference Manual, Mitchell and Gauthier Associates, 1981.

6. Association of American Railroads, Train Track Dynamics to Improve freight train performance, 2d ed., p. 2-36,3-2.

7. Phone Conversation with Ray Ruffer, Electro-Motive Division, General Motors at LaGrange, Illinois, July 25, 1985.

8. Bradshaw, T. A., Increased Engine Output - Traction Improves the Breed, The Next Generation of Diesel Engines for Rail Traction, 1982, pp. 19-27.

9. Gallois T., Pressure Charging Systems for Highly Rated Traction Engines, The Next Generation of Diesel Engines for Rail Traction, 1982, pp. 87-91.

10. Gunther, C., Increased Engine Output, The Next Generation of Diesel Engines for Rail Traction, 1982, pp. 81-86.

Appendices

Appendix A. Program Listing of Simple Model Simulation

```
PROGRAM SIMPLE TRAIN MODEL

     CINTERVAL CINT=1
     NSTEPS NSTP=1

'------------------------ TRAIN CONSTANTS'
     CONSTANT M=155000
     CONSTANT D1=6340
     CONSTANT D2=76.7
     CONSTANT D3=0.0279

'------------------------ RUN PARAMETERS'
     CONSTANT T0=1000      $'LENGTH OF CYCLE'
     CONSTANT F1=8000      $'HIGH FORCE INCREMENT'
     CONSTANT F2=2000      $'LOW FORCE INCREMENT'
     CONSTANT V0IC=88      $'INITIAL VELOCITY FOR TRAIN 0'
     CONSTANT V1IC=88      $'INITIAL VELOCITY FOR TRAIN 1'

     INITIAL
          '--------------------- CALCULATE OTHER RUN PARAMETERS'
          '     ------------- TIME OF APPLICATION OF F1'
          T1 = T0*F2/(F1+F2)
          F0 = D1 + D2*V0IC + D3*V0IC*V0IC
          '     ------------- CONSTANT VELOCITY FORCE'
          IF (V0IC.LT.60)  N0=(40+V0IC)/100
          IF (V0IC.GE.60)  N0=(160-V0IC)/100
          '     -------------- EFFICIENCY FOR TRAIN 0'
     END
```

```
      DERIVATIVE
           '-------------- MODEL FOR TRAIN 0'
           V0D = (F0 - D1 - D2*V0 - D3*V0*V0)/M
           V0 = INTEG(V0D,V0IC)
           E0 = INTEG(F0/N0,0.)
           X0 = INTEG(V0,0.)

           '-------------- MODEL FOR TRAIN 1'
           '     ----------- COMPUTE TIME-VARYING FORCE'
           '      INCREMENT BY CHOOSING F1 OR -F2'
           DF = RSW(T.LT.T1,F1,-F2)
           '     ----------- CHOOSE EFFICIENCY EQUATION'
           N1 = RSW(V1.LT.60,40+V1,160-V1)/100
           V1D = (F0 + DF - D1 - D2*V1 - D3*V1*V1)/M
           V1 = INTEG(V1D,V1IC)
           E1 = INTEG((F0+DF)/N1,0.)
           X1 = INTEG(V1,0.)

           '------------------- END THE PROGRAM AFTER ONE CYCLE'
              TERMT(T.GE.T0)
      END

      TERMINAL
           V1IC=V1
      END
END
```

Appendix B. Program Listing of SD40 Locomotive Model Simulation (3 different program versions)

```
PROGRAM E,M,D, SD40 MODEL

    CINTERVAL CINT=0,001
    NSTEPS NSTP=1

'------------------------- TRAIN PARAMTERS'
    CONSTANT C0=1
    CONSTANT C1=0,480
    CONSTANT C2=0,726
    CONSTANT C3=0,033

'------------------------ RUN PARAMTERS'
    CONSTANT THR=1          $'INITIAL THROTTLE SETTING'
    CONSTANT VIC=0,20       $'INTIAL VELOCITY'
    CONSTANT ENDT=1         $'END TIME'
    CONSTANT CV=,TRUE,      $'CONSTANT VELOCITY CASE'
    CONSTANT VDES=0,60      $'DESIRED VELOCITY'
    CONSTANT VL=0,02        $'VELOCITY TOLERANCE LIMIT'
    CONSTANT THRL=0         $'LOW THROTTLE POSITION'
    CONSTANT THRH=7         $'HIGH THROTTLE POSITION'


    DERIVATIVE
        PROCEDURAL
        IF (CV ,EQ, ,TRUE,) GOTO L1
        '-------------- PERIODIC OPERATION'
        IF (V ,GT, VDES+VL)  THR=THRL
        IF (V ,LT, VDES-VL)  THR=THRH
        L1,,CONTINUE
        END

        PROCEDURAL (P=THR,V)
        '------------- DETERMINE POWER OUTPUT'
        IF (THR ,EQ, 0)  P=0
        IF (THR ,EQ, 1)  P=0,0294
        IF (THR ,EQ, 2)  P=0,120
        IF (THR ,EQ, 3)  P=0,212
        IF (THR ,EQ, 4)  P=0,321
        IF (THR ,EQ, 5)  P=0,467
        IF (THR ,EQ, 6)  P=0,627
        IF (THR ,EQ, 7)  P=0,840
        IF (THR ,EQ, 8)  P=1,00
        END
```

```
        PROCEDURAL (QD=THR)
        '--------------- DETERMINE FUEL FLOW RATE'
        IF (THR .EQ. 0)  QD=0.026
        IF (THR .EQ. 1)  QD=0.051
        IF (THR .EQ. 2)  QD=0.137
        IF (THR .EQ. 3)  QD=0.227
        IF (THR .EQ. 4)  QD=0.334
        IF (THR .EQ. 5)  QD=0.472
        IF (THR .EQ. 6)  QD=0.629
        IF (THR .EQ. 7)  QD=0.839
        IF (THR .EQ. 8)  QD=1.00
        END

        '--------------- DYNAMIC EQUATIONS'
        VD = C0*P/V - C1 - C2*V - C3*V*V
        V = INTEG(VD,VIC)




        X = INTEG(V,0.)
        Q = INTEG(QD,0.)

        TERMT(T.GE.ENDT)
    END

    TERMINAL
        VIC=V
    END
END
```

```
PROGRAM E.M.D. SD40 MODEL

     CINTERVAL CINT=0.001
     NSTEPS NSTP=1

'------------------------- TRAIN PARAMETERS'
     CONSTANT C0=1
     CONSTANT C1=0.480
     CONSTANT C2=0.726
     CONSTANT C3=0.033

'------------------------- RUN PARAMETERS'
     CONSTANT THR=1          $'INITIAL THROTTLE SETTING'
     CONSTANT VIC=0.20       $'INTIAL VELOCITY'
     CONSTANT END=1          $'DETERMINES LENGTH OF RUN'
     CONSTANT CV=.TRUE.      $'CONSTANT VELOCITY CASE'
     CONSTANT VDES=0.60      $'DESIRED VELOCITY'
     CONSTANT VL=0.02        $'VELOCITY TOLERANCE LIMIT'
     CONSTANT THRL=0         $'LOW THROTTLE POSITION'
     CONSTANT THRH=7         $'HIGH THROTTLE POSITION'


     DERIVATIVE
          PROCEDURAL
          IF (CV .EQ. .TRUE.) GOTO L1
          '--------------- PERIODIC OPERATION'
          IF (V .GT. VDES+VL)  THR=THRL
          IF (V .LT. VDES-VL)  THR=THRH
          L1..CONTINUE
          END

          PROCEDURAL (P=THR,V)
          '-------------- DETERMINE POWER OUTPUT'
          IF (THR .EQ. 0)  P=0
          IF (THR .EQ. 1)  P=0.0294
          IF (THR .EQ. 2)  P=0.120
          IF (THR .EQ. 3)  P=0.212
          IF (THR .EQ. 4)  P=0.321
          IF (THR .EQ. 5)  P=0.467
          IF (THR .EQ. 6)  P=0.627
          IF (THR .EQ. 7)  P=0.840
          IF (THR .EQ. 8)  P=1.00
          END
```

```
        PROCEDURAL (QD=THR)
        '--------------- DETERMINE FUEL FLOW RATE'
        IF (THR .EQ. 0)  QD=0.026
        IF (THR .EQ. 1)  QD=0.051
        IF (THR .EQ. 2)  QD=0.137
        IF (THR .EQ. 3)  QD=0.227
        IF (THR .EQ. 4)  QD=0.334
        IF (THR .EQ. 5)  QD=0.472
        IF (THR .EQ. 6)  QD=0.629
        IF (THR .EQ. 7)  QD=0.797
        IF (THR .EQ. 8)  QD=1.00
        END

        '--------------- DYNAMIC EQUATIONS'
        VD = C0*P/V - C1 - C2*V - C3*V*V
        V = INTEG(VD,VIC)




        X = INTEG(V,0.)
        Q = INTEG(QD,0.)

       TERMT(X.GE.VDES*END)
    END

END
```

```
PROGRAM E.M.D. SD40 MODEL

     CINTERVAL CINT=0.001
     NSTEPS NSTP=1

'------------------------- TRAIN PARAMETERS'
     CONSTANT C0=1
     CONSTANT C1=0.480
     CONSTANT C2=0.726
     CONSTANT C3=0.033

'------------------------- RUN PARAMETERS'
     CONSTANT THR=1          $'INITIAL THROTTLE SETTING'
     CONSTANT VIC=0.20       $'INTIAL VELOCITY'
     CONSTANT END=1          $'DETERMINES LENGTH OF RUN'
     CONSTANT CV=.TRUE.      $'CONSTANT VELOCITY CASE'
     CONSTANT VDES=0.60      $'DESIRED VELOCITY'
     CONSTANT VL=0.02        $'VELOCITY TOLERANCE LIMIT'
     CONSTANT THRL=0         $'LOW THROTTLE POSITION'
     CONSTANT THRH=7         $'HIGH THROTTLE POSITION'


     DERIVATIVE
          PROCEDURAL
          IF (CV .EQ. .TRUE.) GOTO L1
          '--------------- PERIODIC OPERATION'
          IF (V .GT. VDES+VL)  THR=THRL
          IF (V .LT. VDES-VL)  THR=THRH
          L1,.CONTINUE
          END

          PROCEDURAL (P=THR,V)
          '-------------- DETERMINE POWER OUTPUT'
          IF (THR .EQ. 0)  P=0
          IF (THR .EQ. 1)  P=0.0294
          IF (THR .EQ. 2)  P=0.120
          IF (THR .EQ. 3)  P=0.212
          IF (THR .EQ. 4)  P=0.321
          IF (THR .EQ. 5)  P=0.467
          IF (THR .EQ. 6)  P=0.627
          IF (THR .EQ. 7)  P=0.840
          IF (THR .EQ. 8)  P=1.00
          END
```

```
        PROCEDURAL (QD=THR)
        '--------------- DETERMINE FUEL FLOW RATE'
        IF (THR .EQ. 0)  QD=0.026
        IF (THR .EQ. 1)  QD=0.051
        IF (THR .EQ. 2)  QD=0.137
        IF (THR .EQ. 3)  QD=0.227
        IF (THR .EQ. 4)  QD=0.334
        IF (THR .EQ. 5)  QD=0.472
        IF (THR .EQ. 6)  QD=0.629
        IF (THR .EQ. 7)  QD=0.839
        IF (THR .EQ. 8)  QD=1.00
        END

        '--------------- DYNAMIC EQUATIONS'
        VD = C0*P/V - C1 - C2*V - C3*V*V
        V = INTEG(VD,VIC)




        X = INTEG(V,0.)
        Q = INTEG(QD,0.)

       TERMT(X.GE.VDES*END)
    END

END
```

Appendix C. Program of SD40 Locomotive with Controller Model

```
PROGRAM E.M.D. SD40 MODEL

    CINTERVAL CINT=0.001
    NSTEPS NSTP=1

'------------------------- TRAIN PARAMETERS'
    CONSTANT C0=1
    CONSTANT C1=0.480
    CONSTANT C2=0.726
    CONSTANT C3=0.033
    CONSTANT C4=0.432
    CONSTANT C5=0.653
    CONSTANT C6=0.033

'------------------------- RUN PARAMETERS'
    CONSTANT THR=1          $'INITIAL THROTTLE SETTING'
    CONSTANT VIC=0.20       $'INITIAL VELOCITY'
    CONSTANT CV=.FALSE.     $'PERIODIC OPERATION'
    CONSTANT VL=0.02        $'VELOCITY TOLERANCE LIMIT'
    CONSTANT V0=0.60        $'INITIAL DESIRED VELOCITY'
    CONSTANT V1=0           $'CHANGE IN DESIRED VELOCITY AT TV1'
    CONSTANT V2=0           $'CHANGE IN DESIRED VELOCITY AT TV2'
    CONSTANT TV1=1.0        $'TIME TV1'
    CONSTANT TV2=2.0        $'TIME TV2'
    CONSTANT H0=0           $'INITIAL HILL FORCE'
    CONSTANT H1=0           $'CHANGE IN HILL FORCE AT TH1'
    CONSTANT H2=0           $'CHANGE IN HILL FORCE AT TH2'
    CONSTANT TH1=1.5        $'TIME TH1'
    CONSTANT TH2=3.0        $'TIME TH2'
    CONSTANT TE=4.0         $'END TIME'

    INITIAL
        VP=VIC
        V=VIC
        FP=VIC*(C1+C2*VIC+C3*VIC**2)
    END

    DYNAMIC
            '-----------------DESIRED VELOCITY PROFILE'
            VDES = V0 + V1*STEP(TV1) + V2*STEP(TV2)
            '-----------------HILL FORCE PROFILE'
            HF = H0 + H1*STEP(TH1) + H2*STEP(TH2)
```

```
DISCRETE
'---------------------- CONTROLLER'
     INTERVAL H=0.01    $'SAMPLING INTERVAL'
     '------------------ OBSERVER'
     PROCEDURAL
     A = (V-VP)/(H-H**2*(PP/VP**2+C5+2*C6*VP)/2)
     FH = PP/VP-C4-C5*VP-C6*VP*VP-A
     PE = VDES*(C4+C5*VDES+C6*VDES**2+FH)
     '------------------ SET OPERATING INTERVAL'
     IF (P .NE. PP) GOTO L2
     THRL = 1
     THRH = 7
     IF (PE .GT. 0.840)  THRL=7
     IF (PE .GT. 0.840)  THRH=8
     L2,.CONTINUE
     VP = V
     PP = P




     END
END

DERIVATIVE
     PROCEDURAL
     IF (CV .EQ. .TRUE.) GOTO L1
     '--------------- PERIODIC OPERATION'
     IF (V .GT. VDES+VL)  THR=THRL
     IF (V .LT. VDES-VL)  THR=THRH
     L1,.CONTINUE
     END
```

```
            PROCEDURAL (P=THR,V)
            '-------------- DETERMINE POWER OUTPUT'
            IF (THR .EQ. 0)  P=0
            IF (THR .EQ. 1)  P=0.0294
            IF (THR .EQ. 2)  P=0.120
            IF (THR .EQ. 3)  P=0.212
            IF (THR .EQ. 4)  P=0.321
            IF (THR .EQ. 5)  P=0.467
            IF (THR .EQ. 6)  P=0.627
            IF (THR .EQ. 7)  P=0.840
            IF (THR .EQ. 8)  P=1.00
            END

            PROCEDURAL (QD=THR)
            '--------------- DETERMINE FUEL FLOW RATE'
            IF (THR .EQ. 0)  QD=0.026
            IF (THR .EQ. 1)  QD=0.051
            IF (THR .EQ. 2)  QD=0.137
            IF (THR .EQ. 3)  QD=0.227
            IF (THR .EQ. 4)  QD=0.334
            IF (THR .EQ. 5)  QD=0.472
            IF (THR .EQ. 6)  QD=0.629
            IF (THR .EQ. 7)  QD=0.797
            IF (THR .EQ. 8)  QD=1.00
            END

            '--------------- DYNAMIC EQUATIONS'
            VD = C0*P/V - C1 - C2*V - C3*V*V - HF
            V = INTEG(VD,VIC)
            X = INTEG(V,0.)
            Q = INTEG(QD,0.)

        END
        TERMT(T.GE.TE)
    END

END
```

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