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Resistance of a Freight Train To Forward Motion - Volume II, Implementation & Assessment

April 1979

INTERIM REPORT

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16. Abstract This interim report is a supplement to a previous report and documents the results of the second portion of an investigation of the train resistance phenomenon. This portion of the effort was specifically directed toward determination of possible fuel savings to be effected through certain design improvements or equipment modifications when a freight train is operated over normal track, including grades and curves. The results of 52 simulated runs of various freight trains over various tracks, both real and artificial, are reported. The simulations show that fuel savings are not directly proportional to reductions in train resistance and that under certain circumstances only a portion of the theoretically attainable fuel savings can be achieved. It is also shown that fuel savings attributable to certain of these modifications are quite dependent upon the nature of the operation in which they are used. Within limits, the computer program developed during this study can be used to determine the fuel consumption of an arbitrary train operated over an arbitrary track to perform sensitivity analyses with respect to locomotive assignment policy, operational speed limit, and the like, and to determine the effect of design improvements or equipment modifications upon fuel consumption under normal operating conditions. The computer program which performs the calculation is explained in detail and the rationale behind its development is given. An example of the results from a separate plotting routine, which plots from the data generated a velocity profile on which is superimposed the instantaneous fuel consumption rate, is given. Complete information on trains and tracks used to generate the material for the report is given in an appendix.

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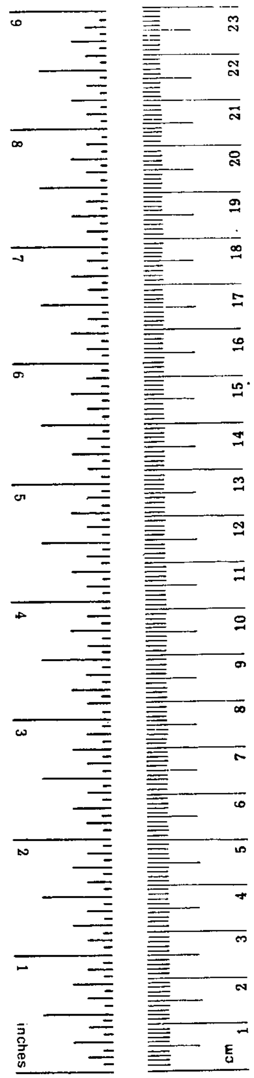
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

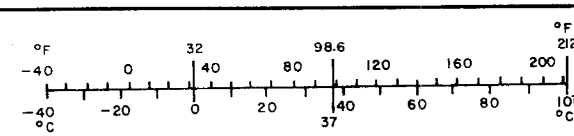
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Few reports are solely the work of a single author, and I gratefully acknowledge the contributions of those individuals listed below as well as many others whose contributions were less specific but no less useful. Among the former are Arne Bang of FRA, whose original inquiry prompted the research; John Koper of FRA, who supplied copies of many related reports and guided the effort; Wilbert Cantey of FRA, whose office through the efforts of Carl Fischer supplied the statistical picture of U.S. track data used herein; Morrin Hazel and A. T. Newfell of TSC, who supplied many helpful comments on train performance simulators and train operation; Richard Verselle of Electromotive Division of General Motors Corp., who graciously supplied the tractive effort curves for the SD-40 locomotive; Dave Reynolds of Southern Railway, who supplied additional helpful comments on train operation; Leonard Cook, Art Smith, and Jim Lawson of Garrett Airesearch, whose discussion of their train performance simulator was enlightening; Dr. Andrew Hammitt, who helpfully provided guidance through the intricacies of Reynolds numbers, boundary layers, and flow separations and also supplied in his several reports referenced herein most of the aerodynamic data used in the program; Dr. Michael Lenard of MITRE, whose earlier paper on the same subject was very useful; Rob Martin of MITRE who wrote the economic section for Volume I and was the source of the economic ideas contained in this volume; John Anderes of MITRE who assisted in some of the more intricate parts of the programming discussed in Volume I and did the same in the early development of the second program; Alan Robbins of MITRE, who assisted in establishing the random number routines; and Donna Kippeny of MITRE, who effected the translation of the program from one computer system to another and wrote the plotting routines for the figures.

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EXECUTIVE SUMMARY

A previous report* documented the examination of possible savings in fuel consumption to be achieved through certain reductions in train resistance when the train is operated over level tangent track. It was noted that some of the conclusions might have to be modified if the train were operated over normal track, including grades and curves. This report documents the subsequent examination of possible savings in fuel consumption which might be achieved by the same reductions in train resistance when the train is operated over normal track. The same design improvements and equipment modifications examined in the first volume were re-examined under the new circumstances.

For the re-examination, a new computer program was devised to calculate fuel consumption when the train is operated over normal track. Operation of the train is assumed to be performed in a smooth and realistic fashion by an engineer who attempts always to maintain the train speed at the speed limit established by the track condition or specified by the program operator. The previously devised program for calculating train resistance, described in the previous report, was incorporated into the new program. In addition, new aerodynamic data** from wind tunnel tests of blocks simulating railroad vehicles was incorporated into the program so that calculation of train aerodynamic drag would be as realistic as present knowledge would permit.

The output of the newly devised program was checked for its sensitivity to certain parameters internal to the simulation of the train operation and found to be satisfactorily insensitive. The program output was also checked against fuel consumption measured in the field by simulation of operation of similar trains over the corresponding tracks. The output was found to be within satisfactory, although not perfect, agreement with the measured field data. Discrepancies were attributed to the likelihood of imperfect replication of the test conditions in the simulation rather than inherent defects in the program.

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* "Resistance of a Freight Train to Forward Motion - Volume I, Methodology and Evaluation", U.S. Department of Transportation, Federal Railroad Administration, Report No. FRA/ORD-78/04.I, April 1978.

** Hammitt, A.G., "Aerodynamic Forces on Freight Trains, Volume III," U.S. Department of Transportation, Federal Railroad Administration, Report No. FRA/ORD-76-295.IV (to be published Spring 1979).

After it was believed the program was operating satisfactorily and producing reliable predictions of fuel consumption, simulated runs of trains of various types were made over three different tracks; each trip was made as a round trip to eliminate the effect of altitude differences between end points. An eastern track and a western track were selected and a third track was contrived artifically from overall statistics on U.S. Class A mainline track (ca. 1971-75) provided by the Federal Railroad Administration.* The eastern track was selected to be representative of operations in mountainous regions, with many grades and curves. The western track was selected to be representative of operation over the western plains, mostly straight and level. All of the tracks were between two hundred and two hundred fifty miles long, and it was arranged that there would be one five-minute stop approximately midway.

A total of 52 runs was initially scheduled, and a few additional runs were made subsequently as checks upon the initial runs when results appeared questionable. The limited total of runs was selected from a large matrix of possible runs which might have been made, with different horsepower to gross trailing ton ratios, different tracks, and different directions of operation. Because cost considerations made it necessary to limit the number of runs made, tracks and trains were selected so as to be representative of the type of operation in which the particular design improvement or equipment modification might be used. The five potential improvements or modifications examined in the initial study were reexamined: light weight equipment, consist rearrangement, improved bearing seals, improved track rigidity, and improved truck design.

(1) <u>Light Weight Equipment</u>:

(a) Light weight hopper cars for unit train service

A unit coal train operation was given extensive coverage and sixteen runs were devoted to examining the potential for light weight hopper cars, in this particular case aluminum cars, although the results may be partially applicable to light weight steel cars. These simulated trains were run over both the eastern track and the western track, hauling a full load of coal in one direction and returning

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* The definition of what constitutes Class A mainline track was not finalized until a report by the Secretary of Transportation was published in January, 1977. Briefly, Class A mainline track carries more than 20 million gross tons annually, or is needed to serve a market generating more than 75,000 carloads annually, or is essential to the strategic rail corridor network. Previous to this report, there was no generally accepted definition of either "mainline" or "branchline." While the data were of the approximate vintage 1971-75, the statistics were in accordance with the latest definition.

empty. Because of the altitude change between end points, the operation had to be made in the opposite sense as well, i.e., starting with the full load at the other end and returning there empty. An operational speed limit of 25 mph was imposed on all loaded trips, and 45 mph on all empty return trips.

The results of the simulated runs were not entirely predictable. Although certain fuel savings can be accrued through the use of the light weight (aluminum) hopper cars, it still appears that, although the savings are higher than from comparable operations on level tangent track, the additional economic investment required is only marginally justified when based upon fuel savings alone. Fuel savings amounted to slightly more than 6 percent. However, when other factors such as higher salvage value and reduced maintenance of way expenditures for the same net pay load are considered, the additional expenditure may be justifiable. These conclusions are virtually the same as the previous conclusions based upon operation over level tangent track, although the fuel savings are somewhat higher. It is also shown, however, that the conclusions are strongly dependent upon the nature of the track over which the operation is simulated and the operational speed limit.

(b) Light weight flat cars for intermodal service

Another sixteen runs were devoted to examination of TOFC/COFC operation using light weight flat cars over the same tracks as above. These were run with average loadings in both directions, but all trips were round trips to avoid the effects of altitude changes. Operational speed limits were all 79 mph on these runs, as it was felt that intermodal freight is desirably high-speed; however, track limitations held the average trip velocity to under 46 mph on the eastern run and under 53 mph on the western run.

The TOFC/COFC runs produced results similar to those using light weight hopper cars. Fuel savings alone were small, on the average about the same as for the light weight hopper cars. The results were very dependent upon the particular operation and particular track and may have been somewhat dependent upon the load, although an average load was selected. Fuel savings resulting from the use of the light weight TOFC flat car were less than those resulting from the COFC light weight flat car as the weight reduction was smaller; fuel savings on both TOFC and COFC operations were smaller on the western track than on the eastern track since the average speed on the former track was higher. It is difficult to draw general conclusions because of the dependency of fuel savings upon the particular operation. Savings ranged from 2 percent to over 9 percent for the operations examined. Fuel consumption per thousand gross-trailing-ton-miles actually increased with the use of light weight equipment, but the consumption per thousand net-trailing-ton-miles diminished. Careful analysis of the particular operation for which the light weight equipment is to be used is therefore advisable. It appears that under certain circumstances the additional financial investment presently required for light weight flat cars may be justifiable; under others, not.

(2) Consist Rearrangement:

The effects of rearranging the consist were felt likely to be most evident at higher speeds where aerodynamic drag is more pronounced, and four runs were made of an average train and the same consist rearranged in a more favorable sequence over the western track with a 79 mph operational speed limit. The average velocities for the trip were again somewhat lower than the speed limit, less than 51 mph.

Rearrangement did not appear to be as favorable as formerly indicated. This was partially attributable to new aerodynamic data, which put a heavier penalty on short gaps between cars, such as those between boxcars, which are not substantially altered by rearrangement. In addition, fuel savings are not directly proportional to reductions in train resistance except for constant speed operation over level tangent track, since fuel consumption during operation over normal track is attributable to several factors, only one of which is reduced through rearrangement, while the others remain fixed. However, the aerodynamic data are still preliminary and results from block tests may not be completely applicable to full scale railroad vehicles. Thus consist rearrangement may still offer meaningful savings.

(3) Improved Bearing Seals and Improved Track Rigidity

These possible modifications did not seem to be related to a particular type of operation or track, and the simulated runs were therefore performed using an average train over the artificially contrived track which incorporated the statistics from all U.S. Class A mainline track. Operation at both low and high speed was simulated by means of imposing a 25 mph and a 79 mph speed limit. These equipment modifications are relatively independent of velocity and were simulated as constant reductions of train resistance. Such reductions can be treated theoretically as reductions in energy per car-mile, which relates directly to fuel consumption for the trip, regardless of the velocity profile or the nature of the track. However, it is shown in the current report that such theoretical reductions are obtainable only on level tangent track with constant speed operation, and that as the track becomes more complex, in the sense of having grades and curves introduced, the percentage of the theoretically attainable reduction which can be achieved diminishes. This occurs because during a significant portion of the operation, i.e., on major downgrades, a reduction in fixed mechanical resistance merely means that braking must be increased in compensation to maintain operation within the speed limit. In contrast, as the nature of the track approaches that of level tangent track, the percentage of the theoretically attainable reduction actually attained approaches 100%. As a consequence the reductions in fuel consumption are quite dependent upon the nature of the track over which the train is operated. In addition, the velocity of the operation also affects the extent to which the theoretically attainable savings are achieved. Although it was indicated in the previous report that both improvements were capable of achieving excellent reductions in train resistance, it appears that as with the other improvements, fuel savings are not simply proportional to reductions in train resistance in normal operations. Savings in fuel consumption were smaller for both modifications than the reductions in train resistance reported in the previous report. Fuel savings for the improved bearing seals were 2.1% and 1.1% for 25 mph and 79 mph operations respectively, and for the rigidized track 6.1% and 3.7% respectively. For this reason, as with several of the other proposed modifications, it is advisable to examine closely the particular operation for which the improvement is recommended in order to determine the economic feasibility of the improvement.

(4) Improved Truck Design

As with the improved bearing seals and track rigidity, simulated operations with an improved truck having less resistance were performed using the average train over the artificial track.

Improved truck design in the simulation resulted in a modest saving in fuel, approximately 2.5% and not dependent upon the velocity of the operation. This value is slightly less than the 3.8% reduction in train resistance reported previously for operation at 60 mph. The fact that the percentage reduction in fuel savings is smaller than the reduction in resistance is not surprising, as the fuel consumption is, as noted earlier, weighted down by other factors not attributable to train resistance. However, since improved curving performance was not specifically modelled, it is possible the figures for certain types of trucks could be more favorable. While it is conceivable that such a reduction could result in a favorable economic justification for the purchase of such improved trucks, it must be recognized that, apart from the possibility of improved curving performance from certain types of trucks, the indicated fuel savings here are the absolute limit, and that, practically, something less would be achieved with the use of any real truck.

In summary, simulated operation of freight trains over realistic track in order to compute fuel savings attributable to design improvements or equipment modifications has shown that fuel savings are not directly proportional to reductions in train resistance, as other factors affect fuel consumption as well, and that under certain operational circumstances only a portion of the theoretically attainable fuel savings can actually be achieved. It has also been shown that fuel savings attributable to certain of these modifications are quite dependent upon the nature of the operation in which such modifications might be utilized, and careful consideration of the intended operation is advised before investment decisions are made on the basis of possible fuel savings.

1.0 INTRODUCTION

A previous report (1)* on the topic of train resistance documented some considerations with regard to freight train operation over level tangent track. The same report pointed out the need to examine the validity of the conclusions drawn for operation over normal track including grades and curves. This report addresses the problem of operation of freight trains over such normal track and describes the calculation of the corresponding fuel consumption.

While fuel consumption is undeniably related to train resistance, other factors in addition contribute considerably to it; in particular, neither energy dissipated in braking nor fuel consumed during idling at stops appears in any calculation of train resistance. The computer program described herein addresses the problem of fuel consumption of a freight train directly and takes such effects into consideration.

It is recognized that most existing train performance simulators also generate fuel consumption data as part of the program output, although that is not normally their primary purpose. These simulators were not felt to be suitable for addressing the particular problem at hand and for this reason the program described herein was devised. It was felt that a calculation designed for the particular problem was likely to be both more accurate than others and less expensive to operate in a computer program. In particular, it was deemed essential to incorporate into the calculation of train resistance the depth of detail of the program developed earlier, as reported in Volume I (1), in order to assess the aerodynamic resistance with proper accuracy. As a result, a program calculating fuel consumption which simply utilized the modified Davis formula was first devised, and subsequently the original program calculating train aerodynamic resistance more accurately was merged into the second program as a substitute for the modified Davis formula. In addition,

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*Numbers in parentheses refer to References.

creation of the new program permitted relatively simple modification of the aerodynamic drag calculation to reflect wind tunnel data on blocks simulating railroad vehicles recently made available.[2]

While the calculation performed by the program inevitably bears a certain resemblance to a train performance simulator, in that the velocity of the train must be computed at every instant of time in order to compute fuel consumption, it is not intended to be more than a slightly sophisticated method of performing otherwise tedious manual calculations. Nevertheless, the program described herein benefitted substantially from the experience of others who had developed and worked on such simulators. An excellent summary of the considerations involved in designing a train performance simulator is given in Hopkins[3] and will not be repeated here. However, certain considerations with regard to the accuracy of the calculation reported herein will of necessity be mentioned.

2.0 APPROACH

The problem to be solved was the determination of the change in fuel consumption of a freight train operating over normal track in a normal position when certain design improvements or equipment modifications were imposed on the train or roadbed and track. A computer program was hence devised to calculate the fuel consumption on a simulated given trip so that the result would be compared with a corresponding value for a trip made under different circumstances. Although it was not essential for these purposes that the absolute value of fuel consumption determined for a given trip be completely accurate, for credibility purposes it was considered desirable that the absolute value correspond closely with values measured in the field under similar conditions. For this reason, inputs were made to the computer program to simulate train runs on which fuel consumption data had been collected, and the program outputs were checked against the measured data. The correspondence of results was deemed to be sufficiently close that the program could be considered calibrated as much as present information and the inherent limitations of the program would permit. The calibration is discussed at some length in the following section.

The computer program, within limits, will evaluate the fuel consumption for the operation of a given train over a given track. Certain limits have been placed on the scope of the program, but these could be modified if necessary. Examples would include limitations on the length of the train, on the number of track records in the track file, on the type of locomotive, etc. Other limitations are inherent and could not be eliminated without rewriting the program. These latter ones are discussed extensively below.

The program requires information about both the train and the track in order to evaluate the fuel consumption. At the present time it also requires certain other information from the program operator regarding how the train is to be operated and how the program is to perform the calculation. From this information the values of some twelve variables at every instant of time are calculated, most of which are essential to the fuel consumption calculation, such as the instantaneous train velocity. These values are printed in numerical form as the program output. Certain others, such as the cumulative distance travelled and the cumulative time for the trip, serve as checks on the calculation or are merely of peripheral interest. The instantaneous rate of fuel consumption was thought to be of considerable interest and was calculated specifically to serve as an input to the plotting routine. The plotting routine, used in conjunction with a CalComp plotter, generates a curve showing the velocity as a function of time, on top of which is superimposed the instantaneous rate of fuel consumption. See Figure 1. Such a figure shows dramatically at which points during the trip the fuel consumption is highest, most notably during periods of high acceleration or on grades.

The study of fuel consumption reported in this document was deliberately related to the five general areas studies previously with relation to operation over level tangent track and reported in Volume I.[1] This was done because the same five areas are still of general interest and because it was deemed desirable to contrast operation over normal track with that over level tangent track.

Nevertheless, the approach taken herein is slightly different and rather than emphasizing the average train or average values for railroad operation in general, in most cases trains and tracks have been selected to typify a particular operation. The fuel consumption of a unit coal train hauling coal in one direction and returning empty was addressed in particular. Trains have been

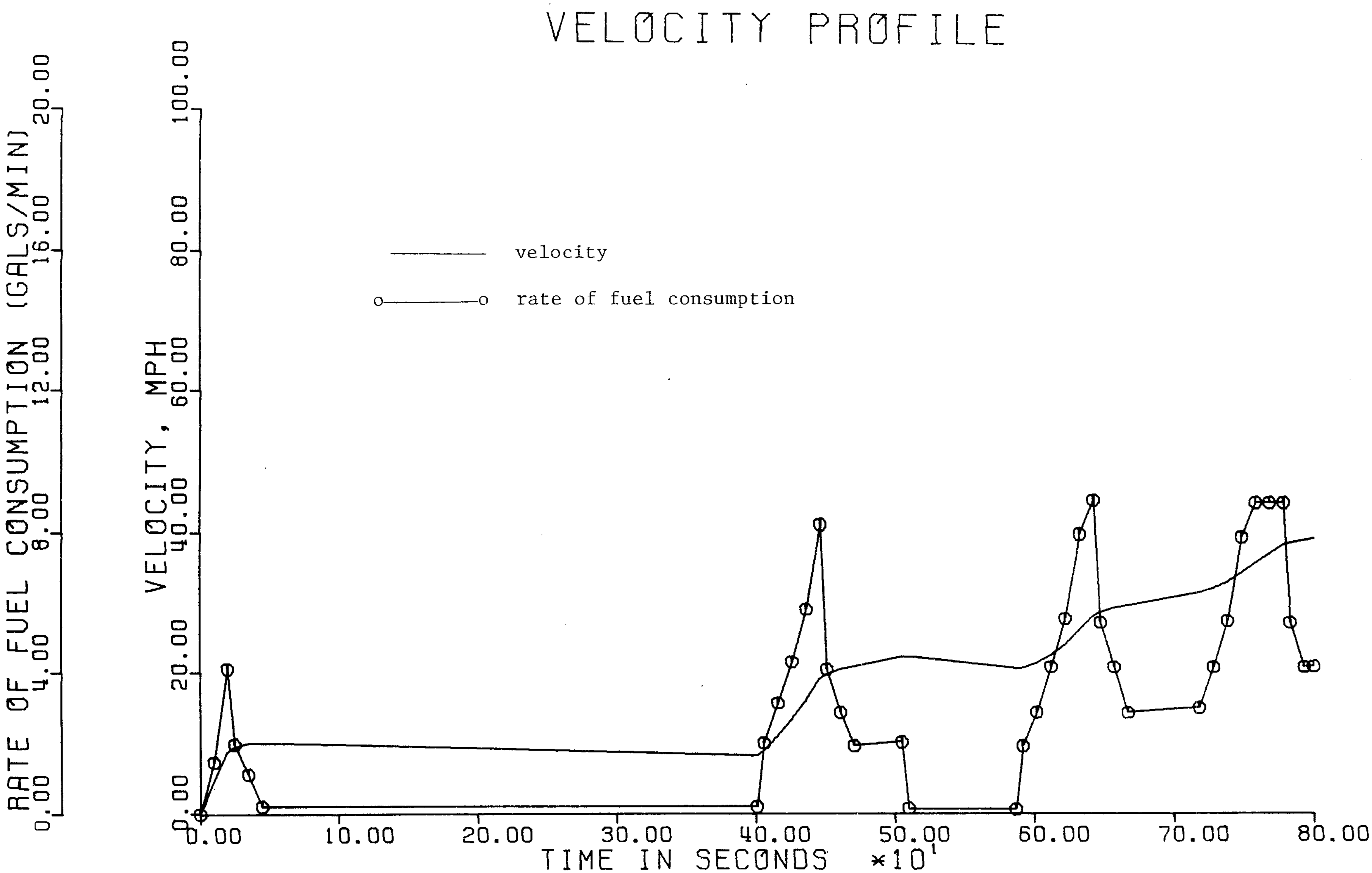

FIGURE 1
VELOCITY PROFILE AND RATE OF FUEL CONSUMPTION

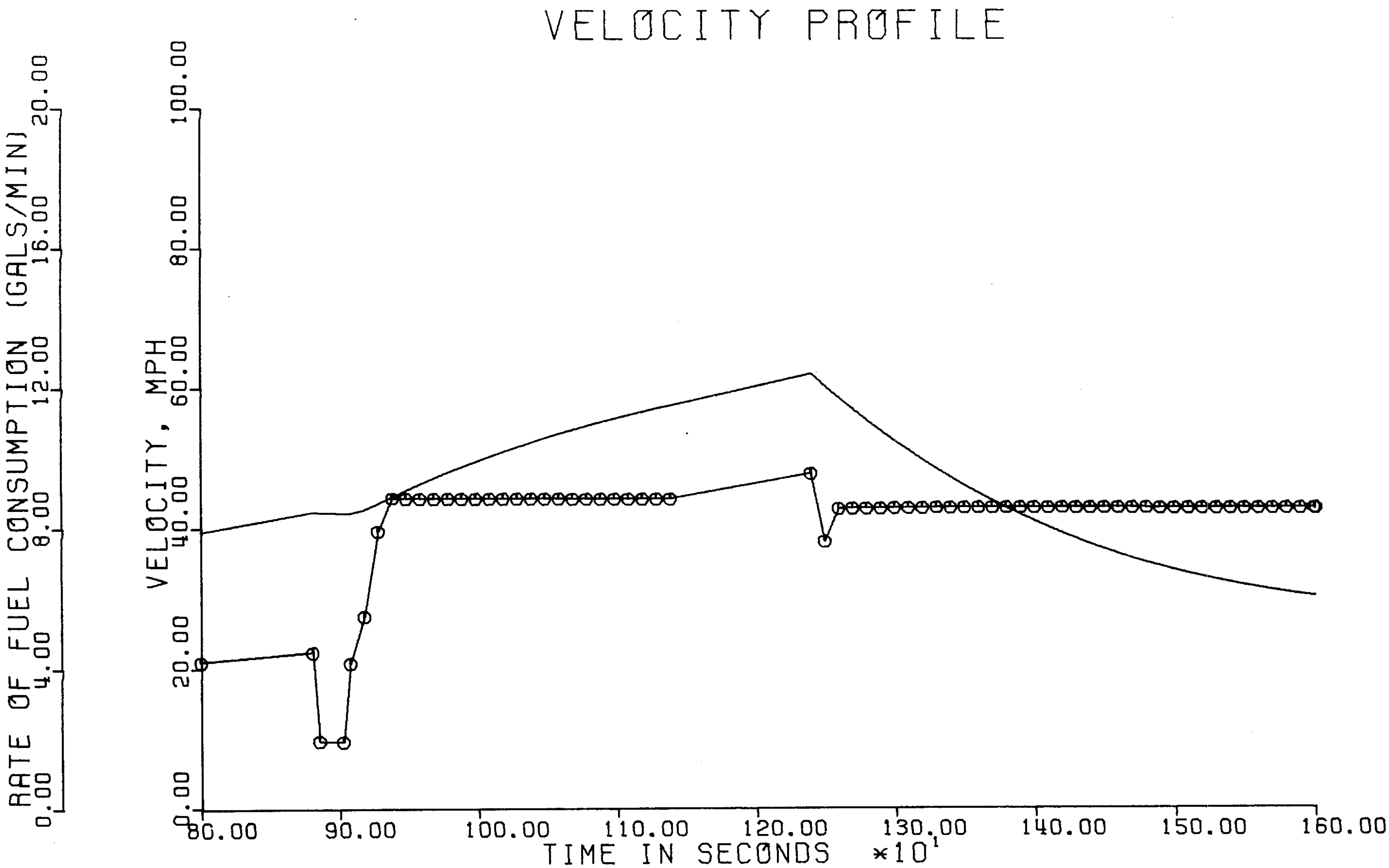

FIGURE 1
VELOCITY PROFILE AND RATE OF FUEL CONSUMPTION
(CONTINUED)

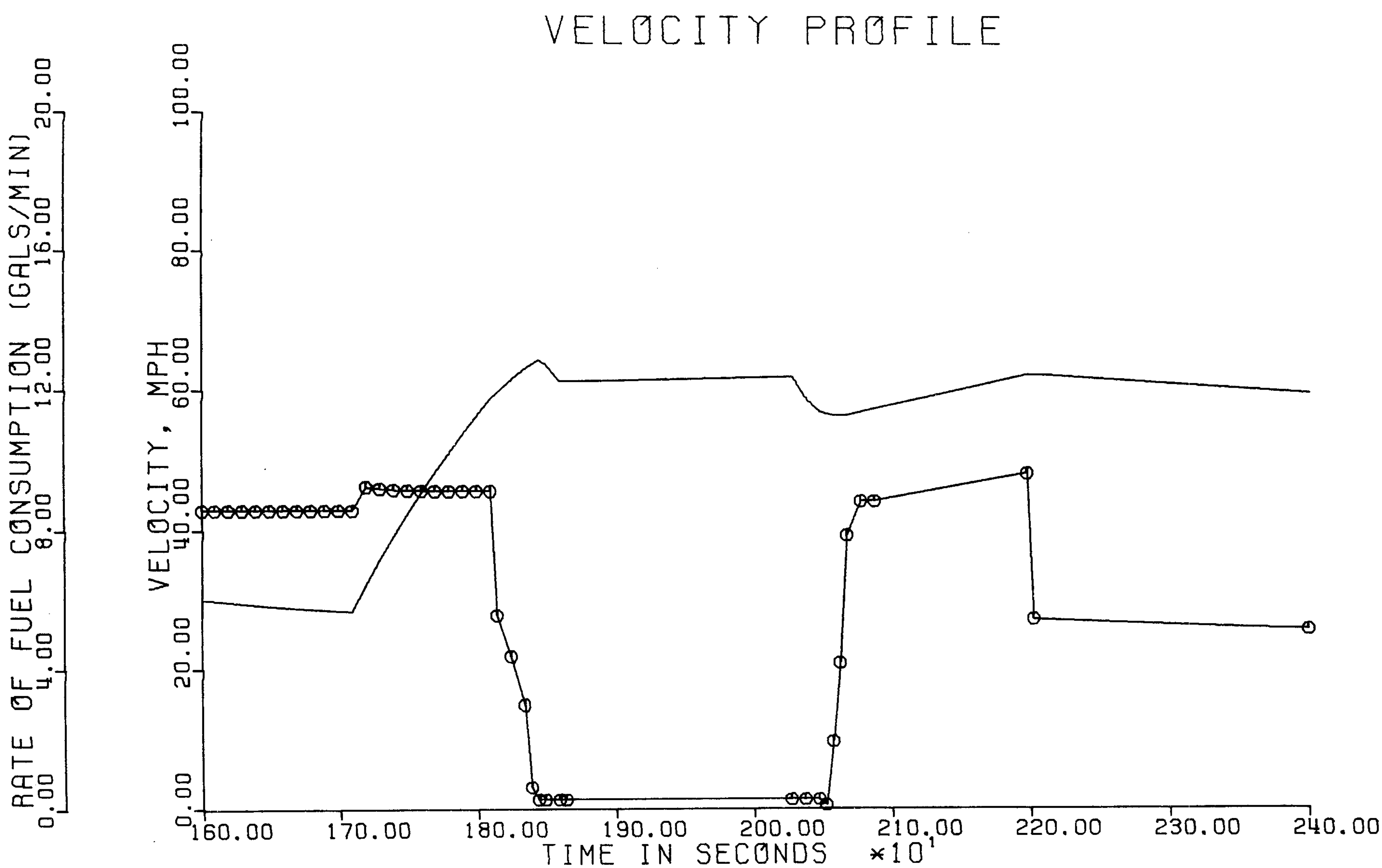

FIGURE 1
VELOCITY PROFILE AND RATE OF FUEL CONSUMPTION
(CONTINUED)

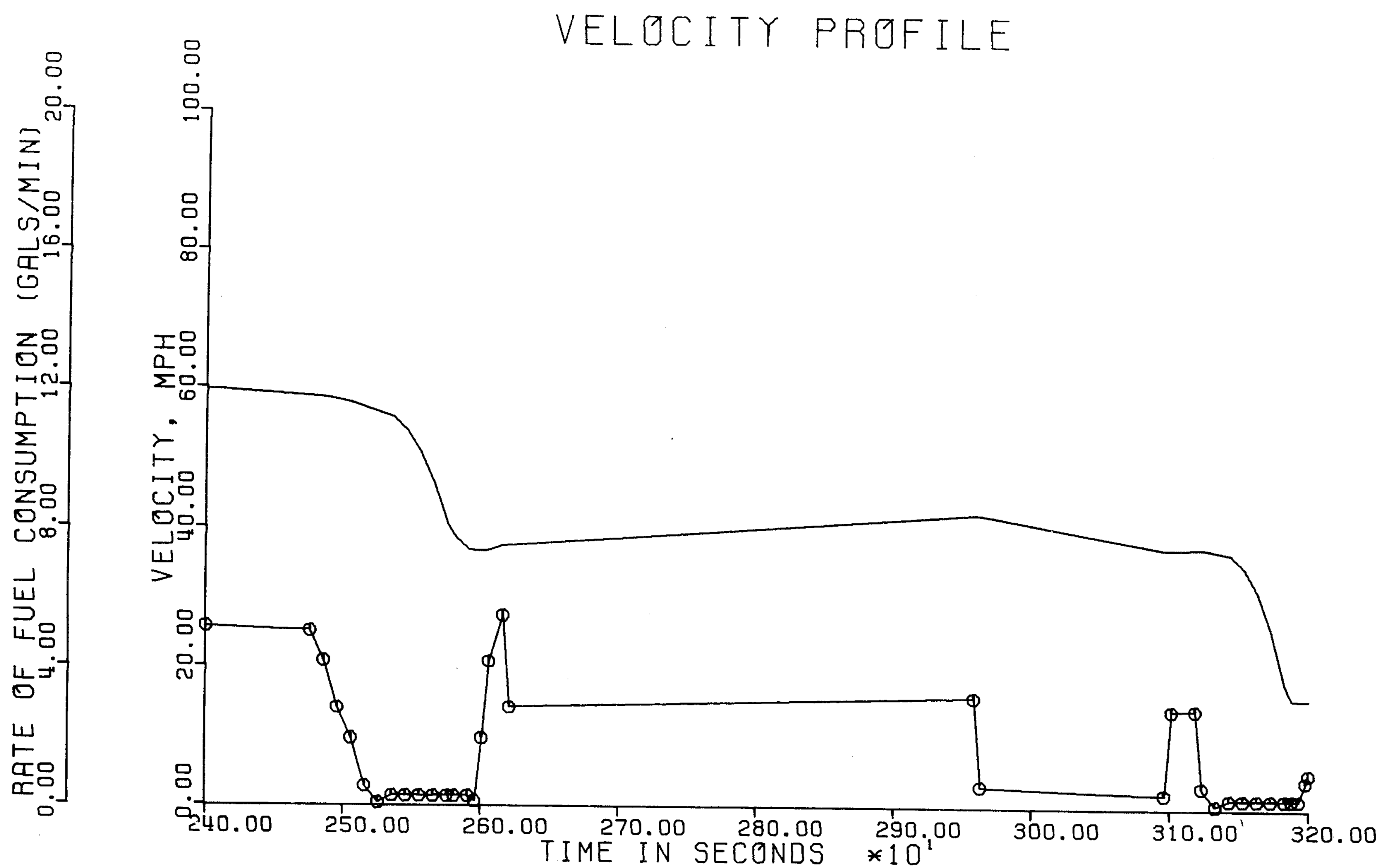

FIGURE 1
VELOCITY PROFILE AND RATE OF FUEL CONSUMPTION
(CONTINUED)

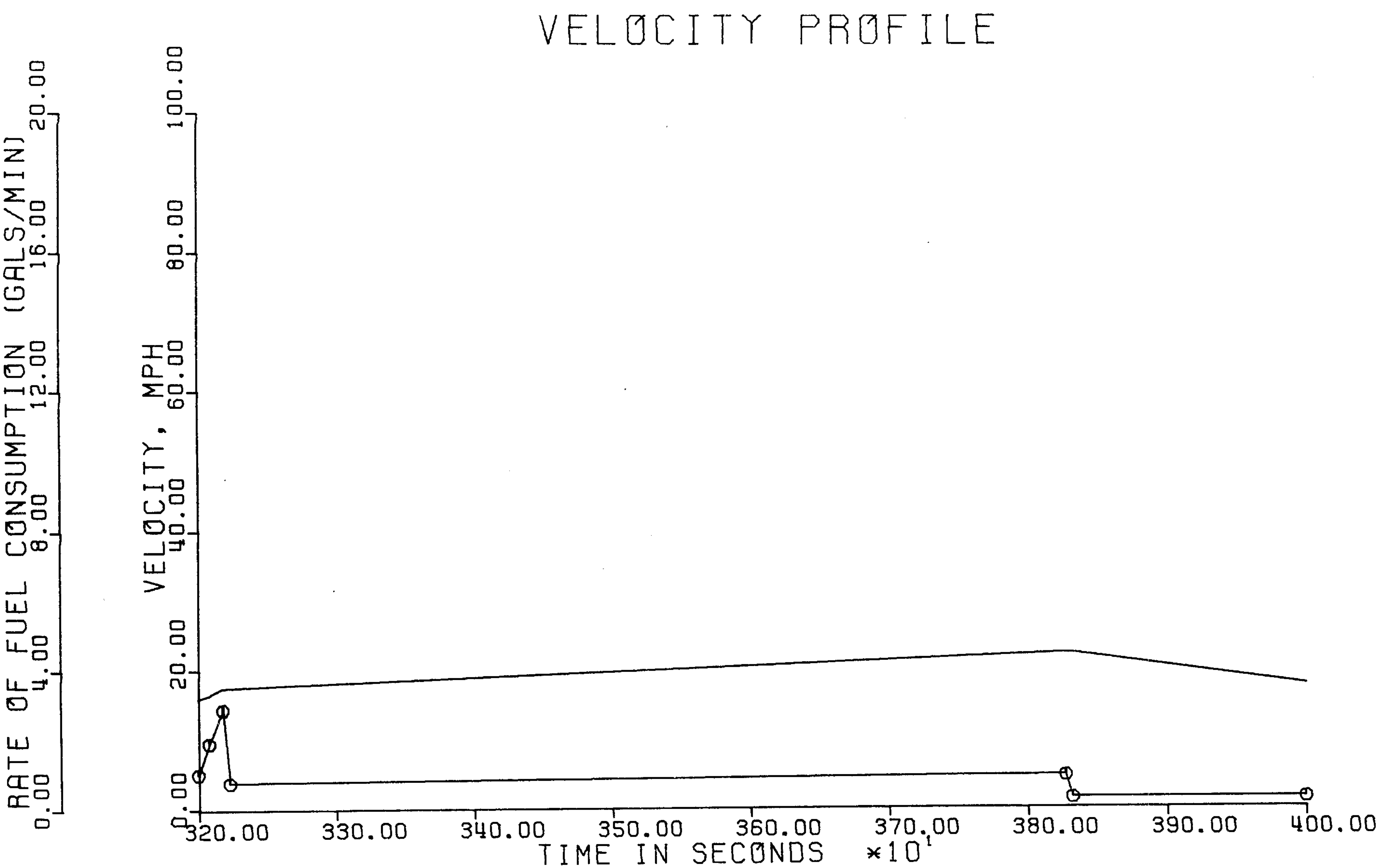

FIGURE 1
VELOCITY PROFILE AND RATE OF FUEL CONSUMPTION
(CONTINUED)

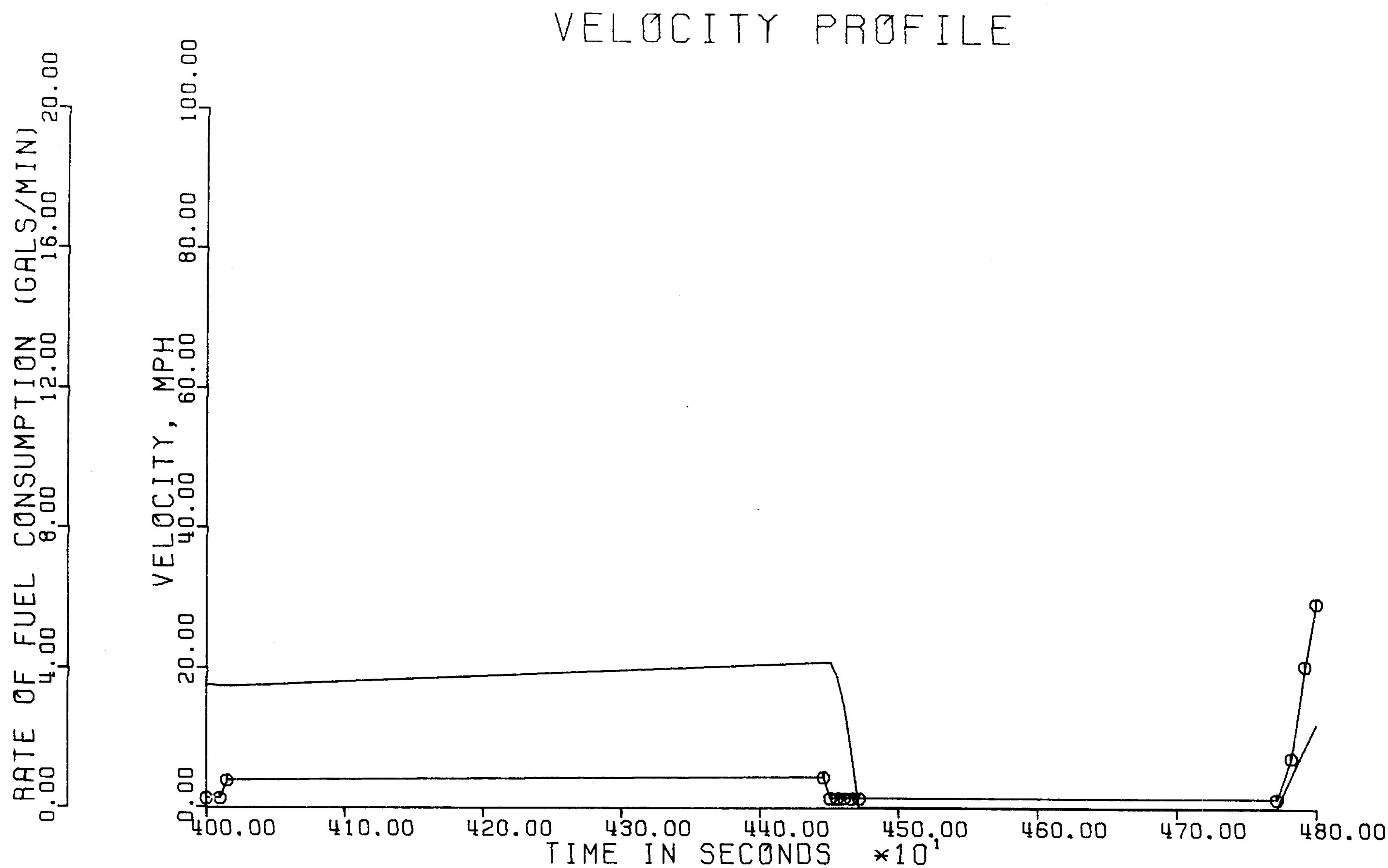

FIGURE 1
VELOCITY PROFILE AND RATE OF FUEL CONSUMPTION
(CONTINUED)

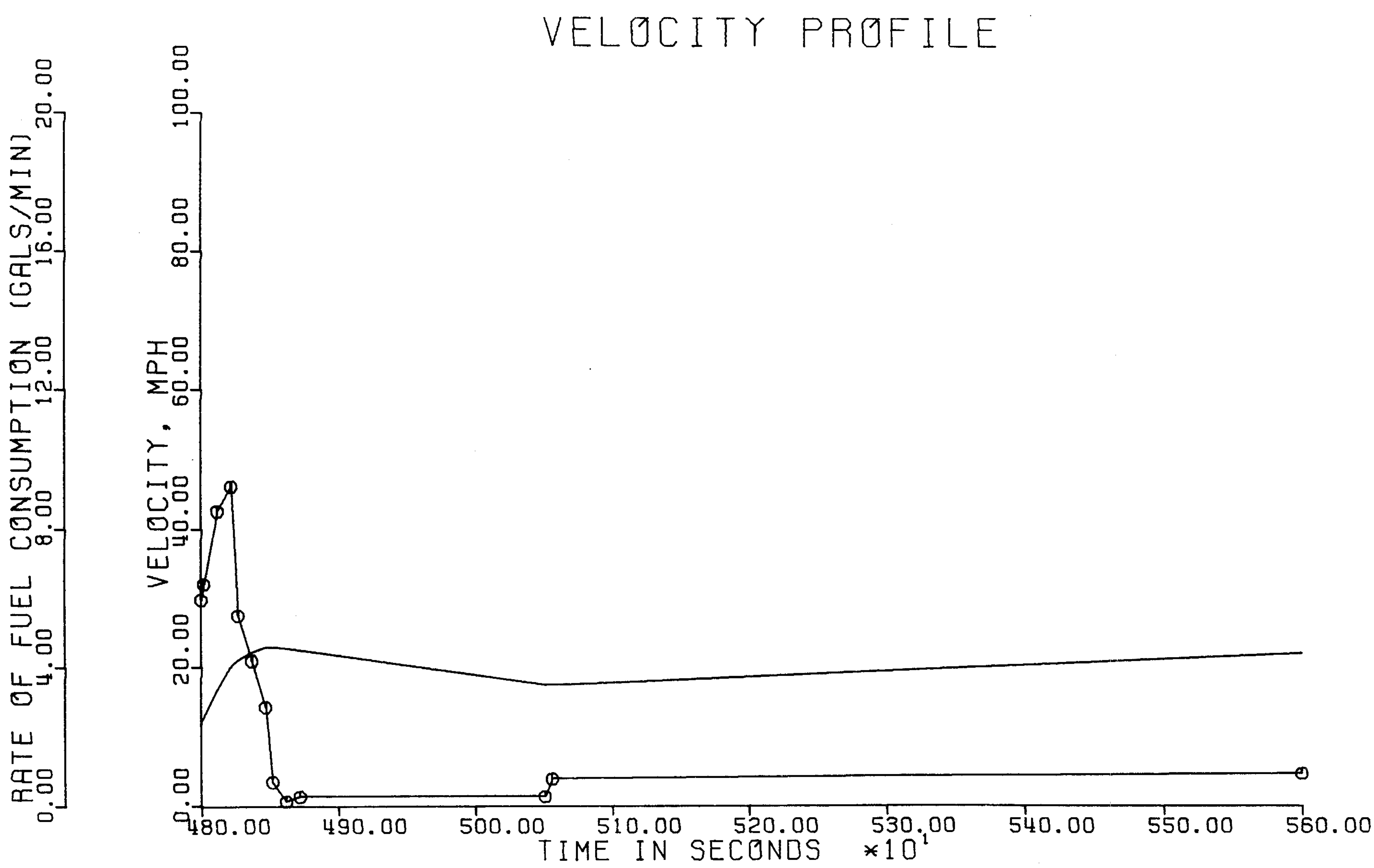

FIGURE 1
VELOCITY PROFILE AND RATE OF FUEL CONSUMPTION
(CONTINUED)

operated over tracks selected to be representative of different geographic conditions, as conclusions might be different for each of these operations because of the different nature of the terrain over which the simulated train is operated. Rather than simulation of such operations at all speeds, speeds likely to be typical of the particular operation were used. In the several cases where it was felt that an average train should be used to evaluate the fuel consumption, operation over an average track was simulated. The "average" track was compiled from statistics about Class A mainline U.S. track made available from the Federal Railroad Administration (FRA) which date from 1971-1975.*

Practical considerations constituted at least a portion of the reason for this approach. The matrix of possible runs of all trains in both directions, loaded and empty in some cases, over all three tracks at many different speeds was quite large, and considerations of both time and expense necessitated a reduction in the number of runs to be examined. A listing of the runs made is given in Section 5.0.

It became apparent quite early in the development of the program that the simulated method of handling the train would be significant in the determination of fuel consumption. The approach taken was then decided to be that method of handling the train as set forth

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*The definition of what constitutes Class A mainline track was not finalized until a report by the Secretary of Transportation was published in January, 1977. Briefly, Class A mainline track carries more than 20 million gross tons annually, or is needed to serve a market generating more than 75,000 carloads annually, or is essential to the strategic rail corridor network. Previous to this report, there was no generally accepted definition of either "mainline" or "branchline." While the data were of the approximate vintage 1971-75, the statistics were in accordance with the latest definition.

in Reference 4, namely that power is to be applied "gently and smoothly, one notch at a time." The algorithms introduced into the program therefore, with certain exceptions, reflect such a procedure as closely as possible. The general approach taken by the program is that the notch setting is adjusted one notch at a time in a direction so as to bring the velocity of the train to the desired velocity. In essence, the program simulates a Type I velocity control loop. The exceptions to this general approach are that under certain circumstances the notch setting will be adjusted two notches at a time, or will be adjusted one notch within a shorter time period. Such exceptions are not necessarily unreasonable, as it is realistic under certain circumstances to expect the engineer to act with more rapidity than at other times.

At this time the program remains flexible, in the sense that the operator may at his discretion alter certain of these parameters which determine in effect the modelling of the operation of the train. The sensitivity of the results of the program to the values of such parameters is discussed in a subsequent section. Recommended values to be used, however, are given.

3.0 PROGRAM CREDIBILITY

3.1 Constraints

It should be noted that the program is not a train performance simulator and was devised for the specific purpose of making an accurate determination of the fuel consumed by a freight train on a particular trip. For this reason, considerations which have entered into the formulation of the program may well be different from those related to such a simulator. Some general assumptions which have been made in the formulation of this program are therefore mentioned for comparative purposes.

(a) No fuel saving devices are used. All locomotives are operated so as to share power equally at any time. All locomotives consume fuel at the same rate which has been assumed to be .0644 gal./brake-HP-Hr., a figure recommended by Poole[5]. A provision is made for notch setting reduction to save fuel if the assumed adhesion limit of .23 is exceeded. Effectively, the notch setting is instantaneously reduced. Algebraic approximations to the tractive effort curves of a GM EMD-SD40 locomotive are incorporated into the program. See Figures 2 and 3. The curves themselves approximate constant power for a given notch setting for velocities above 10 mph. Changes in engine efficiency when operating at different notch settings are not directly modelled.

(b) Brakes are assumed to be instantly and uniformly applied throughout the train. No time of application or delays are considered. It is also assumed that the engineer may select eight discrete units of braking, somewhat analogous to the eight throttle notch settings. Dynamic braking is not presently considered.

(c) The train itself is considered to be a point mass. No train action is considered, and there is no slack being taken up at any time. The resistance of the train is uniform throughout its length, and the velocity of all cars is identical at any instant of time. Energy consumption attributable to the practice of stretching the train is not considered.

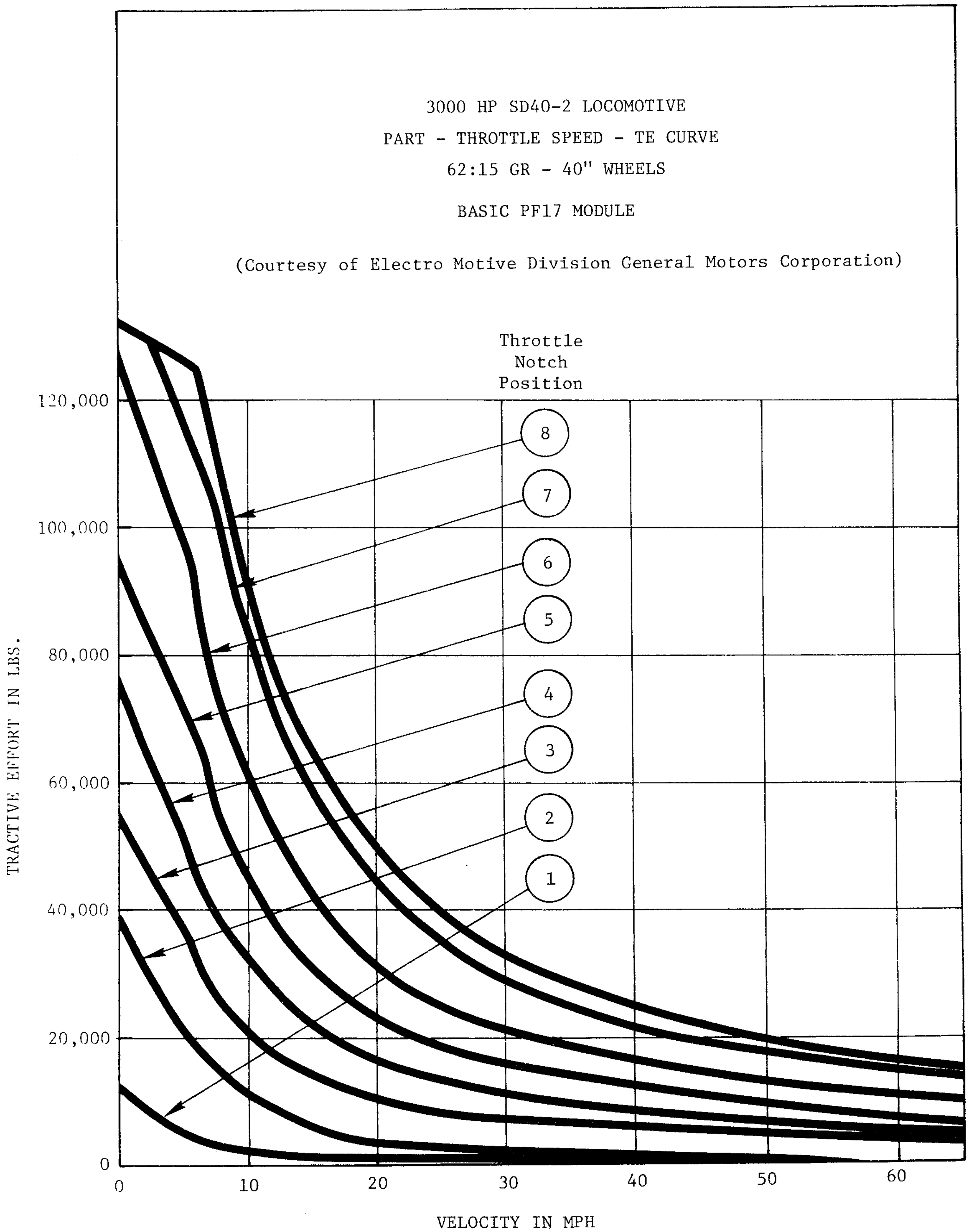

FIGURE 2
SD-40 LOCOMOTIVE TRACTIVE EFFORT CURVES

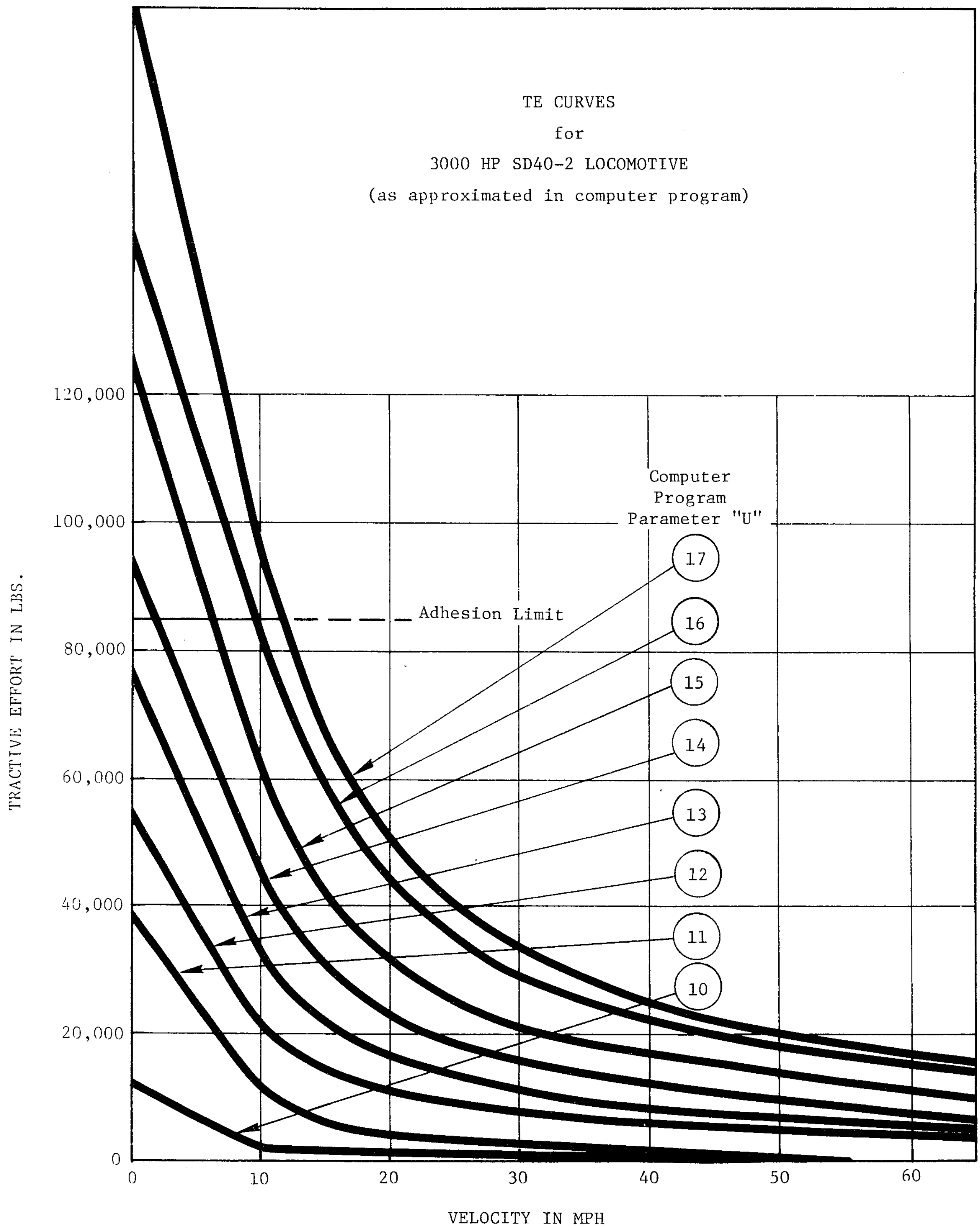

FIGURE 3
APPROXIMATIONS TO TRACTIVE EFFORT CURVES

(d) A perfect engineer has not been assumed. It has been assumed, however, that the engineer will operate the train in a realistic and rational fashion. The algorithms governing decision making on the part of the engineer presently do not expect him to anticipate changes in speed limits, grades, or curves. Notch settings, brake applications, and changes thereto are governed solely by observation of the velocity of the train and the difference between it and the desired speed.

(e) Train resistance is calculated in the early portions of the program according to the rationale developed in Reference 1. The program listed there was incorporated with appropriate but limited modifications directly into the program described herein for the calculation of fuel consumption. The reader is directed to that report for details of the train resistance calculation. The relationship of aerodynamic drag to front and rear gaps has been modified from the functional relationship assumed previously on the basis of new data from wind tunnel tests on wooden blocks simulating railroad vehicles. Smooth algebraic curves approximating the relatively sparse data were used in the program. The data points and the approximations used for the coupling factors are shown in Figures 4 and 5.

Certain other aspects of fuel consumption have been deliberately avoided, such as spillage during refueling, and movement in the yard which might be attributed to the trip. The trips selected for study and reported herein were on the order of 200 miles and included one five-minute stop, but there were no refueling stops considered.

3.2 Sensitivity

Despite the previously mentioned purpose of the program described herein, the program bears some resemblance to a simulation, and its results cannot be insensitive to the modelling technique. The decision-making process, by means of which the velocity profile for a trip is established, forms an influential part of the program. In addition, the choice of values for certain parameters internal

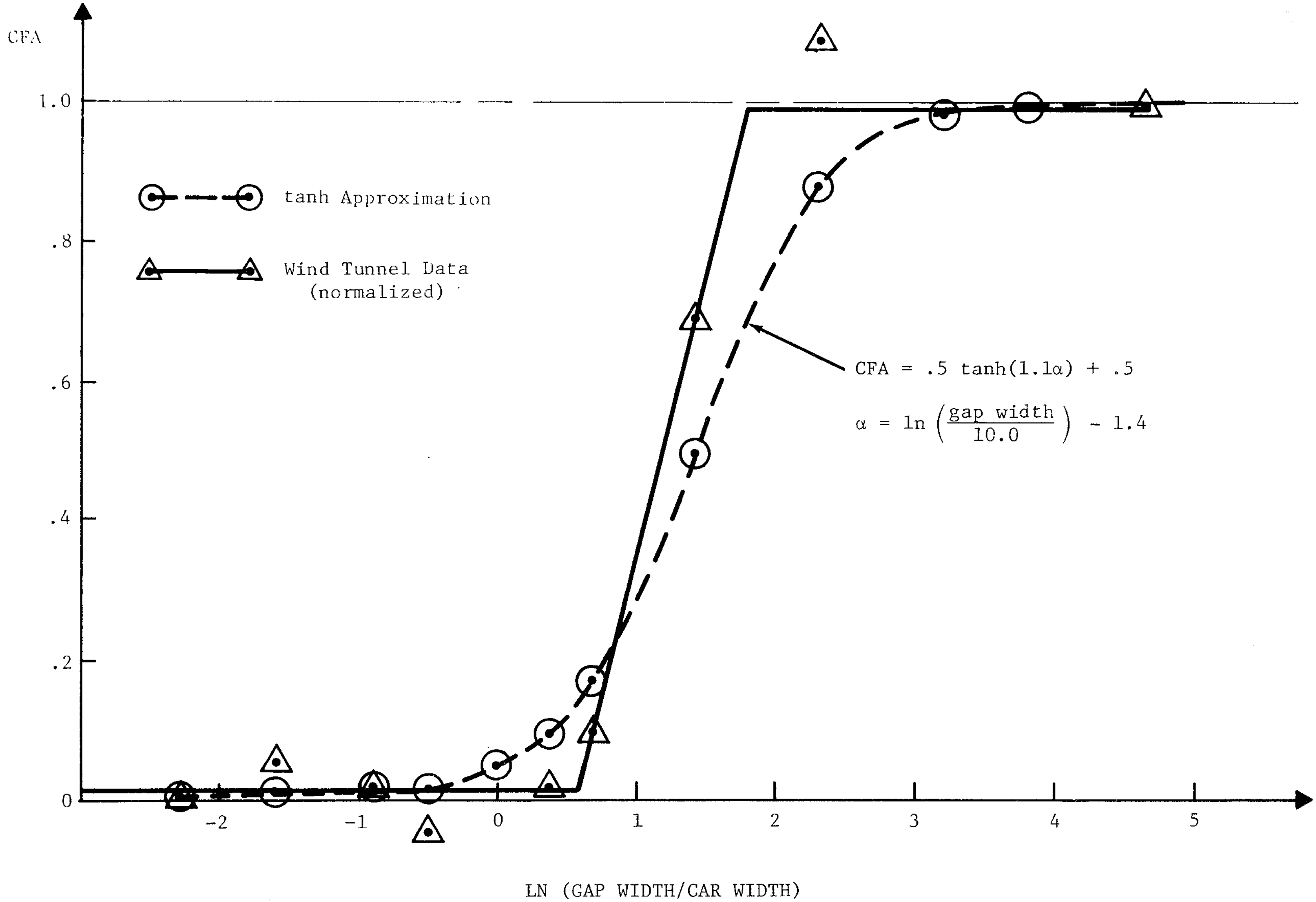

FIGURE 4
APPROXIMATION FOR REAR COUPLING FACTOR FROM WIND TUNNEL DATA

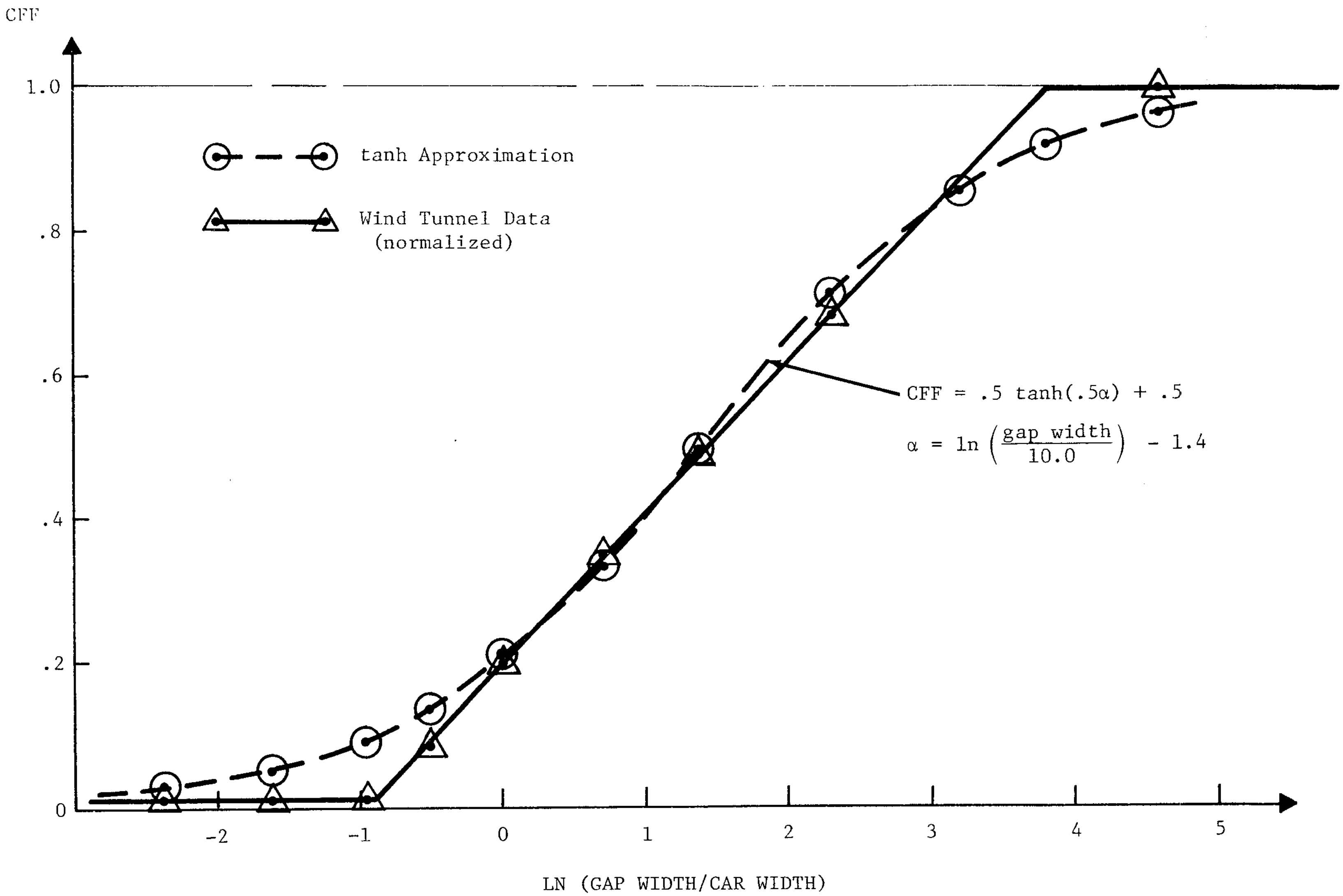

FIGURE 5
APPROXIMATION FOR FORWARD COUPLING FACTOR FROM WIND TUNNEL DATA

to the program exerts a direct effect upon the actual fuel consumption calculation. Finally, certain external factors such as the sequence of grades, curves, and speed limits, for example, over which the modeller has no control, will have an undeniable influence upon the velocity profile and consequently the final results of the program. It was necessary, therefore, to examine the sensitivity of the program results at least to those parameters over which the operator has some control.

The purpose of the program is more nearly to assess the differential impact of certain design modifications to the train or track upon fuel consumption than to determine accurately the absolute value of fuel consumption for a particular trip. Nevertheless, the program determines such impact by calculating the absolute value of fuel consumption and comparing the result with that obtained under normal conditions. It was therefore felt that the difference between these quantities would be credible only if the sensitivity of the absolute values of the results to the above considerations was small and if the absolute value of the result itself were credible, i.e., if the prediction of absolute fuel consumption under normal conditions corresponded closely with predictions from other simulations or with actual field measurements.

For these reasons the sensitivity of the absolute value of fuel consumption to changes in program parameter values was examined and the magnitude of the value checked against other sources. First a base case was established, mainly through trial and error but also partly by intuition and experience, then modified until train operation was satisfactory and the magnitude of fuel consumption properly calibrated. Subsequently, the sensitivities to changes in parameters, one at a time, from their values in the base case, were established.

It is believed that the magnitude of total fuel consumption for the base case is satisfactorily related to other predictions and measurements and that the sensitivity of the results to changes in the program is satisfactorily small. If the latter is true, it is believed that the sensitivity of differences in fuel consumption from one condition of operation to the next to those changes in the program will also be small.

These considerations are discussed in more detail below. In order to avoid any unforeseen influence of track conditions, all sensitivity runs were made by running the average train over a 100 mile course of level, tangent track, with a constant speed limit (60 mph) and no stops en route.

3.2.1 Parameters Within The Decision Making Process

Certain parameters determine in effect how the simulated engineer would operate the train. Decisions are based upon the value of these parameters. As noted earlier, control of the train in this program simulated a Type I velocity control loop. Based upon the preceding velocity and acceleration, a choice is made for the throttle notch setting for the next calculation. The five significant parameters are discussed individually below. The ultimate value selected for each parameter for the base case reflects the manner in which it was felt a reasonable engineer would perform. It was assumed that a "reasonable" engineer would follow the dictates of good train operation laid down in Reference 4, pages 144-166, in general operating the train smoothly and avoiding sudden large changes in throttle setting.

(a) Notch change (NC): The program incorporates an algorithm so that in certain instances the notch is adjusted by more than one position in response to errors in velocity (differences between the observed velocity and the speed limit). The amount of the change is the value selected for NC, an input to the program. A value of 2 appeared after some experimentation to lead to smoothest operation with a satisfactory response time and was selected for the base case. A value of 1 led to less stability, while a value of 3 produced no more smoothness and seemed to violate the requirements of a "reasonable" engineer.

(b) Time Interval (DT): The equations of motion being non-linear, they must be solved by iteration. The time interval is the time in seconds between calculations of velocity and other parameters. Ideally, the time interval should be made as small as possible, so that the integration of the equations of motion is accurately made. On the other hand, the notch operation logic of the simulated engineer depends upon the time interval also. A compromise must be struck also between the number of calculations to be made and the degree of accuracy needed. It was felt that a reasonable engineer might only adjust his throttle position (one notch at a time) every ten seconds (occasionally five seconds); this value also appeared to result in a reasonable response to changes in grade, curvature, or speed limit. Hence, the value of 10 seconds is used for the base case.

(c) Acceleration Window (AW): The program logic requires that if the change of a single notch will not bring the train velocity within the tolerance band within the number of seconds selected for this parameter, the throttle will be changed by more than one notch. A ten-second interval seemed to result in smooth operation with satisfactory rapidity in returning the velocity to an in-band condition and was used for the base case.

(d) Velocity Tolerance Band (TOL): Clearly if the velocity of the train is near enough to the desired speed, no change in throttle setting would be required. A decision must be made on the width of the acceptable velocity band. Although in early experimental runs $\pm$ 1.5 mph was used, it was later felt that this was too severe a restriction, and the band was opened to $\pm$ 2.5 mph for the base case.

(e) In-Band Multiplication Factor (MF): In the interest of reducing the number of calculations the program makes, and concomitantly the number of throttle notch changes the engineer makes, this factor helps determine whether or not the same acceleration will be maintained over the next time interval. If the decision is favorable, the time interval is extended from the 10 second base value to the time the velocity takes to break out from the acceptable band or the time the train takes to move to the next track record. The multiplication factor was introduced as an input to the program while it was being developed as an aid in selecting an appropriate value for use in this logic decision. The program appears to be more sensitive to the choice of this parameter than others. Since the logic decision is based upon a factor (TOL/(MF·DT)), a change in the multiplication factor MF can be nullified by appropriate changes in the time interval DT or the velocity tolerance band TOL. Excessively high values tended to affect train operation by preventing the train velocity from drifting from upper to lower edge of the tolerance band, instead remaining close to one, resulting in a quite different average velocity for the trip. It is possible that one engineer may actually operate the train in such a fashion, as opposed to another engineer; however, it was felt that a slow drift of the velocity from one edge of the tolerance band to the other was more realistic. A value of 5 for this multiplication factor was selected for the base case.

With five significant parameters, there could be many combinations to investigate if more than one parameter were varied at one time. Hence, to limit the sensitivity investigation to reasonable bounds, only one parameter was changed at a time, except in the last two runs in which two were changed. Each of the five parameters was varied only once above and once below the value for the standard case. The results of the investigation are shown in Table I. In the last two cases, DT was modified in the opposite sense to MF, so that the decision making process described in (e) above remained constant, although certain other algorithms were modified.

TABLE I

RESULTS OF SENSITIVITY RUNS

RUN NO.	DT (sec)	TOL (mph)	NC –	AW (sec)	MF –	TOTAL FUEL CONSUMPTION (gal)	AVERAGE VELOCITY (mph)
1 (std)	10	2.5	2	10	5	595.6	50.1
2	5					597.3	50.7
3	20					572.5	49.0
4		1.5				593.0	50.1
5		5.0				593.7	51.8
6			1			589.3	50.2
7			3			592.8	50.0
8				5		594.0	50.1
9				20		593.1	50.1
10					2	596.9	50.6
11					10	576.2	49.2
12	5				10	597.8	50.1
13	20				2.5	595.2	50.3

Note: Blank spaces indicate use of standard values for parameters

With the exception of the two cases where the fuel consumption dropped to below 580 gallons, the average deviation from the value of 595.6 gallons for the standard run was only 1.3 gallons, or .2%. The two exceptional cases were those where either MF or DT was doubled, and both show a slightly lower average velocity for the trip, attributable to the slightly different decision-making process discussed above. Lower average velocities will of course mean lower fuel consumption. When the MF and DT are modified simultaneously no such comparatively large change in fuel consumption (3.6%) occurs.

The overall sensitivity to the choice of parameters seems acceptably small. Deviations from an expected value of fuel consumption should therefore not be judged to be attributable to a wrong or unfortunate choice of decision-making parameters.

3.2.2 Other Parameters Within Program

The calibration of the program input is directly related to the figure used in the program for the conversion of fuel into available energy, .0644 gallons per delivered brake-HP-hr. The figure was obtained from Poole[5] and is deemed representative of an average efficiency of conversion of fuel to energy by Diesel locomotives. Changes in this figure, except for fuel consumed during idling, which is charged at a rate of 5.5 gal./hr.,[6] will be proportionately reflected in changes in the predicted fuel consumption.

The program presently utilizes the density of air at standard conditions of pressure and temperature. Aerodynamic drag is directly related to this parameter and will be reduced in train operation in high-altitude mountainous regions. However, the reduction will not be proportionate, as aerodynamic drag is only a portion of total drag. Over the same track at the same speed, a 20% reduction in air density was found to reduce fuel consumption by 12.6%.

The figure used for adhesion would under normal circumstances affect the velocity profile and consequently the fuel consumption. However, the program reflects the installation of anti-wheelslip devices which automatically reduce the notch setting when the adhesion limit is exceeded. For the average train used previously, even over terrain with a 2% grade, adhesion limit effects were miniscule.

3.3 Calibration

In order to ensure the accuracy of the fuel consumption prediction before making the final runs, some calibration runs were made so that the predictions could be measured against actual measured fuel consumption and in one case against the predictions of another train performance calculator (TPC). Results from the TPC were taken from Reference 7. The track used in arriving at the MITRE results was only a partial simulation of the actual track, as speed limit information was not available. Results from actual field measurements were taken from Reference 8. Tracks used in arriving at the MITRE results had to be tracks for which complete track data was available and over which measurements had been taken. Also, the length of the run had to be compatible with the present requirements of the program.

The results of the calibration runs are shown in Table II. Fuel consumption for the average train was first computed using the modified Davis formula for train resistance. Next, the MITRE program was run simulating an operation over level tangent track. A comparison was then made with the results from the TPC of a major railroad by simulating a run over a partial simulation of the eastern track, as explained in the preceeding paragraph. Two different runs were then selected for comparison with actual field data, and a simulation of operation of a replica of the actual train over the actual track was made for each of those tracks.

TABLE II

SUMMARY OF CALIBRATION RUNS

#	TYPE	TRACK	TRAIN	HP / GTT	MILES (3)	AVERAGE SPEED	GALLONS / 1000GTTM
1	Modified Davis, from calculations	Level Tangent	Average (1)	N.A.	100	39.0	.73
2	MITRE Program	Level Tangent	Average	2.1	100	38.8	.93
3	Major RR TPC (10)	Eastern	As Reported	2.3	145.6	Max SL. 60 mph average not reported	1.95 (5)
	MITRE Program	Partly simulating same	(2)	2.7	145	44.8	2.01
4	Measured Fuel (11) Consumption	(6) ICG Hammond - McComb	As Reported	4.9	52	28.4 (9)	(8) 3.32
	MITRE Program		(2)	5.6	52.3 (4)	34.7	2.75
5	Measured (11) Fuel Consumption	ICG (7) Memphis - Jackson	As Reported	1.5	198	17.8 (9)	1.68
	MITRE Program		(2)	1.4	215.38 (4)	36.1	1.27

NOTE:

1. See Section 4.1 for discussion of Average Train.
2. Replica of reported train and HP/ton, as closely as information and program would permit.
3. Note minor discrepancies in mileages.
4. From track charts.
5. Apparently GTM, not GTTM.
6. Mostly uphill.
7. Mostly downhill.
8. Highest of ICG non-TOFC runs. Range of 1.1 to 3.3 reported. ICG figures are substantially higher than the UP figures of 1.0 to 2.3. The discrepancy could be attributable to many unknown factors.
9. It is noted in Reference 8 that the average speed is presumably substantially lower than typical running speeds.
10. Reference 7.
11. Reference 8.

The program results are deemed to be in sufficient correspondence with the results from the field tests and the other simulation that the program can be presumed to be as satisfactorily correlated as possible at the present time and for the purpose of this study. The largest deviations of the MITRE figures from the reported figures were indeed the result of the runs which simulated operation over the two actual tracks, but since it was not always possible during the actual runs to record time associated with various stops and delays nor were weigh-in-motion scales available, a somewhat larger deviation from the figures reported from the field[8] is understandable.

4.0 TRAIN AND TRACK SELECTION CONSIDERATIONS

The previous examination of train resistance was reported in Volume I.[1] At that time changes in the resistance of a freight train attributable to certain factors were calculated as a function of velocity. Certain benefits were then derived based upon operation at a certain velocity.

In this investigation the savings in fuel attributable to those same factors when the train is operated over a given track are calculated for operation up to a certain maximum velocity. This change in approach necessitated changes in the process of selection of runs to be made for reporting herein. The matrix of candidate runs was too large to permit every case to be examined even at only three different velocities. In general, it was desired to simulate operation of the test train over a track representative of operation in mountainous regions, with many grades and curves; a track representative of operation over the western plains, mostly straight and level; and a track representative of all U.S. railroads in a statistical sense. Unfortunately, the operation of a unit coal train leaving full and returning empty requires four runs alone for a single track at a single operational speed because of the difference in altitude between end points. Such considerations demanded careful formulation of criteria for selection of runs to be made so that an appropriate compromise was reached between quantity of runs and meaningfulness of results.

In view of the current interest in light weight equipment, considerable emphasis was placed upon fuel consumption with respect to such equipment. Although as a follow-on to the previous report the light weight hopper car section was devoted to an analysis of the use of aluminum hopper cars, much of the material and many of the conclusions are equally applicable to light weight steel hopper cars or gondolas, several of which have recently been nationally advertised in railway trade journals.

4.1 Train Selection

Results from a few preliminary runs indicated that the initial concept of operating the same train for comparative purposes over tracks through widely different terrain was faulty. The train was overpowered on the mostly straight and level western track and ran continually in the lower notch positions; the same train operated over the eastern track failed to ascend the first steep grade, as the absolute limit on drawbar pull had been set by the program to be 250,000 pounds according to the recommendation in Reference 4.

Hence, it was decided for test purposes to select trains which would be typical for the particular operation, and the number of locomotives would be determined on the basis of appropriateness for that operation. The average length train was used as a starting point (68 cars, see Reference 9). The gross trailing tonnage was calculated and the number of locomotives was assigned with the use of the average or typical HP/GTT figure for that type of operation reported in Reference 8. A minimum of three locomotives was always used, and the same number of locomotives was used for the return trip, even though weight considerations might have led to dropping some of them. Considerations of maximum allowable drawbar pull (see previous reference above) led to a limitation on the length of the unit coal train.

These policies are somewhat arbitrary and may have colored the results of the runs in the sense that had locomotives been assigned on a different basis, the change in fuel consumption may have been more dramatic, or less so, when equipment changes or design modifications were introduced. But locomotive assignment policies differ widely from railroad to railroad, and the introduction of still another variable to the matrix of runs to be made was not possible; it is hoped that the choices made were reasonable enough that the results will relate meaningfully to operations of a similar type.

The train files used in making the runs for the report are given in Appendix C.

4.2 Track Selection

It had been decided early in the task to select an eastern track and a western track in addition to the contemplated statistically representative track over which to simulate runs. It was intended that the western track be representative of track over which trains operated at comparatively high speed, relatively unimpeded by grades or curves. In contrast, the eastern track was to typify operation in mountainous areas, where grades and curves predominate, and typical operating speeds are lower. The statistically representative track would be used to simulate operations in the entire United States, where the design improvement or equipment modification might logically be expected to be introduced or performed throughout the country on railroads in general, rather than being confined to a single railroad or type of operation.

Some practical considerations governed the selection of the eastern and western track. Track data had to be readily available, and sections of a length compatible with the program and other tracks selected had to be available. It was decided that a run of about two hundred miles with one predetermined stop in the middle would be used. As a result, a track between two midwestern cities, a portion of a route to the West Coast, was selected as the western track. As a contrast, a track between two cities through the Appalachian Mountains was selected as the eastern track. The western track conforms well with the assumption of limited grade and curvature; maximum combination of grade and curvature (in percent grade equivalent) is only .59 percent and the track has only

.67 track records per mile, some indication of the relative paucity of changes in track character. Despite being laid over the western plains, however, the track rises between end points 543 feet, more than the change in altitude between end points on the eastern track. The difference nevertheless is that the grade is almost consistently in one sense in the western route, while it changes continually in the eastern route. The eastern route is substantially more difficult to negotiate, having a maximum grade equivalent of 1.5 percent, and has .90 track records per mile, with continually changing grades and curves.

The statistically representative track was created artifically from statistics about U.S. Class A mainline track (1971-75) on file at the Federal Railroad Administration and made available in statistical form to MITRE for this purpose. The creation of a track truly mathematically defensible from a statistical viewpoint appeared unjustifiably difficult and was not attempted, in the absence, for instance, of correlation data between grades and curves or the distribution of track record lengths. However, an effort was made to make the track created have properties which would be representative of the average of such U.S. track.

Track record lengths were first assigned on the basis of a mean value of 1.3 miles, to which a variation of between -.5 and +.5 miles with a uniform distribution was added by means of a random number table[10]. A figure representing hundredths of miles was added afterward from the same table in a random fashion. Grades, curves, and speed limits were then independently assigned to these track records by means of the same table. Signs of grades were made + or - on the basis of whether the final digit in the track record was odd or even. The complete track file for the statistically generated track as used in the report is shown in Figure 6. The file is formatted in accordance with present requirements of the program. The first column lists the milepost number; the second column the milepost; the third, fourth, and fifth columns the grade, grade equivalent of curvature, and the speed limit for the following track section. Summary information on all tracks used in making the runs is given in Table III. Complete track files for Tracks 21 and 32 in the same format are given in Appendix C.

Certain general considerations with regard to these tracks belong in this report. The track data on file date from the early seventies and may no longer be completely accurate. Certainly temporary speed limit restrictions have probably been removed and replaced by others. There appear to be minor discrepancies with regard to differences in altitudes between end points between the track record data and information from a commercial atlas [11], probably attributable to different end points. Nevertheless, it is felt that these considerations should not invalidate any conclusions drawn from making the runs.

Certain liberties were also taken with the raw track record information in order to make it compatible with the needs of the program. Mileposts need to be consecutive for use with this program and it was found that on a long run this is not necessarily the case. It is also necessary that the first milepost information be altered for compatibility purposes. In addition, track records as they often appear needed to be modified slightly so that the zero length records not appear, in order to avoid digital problems. Track records of zero length appearing in the track records used in formulating the data given in this report were therefore uniformly adjusted to be 0.1 miles, thus avoiding having two different speed limits for the same milepost. Occasional redundancies were purged, if observed, in order

FILE: TRACK13 DATA A

101	0.00	.38	.02	10.0
102	1.24	.63	.02	20.0
103	2.86	.38	.02	40.0
104	4.48	.38	.02	45.0
105	5.32	.88	.02	45.0
106	6.62	.12	.06	55.0
107	7.52	.12	.18	55.0
108	8.51	-.12	.02	65.0
109	10.17	-.88	.02	79.0
110	11.78	.12	.02	55.0
111	13.25	-.12	.02	65.0
112	14.70	.12	.02	65.0
113	15.96	.12	.02	65.0
114	16.96	.63	.10	55.0
115	18.54	.12	.02	65.0
116	19.95	-.12	.02	55.0
117	21.16	.38	.06	35.0
118	22.20	.12	.02	65.0
119	23.58	.38	.02	55.0
120	24.58	.12	.02	45.0
121	25.94	.12	.02	45.0
122	26.93	-.12	.02	55.0
123	28.13	-.12	.02	35.0
124	29.84	.12	.02	45.0
125	31.24	.12	.02	55.0
126	32.83	-.63	.02	45.0
127	34.49	-.12	.02	55.0
128	35.31	-.12	.06	65.0
129	36.41	-.38	.02	65.0
130	37.89	-.38	.02	65.0
131	39.15	-.38	.02	55.0
132	40.85	-.12	.02	65.0
133	41.92	.12	.02	65.0
134	43.11	-.12	.02	65.0
135	44.59	-.63	.02	65.0
136	45.93	-.12	.10	45.0
137	47.19	-.38	.02	65.0
138	48.64	.12	.06	55.0
139	50.07	-.12	.02	35.0
140	51.29	-.12	.02	55.0
141	52.73	-.38	.02	55.0
142	53.90	.38	.02	65.0
143	55.39	-.38	.02	45.0
144	56.93	-.12	.02	65.0
145	58.55	-.12	.02	55.0
146	60.25	-.12	.02	65.0
147	61.90	.63	.02	55.0
148	63.44	.12	.02	55.0
149	64.23	-.12	.06	65.0
150	65.00	.12	.02	45.0
151	66.58	.12	.22	65.0
152	67.57	-.38	.02	45.0
153	68.85	-.88	.02	65.0
154	70.16	.12	.02	55.0
155	71.73	-.38	.02	65.0

FIGURE 6
STATISTICAL TRACK DATA (TRACK 13)

FILE: TRACK13 DATA A

156	73.47	-.12	.02	65.0
157	74.93	-.63	.02	55.0
158	76.25	-.63	.02	35.0
159	77.14	.12	.02	65.0
160	78.06	.38	.06	55.0
161	79.27	-.12	.02	65.0
162	80.99	-.63	.02	65.0
163	81.94	.12	.02	65.0
164	83.23	-.12	.02	65.0
165	84.70	.38	.10	79.0
166	85.95	-.12	.02	55.0
167	86.79	-.38	.02	45.0
168	87.92	.12	.02	45.0
169	89.16	.38	.02	55.0
170	90.01	-.12	.02	55.0
171	90.85	-.63	.06	65.0
172	92.28	.12	.06	65.0
173	93.70	.12	.02	65.0
174	94.72	.38	.02	65.0
175	95.89	-.38	.02	65.0
176	97.16	.88	.02	25.0
177	97.95	-.12	.02	45.0
178	99.50	.88	.02	55.0
179	101.11	-.88	.02	55.0
180	102.88	.63	.02	35.0
181	103.91	-.12	.02	55.0
182	105.65	-.12	.02	55.0
183	107.07	-.12	.06	45.0
184	108.41	-.63	.02	45.0
185	110.12	.38	.02	40.0
186	111.52	.12	.10	20.0
187	123.23	-.38	.02	10.0
188	124.40	.38	.02	0.0
189	124.50	.12	.02	10.0
190	126.02	.12	.02	20.0
191	126.92	.12	.02	40.0
192	127.84	.12	.02	55.0
193	128.96	.12	.02	55.0
194	129.91	-.63	.06	79.0
195	131.35	-.38	.02	55.0
196	132.61	-2.00	.02	45.0
197	134.27	-.38	.02	55.0
198	135.01	-1.50	.02	65.0
199	136.31	-.88	.02	65.0
200	137.49	-.38	.26	55.0
201	139.17	-.63	.02	35.0
202	140.10	.12	.02	45.0
203	141.22	.38	.02	55.0
204	142.42	.88	.02	65.0
205	143.95	-.63	.06	65.0
206	145.40	.12	.02	65.0
207	146.87	-.12	.02	45.0
208	148.41	-.38	.02	55.0
209	150.11	-.63	.02	65.0
210	151.74	.12	.02	65.0

FIGURE 6
STATISTICAL TRACK DATA (TRACK 13)
(CONTINUED)

FILE: TRACK13 DATA A

211	153.28	.12	.02	55.0
212	154.31	-.12	.02	65.0
213	155.99	-.12	.02	65.0
214	156.84	.63	.02	55.0
215	158.10	.12	.02	65.0
216	159.59	-.12	.02	65.0
217	161.16	.12	.02	55.0
218	162.52	.12	.06	55.0
219	163.33	-.38	.02	45.0
220	164.85	-.12	.02	35.0
221	166.04	.38	.02	65.0
222	167.21	-.88	.02	55.0
223	168.55	-.12	.02	45.0
224	169.98	.12	.02	55.0
225	171.32	.63	.02	65.0
226	172.88	.12	.02	65.0
227	173.96	.12	.10	45.0
228	175.44	.38	.02	65.0
229	176.34	.88	.06	79.0
230	177.64	.12	.02	65.0
231	178.84	.38	.02	55.0
232	180.10	.63	.02	65.0
233	181.82	.12	.02	45.0
234	182.84	.12	.02	65.0
235	184.31	-.12	.02	65.0
236	185.75	-.12	.02	25.0
237	187.46	.38	.14	65.0
238	189.13	-.63	.02	65.0
239	190.22	.38	.02	55.0
240	191.08	.12	.06	55.0
241	191.80	.88	.02	35.0
242	193.11	-.38	.02	65.0
243	194.19	-.38	.02	65.0
244	195.34	.88	.02	65.0
245	196.92	.63	.02	45.0
246	197.83	-.12	.02	45.0
247	198.75	-.12	.02	40.0
248	199.63	-.12	.02	20.0
249	200.66	.12	.06	10.0
250	202.18	.12	.02	0.0

FIGURE 6
STATISTICAL TRACK DATA (TRACK 13)
(CONTINUED)

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TABLE III

SUMMARY INFORMATION ON TRACKS USED IN RUNS

TRACK NO.	ORIGIN-DESTINATION *	DISTANCE (MILES)	RISE BETWEEN END POINTS (FEET)	NO. OF TRACK RECORDS	MAXIMUM GRADE + CURVE COMBINATION (%)
21	W1 - W2	220.81	542.73	147	.59
26	W2 - W1	220.81	-542.74	147	.56
32	E1 - E2	254.43	411.52	229	1.33
37	E2 - E1	254.43	-411.55	229	1.50
13	S1 - S2	202.18	-315.93	150	.94
14	S2 - S1	202.18	315.93	150	2.02

* W1 and W2 designate the terminal points of the western track; E1 and E2 the terminal points of the eastern track; and S1 and S2 the terminal points of the statistical track.

to reduce the number of track records in the files. Some illustrative examples of modifications to the track records appear in Appendix A.

Speed limit information was available only as a separate file and was manually interspersed among the track data for use with the program. Speed limits near the end points or the stopping point in the middle were adjusted arbitrarily in the following fashion to ensure relatively smooth departure and arrival: speed limits of 10, 20, and 40 mph were imposed for the first three track lengths on either side of a stopping, starting, or end point, unless existing limits were lower. Occasionally this required the introduction of additional mileposts.

The consequences of these minor changes in the track record should be far below the level of uncertainty in the absolute figure for fuel consumption.

5.0 RESULTS

A numerical summary of the results from all runs made is given in Table IV. The runs for each type of equipment modification are discussed in the following paragraphs.

5.1 Light Weight Hopper Cars

The first eight runs compare the use of 67 standard weight hopper cars (29.8 tons) in a unit coal train operation with 63 aluminum hopper cars (23.5 tons) in the same operation, hauling a full load of coal in one direction at a maximum speed of 25 mph and returning empty to the point of origin at a maximum speed of 45 mph. The shorter aluminum car train carries approximately the same net tonnage per trip (6804 tons vs. 6814 tons). The runs were made on the western track, first starting full at W1 and returning empty from W2, then starting full at W2 and returning empty from W1. This was done because there is a 543-foot difference in elevation between end points and also because it is possible the sequence of grades and curves has some significance.

The rewards for using the lighter weight cars over this particular terrain are modest. The reduction in fuel usage (see Table IV) was from 4175 gallons to 3918 gallons in the two-direction operation, a reduction of 6.1 percent. If the train operates approximately 100,000 miles per year, making 113 round trips, 29,041 gallons per year would be saved, and at $ .35 per gallon[9] a net annual saving of $10,164 would result, or approximately $161 per car. This is 66% larger than the $97 per car reported in Reference 1 for a similar but not identical operation over level tangent track.

While it is beyond the scope of this report to perform a detailed economic analysis on the effects of such savings on investment decisions, nevertheless a few figures are of interest. The total investment required for the standard weight cars is 67 times the estimated

TABLE IV
SUMMARY OF FUEL CONSUMPTION RUNS

RUN NO.	TRACK NO.	ORIGIN-DESTINATION	RISE BETWEEN END POINTS (FEET)	DISTANCE (MILES)	NO. OF TRACK RECORDS	OPERATIONAL SPEED LIMIT (MPH)	TRAIN NO.	NO. OF LOCOMOTIVES	TOTAL NO. OF VEHICLES	NET TRAIN LOAD (TONS)	GROSS TRAIN WEIGHT (TONS)	HP/GTT	TOTAL FUEL CONSUMPTION (GALLONS)	ROUND TRIP FUEL CONSUMPTION (GALLONS)	AVERAGE RATE OF FUEL CONSUMPTION (GALS./MIN)	AVERAGE VELOCITY FOR TRIP (MPH)	GALLONS PER 1000 GTTM	TOTAL FUEL CONSUMPTION 2-DIRECTION OPERATION	FUEL CONSUMPTION GALLONS PER THOUSANDS OF NET TON-MILES
1	21	W1-W2	543	221	147	25	3	3	71	6814	9391	1.0	1534	2250	2.72	23.5	.785	4175	1.386
2	26	W2-W1	-543	221	147	45	4	3	71	0.0	2577	4.4	716		2.08	38.5	1.60		
3	26	W2-W1	-543	221	147	25	3	3	71	6814	9391	1.0	1059	1925	1.90	23.8	.54		
4	21	W1-W2	543	221	147	45	4	3	71	0.0	2577	4.4	866		2.46	37.7	1.94		
5	21	W1-W2	543	221	147	25	21	3	67	6804	8865	1.1	1449	2090	2.58	23.6	.79	3918	1.302
6	26	W2-W1	-543	221	147	45	22	3	67	0.0	2061	6.0	641		1.86	38.4	1.92		
7	26	W2-W1	-543	221	147	25	21	3	67	6804	8865	1.1	1010	1838	1.81	23.7	.55		
8	21	W1-W2	543	221	147	45	22	3	67	0.0	2061	6.0	828		2.39	38.2	2.49		
9	32	E1-E2	412	254	229	25	23	4	65	6102	8654	1.5	2885	4070	4.33	22.9	1.43	7930	2.56
10	37	E2-E1	-412	254	229	45	24	4	65	0.0	2552	6.6	1185		3.03	39.0	2.57		
11	37	E2-E1	-412	254	229	25	23	4	65	6102	8654	1.5	2573	3860	3.84	22.8	1.28		
12	32	E1-E2	412	254	229	45	24	4	65	0.0	2552	6.6	1287		3.30	39.2	2.79		
13	32	E1-E2	412	254	229	25	25	4	62	6156	8260	1.6	2779	3833	4.19	23.0	1.45	7418	2.37
14	37	E2-E1	-412	254	229	45	26	4	62	0.0	2104	8.8	1054		2.69	38.9	3.04		
15	37	E2-E1	-412	254	229	25	25	4	62	6156	8260	1.6	2447	3585	3.67	22.9	1.28		
16	32	E1-E2	412	254	229	45	26	4	62	0.0	2104	8.8	1138		2.93	39.3	3.28		

TABLE IV (Continued)

RUN NO.	TRACK NO.	ORIGIN-DESTINATION	RISE BETWEEN END POINTS (FEET)	DISTANCE (MILES)	NO. OF TRACK RECORDS	OPERATIONAL SPEED LIMIT (MPH)	TRAIN NO.	NO. OF LOCOMOTIVES	TOTAL NO. OF VEHICLES	NET TRAIN LOAD (TONS)	GROSS TRAIN WEIGHT (TONS)	HP/GTT	TOTAL FUEL CONSUMPTION (GALLONS)	ROUND TRIP FUEL CONSUMPTION (GALLONS)	AVERAGE RATE OF FUEL CONSUMPTION (GALS./MIN)	AVERAGE VELOCITY FOR TRIP (MPH)	GALLONS PER 1000 GTTM	TOTAL FUEL CONSUMPTION 2-DIRECTION OPERATION	FUEL CONSUMPTION GALLONS PER THOUSANDS OF NET TON-MILES
17	21	W1-W2	543	221	147	79	6	5	73	1765	5266	3.5	2409	4569	9.33	51.3	2.51	4569	5.86
18	26	W2-W1	-543	221	147	79	6	5	73	1765	5266	3.5	2160		8.50	52.2	2.25		
19	21	W1-W2	543	221	147	79	6a	5	73	1765	4626	4.0	2361	4478	9.33	52.3	2.88	4478	5.74
20	26	W2-W1	-543	221	147	79	6a	5	73	1765	4626	4.0	2117		8.43	52.7	2.58		
21	21	W1-W2	543	221	147	79	14	5	73	2096	5596	3.2	2326	4333	9.01	51.3	2.25	4333	4.68
22	26	W2-W1	-543	221	147	79	14	5	73	2096	5596	3.2	2007		8.03	52.9	1.94		
23	21	W1-W2	543	221	147	79	14a	5	73	2096	4585	4.1	2191	4141	8.72	52.7	2.70	4141	4.47
24	26	W2-W1	-543	221	147	79	14a	5	73	2096	4585	4.1	1950		7.84	53.3	2.41		
25	32	E1-E2	412	254	229	79	6	5	73	1765	5266	3.5	2649	5013	7.82	45.1	2.40	5013	5.59
26	37	E2-E1	-412	254	229	79	6	5	73	1765	5266	3.5	2364		6.87	44.4	2.14		
27	32	E1-E2	412	254	229	79	6a	5	73	1765	4626	4.0	2490	4735	7.48	45.8	2.65	4735	5.28
28	37	E2-E1	-412	254	229	79	6a	5	73	1765	4626	4.0	2245		6.56	44.6	2.39		
29	32	E1-E2	412	254	229	79	14	5	73	2096	5596	3.2	2658	4996	7.85	45.1	2.24	4996	4.70
30	37	E2-E1	-412	254	229	79	14	5	73	2096	5596	3.2	2338		6.74	44.0	1.97		
31	32	E1-E2	4.2	254	229	79	14a	5	73	2096	4585	4.1	2374	4526	7.14	45.9	2.55	4526	4.25
32	37	E2-E1	-412	254	229	79	14a	5	73	2096	4585	4.1	2152		6.32	44.9	2.31		
33	21	W1-W2	543	221	147	79	1	3	71	2030	4774	2.1	1749	3308	6.29	47.6	1.87	3308	3.68
34	26	W2-W1	-543	221	147	79	1	3	71	2030	4774	2.1	1559		5.81	49.3	1.67		

TABLE IV (Continued)

RUN NO.	TRACK NO.	ORIGIN-DESTINATION	RISE BETWEEN END POINTS (FEET)	DISTANCE (MILES)	NO. OF TRACK RECORDS	OPERATIONAL SPEED LIMIT (MPH)	TRAIN NO.	NO. OF LOCOMOTIVES	TOTAL NO. OF VEHICLES	NET TRAIN LOAD (TONS)	GROSS TRAIN WEIGHT (TONS)	HP/GTT	TOTAL FUEL CONSUMPTION (GALLONS)	ROUND TRIP FUEL CONSUMPTION (GALLONS)	AVERAGE RATE OF FUEL CONSUMPTION (GALS./MIN)	AVERAGE VELOCITY FOR TRIP (MPH)	GALLONS PER 1000 GTTM	TOTAL FUEL CONSUMPTION 2-DIRECTION OPERATION	FUEL CONSUMPTION GALLONS PER THOUSAND OF NET TON-MILES
35	21	W1-W2	543	221	147	79	1a	3	71	2030	4774	2.1	1686	3188	6.15	48.3	1.81	3188	3.55
36	26	W2-W1	-543	221	147	79	1a	3	71	2030	4774	2.1	1502		5.71	50.3	1.61		
37	13	S1-S2	-316	202	150	25	1	3	71	2030	4774	2.1	945	1971	1.80	23.1	1.11	1971	2.40
38	14	S2-S1	316	202	150	25	1	3	71	2030	4774	2.1	1026		1.96	23.2	1.20		
39	13	S1-S2	-316	202	150	79	1	3	71	2030	4774	2.1	1507	3116	4.76	38.3	1.77	3116	3.80
40	14	S2-S1	316	202	150	79	1	3	71	2030	4774	2.1	1609		4.93	37.2	1.87		
41	13	S1-S2	-316	202	150	25	1b	3	71	2030	4774	2.1	922	1929	1.75	23.0	1.08	1929	2.35
42	14	S2-S1	316	202	150	25	1b	3	71	2030	4774	2.1	1007		1.92	23.1	1.18		
43	13	S1-S2	-316	202	150	79	1b	3	71	2030	4774	2.1	1491	3083	4.69	38.2	1.75	3083	3.76
44	14	S2-S1	316	202	150	79	1b	3	71	2030	4774	2.1	1592		4.91	37.4	1.87		
45	13	S1-S2	-316	202	150	25	1c	3	71	2030	4774	2.1	881	1851	1.67	23.0	1.03	1851	2.26
46	14	S2-S1	316	202	150	25	1c	3	71	2030	4774	2.1	970		1.84	23.1	1.14		
47	13	S1-S2	-316	202	150	79	1c	3	71	2030	4774	2.1	1437	3002	4.54	38.3	1.68	3002	3.66
48	14	S2-S1	316	202	150	79	1c	3	71	2030	4774	2.1	1565		4.84	37.5	1.84		
49	13	S1-S2	-316	202	150	25	1d	3	71	2030	4774	1.9	918	1924	1.74	23.1	1.08	1924	2.35
50	14	S2-S1	316	202	150	25	1d	3	71	2030	4774	1.9	1006		1.92	23.1	1.18		
51	13	S1-S2	-316	202	150	79	1d	3	71	2030	4774	1.9	1455	3037	4.58	38.2	1.71	3037	3.70
52	14	S2-S1	316	202	150	79	1d	3	71	2030	4774	1.9	1582		4.83	37.1	1.85		

Notes for Table IV:

1. Train No. — Train Description (See Note 3)

Train No.	Train Description (See Note 3)
3	Std. Wt. Unit Hopper Car Train, Loaded, 67 cars
4	" " " " " " , Empty, 67 cars
21	Lt. " " " " " , Loaded, 63 cars
22	" " " " " " , Empty, 63 cars
23	Std. Wt. Unit Hopper Car Train, Loaded, 60 cars
24	" " " " " " , Empty, 60 cars
25	Lt. " " " " " , Loaded, 57 cars
26	" " " " " " , Empty, 57 cars
6	Std. Wt. TTX Cars, Unit TOFC Train
6a	Lt. " " " " " "
14	Std. " " " " COFC "
14a	Lt. " " " " " "
1	Average Train, Random Consist Arrangement
1a	" " , Rearranged Consist
1b	" " , with Improved Bearing Seals
1c	" " , over Improved Track
1d	" " , with Improved Trucks

2. Origins & Destinations are referred to in Table as follows:

W1	One end of western track
W2	Other end of western track
E1	One end of eastern track
E2	Other end of eastern track
S1	One end of statistical track
S2	Other side of statistical track

3. Figures for number of cars given in Note 1 do not include locomotives or caboose.

$28,000 price, or $1,876,000. The total investment for the light weight cars is 63 times the estimated $38,500[10] price, or $2,425,000. The additional investment of $549,000 with annual savings of only $10,164 does not appear attractive by itself, with a return on investment (ROI) of less than 2%.

It is undeniable, however, that other benefits would accrue, as has been noted elsewhere[12], not the least of which is a reduction of 8.7 percent in gross ton mileage for the operation. Presumably lower maintenance costs and higher salvage value would enhance this figure, so that the investment for even this operation over comparatively straight and level track might be made attractive if benefits beyond mere fuel savings were considered.

The operation looks somewhat more attractive when carried out in mountainous terrain, such as the portion of the eastern route investigated in the second eight runs. The same types of runs were made to eliminate the effect of change in altitude between end points or the sequence of grades and curves; only the rapidity of the changes in the track characteristics or the magnitude of the changes are in effect considered. However, the trains were shortened slightly because of drawbar pull limitations over the maximum grade (limited to 250,000 pounds per recommendation in Reference 4) and a locomotive was added to avoid the adhesion restriction.

The reduction in fuel usage for using the lighter weight cars in the same operation over this more difficult terrain was from 7930 gallons to 7418 gallons, or 6.5 percent, only slightly greater than that for the western operation. The total fuel consumed and the absolute value saved are both considerably larger, however, making the monetary savings per year rise to $20,250, or approximately $321 per car. Thus, while the percentage reduction is only slightly higher, the monetary savings are virtually double the figure for the previous operation. Because of the difference in the composition of the train, the economics are slightly different, and for the simulated operation, only an additional investment of $514,500 is required. The ROI is then 3.9 percent, more than twice the previous figure.

The reduction in gross ton mileage must also be taken into consideration, as was noted previously, in any economic analysis, as well as certain other factors. However, because of the additional locomotive, the percentage reduction in gross ton mileage is not quite as large, only 7.5 percent.

It is possible that with this type of operation, where the fuel per gross-ton-mile is high, the combined savings could justify the additional investment. The total additional investment is only slightly over 25 times the annual savings from fuel alone. Additional benefits accruing from this operation might bring the payout period to an acceptable level.

5.2 Light Weight Flat Cars

The use of light weight flat cars for intermodal service was investigated in a similar fashion, although it was assumed that the return trip was also in a loaded condition. Efforts were directed towards making the train as representative of intermodal service as possible. Loads were established from the average of loads reported for TOFC/COFC runs in Reference 8, trailers and containers were assumed to be 40 feet long and weights were taken from Reference [13], and the ratio of the number of trailers to twice the number of cars was taken again from the averages reported in Reference [8]. The approximately 10 percent of flat cars carrying only a single trailer or container were interspersed at random points throughout the train.

Because intermodal service is not necessarily restricted to operation in the western plains, the runs were made both over the western route and the eastern route. However, because it is likely that emphasis is placed on high speed operation in order to remain competitive with trucking lines, no operational speed limit was imposed other than the maximum allowable 79 mph. This does not mean that simulated operation took place at this velocity; average speeds computed by the program were approximately 53 mph on the western track and 45 mph on the eastern track. The difference is attributable to the fact that speed on the eastern track is restricted below the 79 mph level by the track itself, while the western track is not as severely restricted.

Results percentage-wise were comparable with the results from the runs with light weight hopper cars. The reductions in fuel consumption are listed in Table V along with reductions in gross weight; the figures from the light weight hopper car trains are also shown for comparison.

The reduction in fuel was least on the TOFC western W1-W2-W1 round trip, 2 percent. The reduction on the COFC run is larger, 4.4 percent, because the percentage reduction in weight was larger. On the eastern E1-E2-E1 round trip the TOFC-COFC relationship was the same for the same reason, but the percentage reductions in fuel in both cases were larger. The reason is that the average speeds were lower over the more difficult terrain, and comparatively more fuel is expended under such circumstances against weight-dependent resistances than at higher velocities at which the velocity-squared dependent aerodynamic drag assumes more importance. Moreover, it is shown in Appendix D that greater savings are occasioned by a steeper average grade, although the relationship is not simple.

TABLE V

COMPARISON OF FUEL SAVINGS, UNIT COAL TRAIN
AND INTERMODAL TRAINS

RUN	TYPE	% ROUND TRIP FUEL SAVINGS	% WEIGHT REDUCTION
W1-W2-W1	TOFC	2.0	12
	COFC	4.4	18
	Unit Coal Train	6.1	5.6 Depart 20.0 Return
E1-E2-E1	TOFC	5.5	12
	COFC	9.4	18
	Unit Coal Train	6.5	4.6 Depart 17.5 Return

The reductions due to the light weight hopper cars were comparable. The reduction was greater on the E1-E2-E1 round trip than on the W1-W2-W1 round trip, as the average velocity was lower. On the W1-W2-W1 round trip, the light weight hopper car train showed up more favorably than either the TOFC or the COFC trains, despite the apparently greater percentage weight reduction on the latter. The weight reduction cannot be compared precisely, because the hopper car train departed in a loaded condition and returned empty, so that the percentage weight reductions are different for each portion of the trip. Furthermore, the average velocities were different for each portion of the trip.

The average weight reduction for the light weight hopper cars is nevertheless in the same range as those of the TOFC/COFC trains. But the light weight hopper car achieved a percentage fuel reduction almost twice as large as the average intermodal fuel reduction. Again, the average velocity is no doubt the answer. The average velocity for the hopper car train for the entire W1-W2-W1 round trip was only 31 mph, whereas the intermodal trains averaged 52 mph. On the E1-E2-E1 round trip, the hopper car train average velocity remained at 31 mph while the average velocity of the intermodal trains dropped only slightly from 52 mph to 45 mph. Under such circumstances, the same percentage weight reductions will appear more favorably at the lower velocity. In addition, as is shown in Appendix D, operation at lower velocities permits greater savings to be effected at a smaller average grade.

While the percentage fuel reductions for the TOFC/COFC trains on the W1-W2-W1 round trip (2.0 percent and 4.4 percent respectively) were on the same order of magnitude as the percentage reductions in train resistance reported for 60 mph operation in Reference 1, the corresponding reductions on the E1-E2-E1 round trip (5.5 percent and 9.4 percent respectively) even at an average velocity of 45.0 mph were larger than the reductions in train resistance (4.2 percent and 6.7 percent) reported in Reference 1 for 20 mph operation. Although the trains in the two reports were not identical, nevertheless the figures are significant. The W1-W2-W1 track is comparatively free from rapid and severe changes in grade and curvature, and except for the altitude change probably approaches the ideal level tangent track as closely as most U.S. railroads ever do. The effect of altitude change is eliminated by round trip operation. In such an operation, fuel savings could be expected to closely correspond with reductions in train resistance reported in Reference 1 for operations at similar velocities. Savings are small, as weight reduction does not reduce overall resistance significantly at high speeds, particularly for vehicles with larger aerodynamic drag, such as TOFC/COFC equipment. The E1-E2-E1 track is significantly more complex, leading to lower operational velocities. It should be expected that the lower velocities would increase the percentage of fuel savings over the higher velocity operation. But the complexity of the track evidently had a significant effect upon fuel savings, as the percentages of fuel reduction were higher at an average velocity of 45 mph than the reduction in train resistance at 20 mph. It is clear that fuel is not saved by operation in mountainous regions, but what emerges from the figures is that as the track becomes more complex and the operational velocity becomes smaller, the potential gains from the use of light weight equipment become significantly larger. In contrast, as the operational velocity becomes greater and the nature of the track more closely resembles that of level tangent track, the rewards reflect the absolute reduction in train resistance more closely. Appendix D contains some pertinent additional considerations with regard to light weight equipment and the rewards which may be expected from its use.

5.3 Consist Rearrangement

The effects of consist rearrangement were investigated by examining the operation of an average train with a random arrangement of cars over the W1-W2-W1 track and comparing it with the operation of the rearranged train over the same track. The W1-W2-W1 track was selected since it permitted higher average speeds and the effect of consist rearrangement is purely reduction of aerodynamic drag, a phenomenon of significance only in the higher velocity ranges. Hence the impact of rearranging the consist should be greater on this track than on the other tracks used for simulation purposes.

Runs 33-36 show the effect of rearrangement over the W1-W2-W1 track. The rearranged consist showed a reduction of fuel consumption from 3308 gallons to 3188 gallons, a reduction of 3.6 percent at an average velocity of approximately 49 mph. This value is considerably less than the value reported in Reference 1 for the reduction in resistance on level tangent track, a 13.5 percent reduction at 60 mph, and some explanation is required. The difference can be accounted for as follows. A check of the resistance curves for the standard train and for the rearranged train revealed that the curve for the latter had not diminished as much as formerly: at 49 mph, the reduction in resistance was only 6.5 percent instead of 12.6 percent. While there were slight differences in the weights of the train and their makeup (the train in the former report had only two locomotives as opposed to three), the reduction in resistance should not have been greatly affected by these considerations. What the difference is attributable to is that the aerodynamic drag calculation has been modified on the basis of the latest wind tunnel data on tests of blocks and the effect of block spacing. The new information places a heavier penalty on shorter gaps; this will mitigate to a certain degree the advantages of rearranging the consist, as the shorter gaps are not affected substantially by rearrangement. Hence, the resistance curve for the rearranged train is not quite so beneficial as formerly.

Still, a 6.5 percent reduction is significant and should be reflected in diminished fuel consumption. However, only a 3.6 percent reduction in fuel consumption was found. This is attributable to the fact that fuel consumption over a long trip is not related in a completely simple fashion to train resistance, and the diminution of resistance is mitigated to a certain degree by factors determining fuel consumption not affected by train resistance, such as idling time and energy dissipation in the braking mode.

While these results are somewhat negative in that the effects of consist rearrangement no longer appear so favorable, it was not completely unexpected that the reduction in fuel consumption would be blurred by other factors. However, as the aerodynamic data for blocks is still unverified by field testing on full scale railroad vehicles, consist rearrangement may still offer meaningful fuel savings.

5.4 Equipment Improvements

Runs 37-40 were made to serve as a base against which to measure the reduction in fuel consumption attributable to the various equipment improvements to be examined. The runs were made using the average train and the track generated artificially from statistical data on U. S. mainline Class A track mentioned earlier. The same train and track were then used to simulate runs made with improved bearing seals, rigidized track, and improved trucks to examine the effects of these modifications on fuel consumption. As in Reference 1, the equipment improvements were simulated by making modifications to the terms of the resistance equation corresponding as closely as possible to the reductions in resistance resulting from the improvements. Such simulations may not be completely accurate, but until better understanding of the precise contributions to train resistance of every constituent component is achieved, no alternative means of evaluation are available.

5.4.1 Improved Bearing Seals

These were simulated by reduction of the value of the term in the modified Davis formula corresponding to a fixed drag of 80 pounds per car for a four-axle (16 bearing) car. The corresponding term in the locomotive resistance equation for six axle vehicles was similarly reduced. The magnitude of the average reduction, as in Reference 1, was 18 percent. Instead of the following expression for the first two terms,

$$R(\text{lb. per car}) = 80 + .6\ W_o$$

where W_o is the gross weight of the car, the expression below was used:

$$R = 65.6 + .6\ W_o$$

Runs 41-44 show the fuel consumed with a low (25 mph) speed limit imposed and an unrestricted speed limit over the same track. The low speed operation with better seals showed a 2.1 percent improvement in fuel consumption, the higher speed operation 1.1 percent. The higher speed operation again shows a smaller percentage improvement, at least partly because the fuel consumption is more heavily weighted with consumption attributable to aerodynamic drag.

As discussed in Reference 1, the reduction in drag is a fixed value per car; thus under certain circumstances the energy saved per car-mile is a more meaningful statistic. At a reduction in drag of 14.4 pounds per car (above) and at a penalty to the locomotive of .0644 gallon per delivered HP-hr,[5] the $28.8 \cdot 10^9$ annual freight car miles theoretically result in annual savings of $24.9 million per year at a diesel fuel cost of $.35/gallon.[9] This theoretical figure represents 1.8 percent of the railroad's annual fuel bill and although computed on a slightly different basis from the previous figure[1] is consistent with it. Unfortunately, the full 100 percent of the theoretical savings are not in general available for the reasons advanced in the following section. Although during operation over level tangent track the full potential should be realized, as the track becomes comprised of more grades the realizable percentage of the full potential diminishes. This concept is developed more fully in the following section. Thus the actual savings in fuel computed by this program are judged to be a more realistic appraisal of what actual savings might be achieved rather than the theoretical limit, and operation over the statistically representative track shows that something less than the theoretical potential is likely to be achieved in normal operation.

5.4.2 Improved Track Rigidity

Improvements to track rigidity were simulated by eliminating the weight-dependent term of the non-velocity-dependent terms of the modified Davis formula. This is not completely accurate, as portions of the velocity-squared term may be assignable to losses of kinetic energy due to poor quality track. Nevertheless, as noted in Reference 1, Keller[14] attributes certain train resistance in pounds per ton to rail deflection caused by train weight, and elimination of this term in its entirety will certainly remove such train resistance from consideration.

Runs 45-48 show the fuel consumed with the same 25 mph and unrestricted speed limits as before. The low speed operation showed a 6.1 percent reduction in fuel and the high speed a 3.7 percent reduction. These figures are substantially smaller than the value reported in Reference 1 for the reduction in resistance attributable to rigidizing the track, approximately 26 percent and 9 percent respectively, and some explanation is required.

In order to ensure that no mistakes were being incurred, several supplementary runs not listed in Table IV were made, some of the results of which appear in the following two tables. These runs showed that, like the results of Reference 1, a fixed reduction in resistance independent of velocity results from the simulation of rigid track, regardless of whether the track is level tangent track or is comprised mainly of hills and curves. However, these are not proportionately reflected in fuel savings.

Tables VI and VII display data from runs over the two real tracks, the statistical track, and an artificially created level tangent track of almost the same one-way length. Again the trains were run in both directions to eliminate the effects of the change in altitude between end points. Like the case of the improved bearing seals, since the reduction in resistance is not a function of velocity and is constant in value, the reduction in energy consumption per mile is the significant parameter and can be directly calculated from the reduction in work done against train resistance, converting work to fuel consumption with the use of the same .0644 gallons/brake-HP-hr. figure mentioned earlier and in Reference 5. A comparison of the theoretical reductions and the reductions reported by the simulations is shown in Table VI, along with the percent reduction of total fuel consumption. The tracks are listed in order of what might be called their complexity, for

TABLE VI

COMPARISON OF ACTUAL AND EXPECTED REDUCTIONS

(Improved Track Rigidity)

TRACK	TOTAL MILES	EXPECTED REDUCTION, GALLONS	ACTUAL REDUCTION, GALLONS	% OF EXPECTED REDUCTION	REDUCTION % OF TOTAL CONSUMPTION
E1-E2-E1	508.86	250.25	123.0	49.1	4.1
STAT	404.36	198.86	120.0	60.3	6.1
W1-W2-W1	441.62	217.19	133.0	61.2	8.0
L.T.T.	220.00	108.19	107.9	99.7	20.4

TABLE VII

EXCESS OF FUEL CONSUMPTION OVER PREDICTIONS FROM RESISTANCE CALCULATIONS

(Improved Track Rigidity)

TRACK	TOTAL MILES	AVERAGE SPEED, MPH	SIMULATED FUEL CONSUMPTION, GALLONS	THEORETICAL FUEL CONSUMPTION, GALLONS	PERCENT EXCESS	FUEL CONSUMPTION GAL/MI
E1-E2-E1	508.86	23.4	2985.56	1135.93	162.8	5.87
STAT	404.36	23.1	1971.25	902.66	118.4	4.87
W1-W2-W1	441.62	23.5	1658.94	985.83	68.3	3.75
L.T.T.	220.00	24.6	528.26	491.10	7.6	2.40

lack of a better term, with the E1-E2-E1 route being the most complex, with many curves and steep grades. Less complex are the succeeding tracks, with level tangent track the simplest at the bottom. The percent of the expected reduction which was actually achieved varies smoothly but inversely with the complexity, so that fuel savings relate almost perfectly to reduction in train resistance over level tangent track, but less so the more complex the track.

It is possible to compute the expected fuel consumption for a constant speed operation using the known train resistance. Table VII shows the excess of the fuel consumption predicted by the simulations over that predicted using resistance calculations. The excess is a certain indication of the previously mentioned complexity of the track. On level tangent track, the indicated fuel consumption is only 7.6 percent in excess of what train resistance calculations would indicate, while over the most complex track the excess is 162.8 percent.

The excess is explained by energy dissipation during braking and in idling the engines during the same period and during stops. Percentage fuel savings are related to the weighting of the actual fuel consumption with these energy dissipations. Still, it is not obvious why, with a fixed reduction in resistance per mile, the fuel saved per mile is not constant. This too is related to braking and the speed limit to be maintained. An examination of Figures 7 and 8 will be of assistance.

For anything other than level tangent track, grade resistance predominates. See Figures 4 and 5, Reference 1, for example. If the grades are small enough, work done against gravity on the upslope is recovered on the downslope. However, for steeper slopes, this is not the case; the potential energy has to be dissipated in

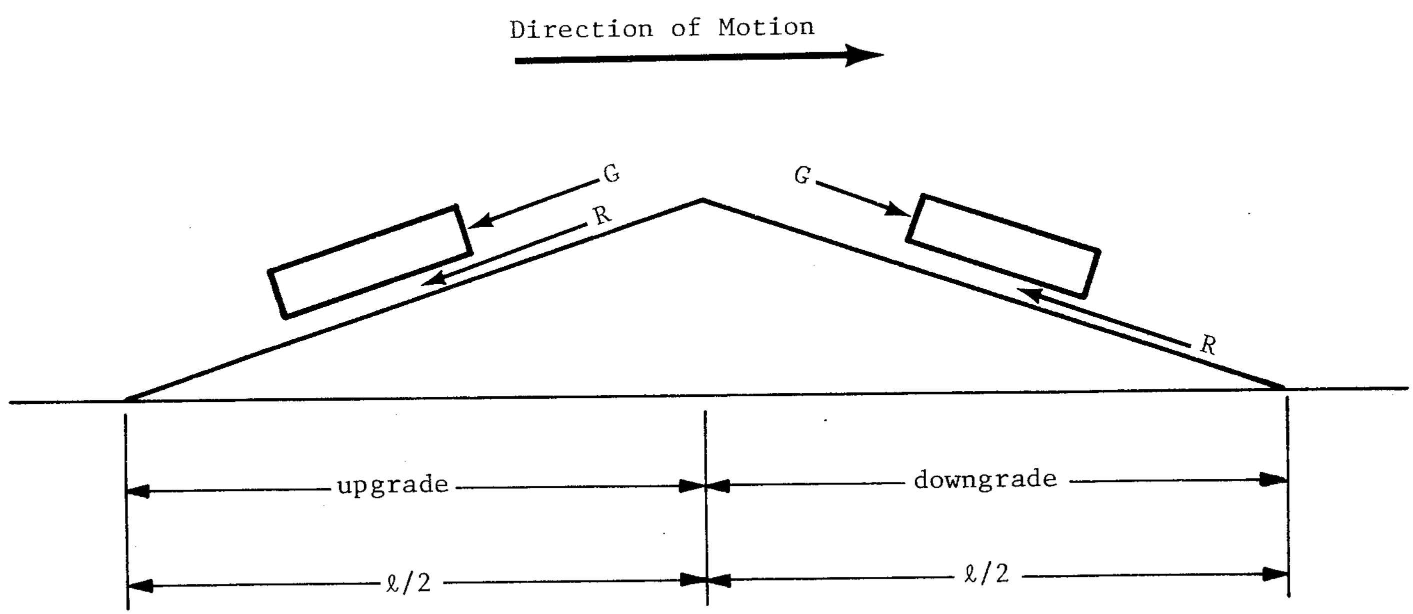

FIGURE 7
SIMPLE UP AND DOWN OPERATION

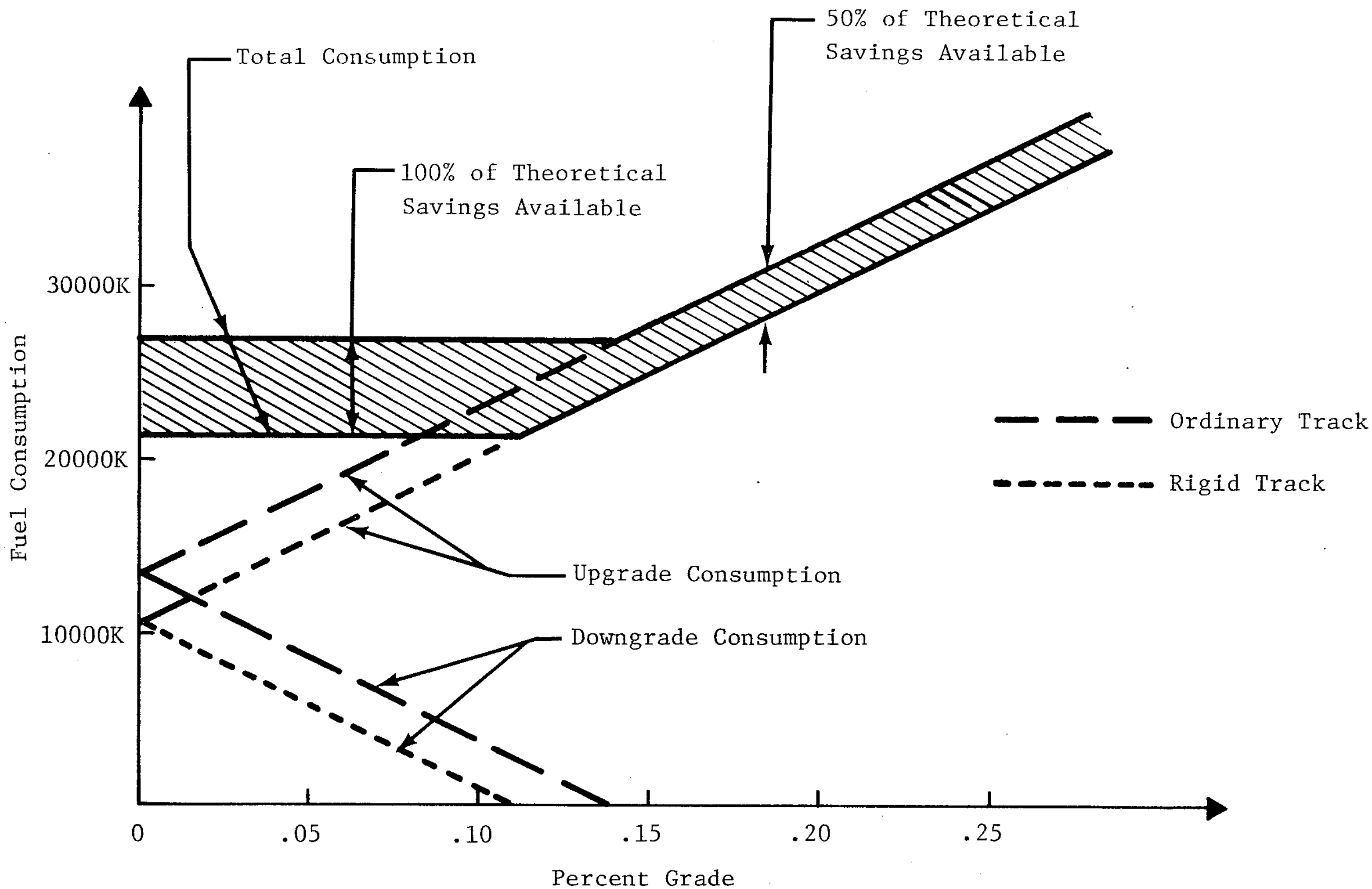

FIGURE 8
FUEL CONSUMPTION FOR SAMPLE OPERATION

braking to remain within the speed limit. For a particular operation, the slope in excess of which the energy is not recoverable can be computed, assuming a simple up-and-down grade of equal length and a constant speed operation (see Figure 7); it is the grade at which the gravity pull downward equals the train resistance at that speed.

Figure 8 shows limits of possible savings in rigidizing the track as a function of the grade for the above mentioned up-and-down-again, constant speed operation. The numbers relate to operation of the particular average train used in other places in the report at 25 mph. On ordinary track the limiting grade is for that speed only .14 percent. Below this grade, energy expended against gravity forces on the upslope is recoverable on the downslope, as G will be equal to or less than R. Above this grade, G will be larger than R and some energy will be dissipated in braking. The limiting grade for the rigidized track is .11 percent.

Total fuel expended on this operation as a function of the grade on either side of the track is shown in the figure. The possible savings resulting from rigidizing the track are shown as a function of grade on the same figure as the difference between the total fuel expenditure curves (the sum of the curve for the upgrade portion and the downgrade portion of the operation). Fuel units on the ordinate are the train resistance in pounds times a conversion factor K equal to $5280 \cdot 5.05\text{-}10^{-7} \cdot .0644 \cdot \ell$, where ℓ is the length of the run in miles, $5.05 \cdot 10^{-7}$ is HP $\cdot$ hr/ft.lb and .0644 is the fuel consumption per brake HP-hr.

Theoretical fuel savings below .11 percent grade are equal to 100 percent of the figure resulting by multiplying the reduction in train resistance by the conversion factor. Between .11 percent and .15 percent the figure is diminished slightly, and above .15 percent savings are only achieved on the upgrade; rigidizing the track on the downgrade at these higher slopes, for this particular operation, is useless, as it merely means brakes must be applied more heavily. Possible fuel savings are equal to only 50 percent of the theoretical potential

The tracks over which the simulated runs were made are naturally not related to this operation in a simple fashion, but the level tangent track (L.T.T.) is the limiting case for this operation, with a zero grade, and the percent of the expected reduction approaches the 100 percent level very closely (99.7 percent). Since the trains were operated in the reverse direction also over the other tracks, it can be said that for every upgrade there was an equal length downgrade. However, there were many different grades, and one would expect results somewhere between the percentage reduction for L.T.T. and the 50 percent reduction expected for higher grades.

This is indeed the case, and the percentages of the expected reduction for the W1-W2-W1 and statistical tracks lie between these values. The value for the most complex track, the E1-E2-E1 track, is slightly below the minimum 50 percent level. The reason for this is that there are slight inaccuracies in the calculation of the fuel consumption itself, slight errors in taking differences of numbers close in value, and round-off errors. In addition, the analysis is clouded by the presence of a five-minute stop during which the engines were idling.

The conclusion is therefore that on level tangent track the reduction in fuel consumption is closely related to the reduction in train resistance but as the track becomes more complex, in terms of having more grades, the percentage of the expected reduction in gallons per mile for a particular train diminishes. Also, as the absolute consumption per mile grows as the track becomes more complex, in this case including both grades and curves, the percentage of total consumption which fuel savings represent falls rapidly, as the theoretical savings in fuel per mile remain a constant.

Since the use of light weight equipment also reduces train resistance to a certain extent by a constant amount, a figure relevant to the use of such equipment analogous to Figure 8 is considered in Appendix D.

5.4.3 Improvements in Truck Design

Improvements in truck design were simulated by eliminating the velocity-dependent term from the modified Davis formula, on the grounds that this term represents flange resistance and rubbing of the wheel flanges against the track will be eliminated by means of self-steering trucks through elimination of hunting. It is known that this term contributes the least resistance of all terms (see Figure 10, Reference 1), so that not too impressive reductions in fuel consumption were to be expected.

Runs 49-52 show the fuel consumption with the same speed limits as before. The low-speed operation showed a reduction of 2.4 percent and the high speed a reduction of 2.5 percent. Although the other improvements showed a decrease in the percentage reduction at the higher speed, the percentage reduction in this case remained about the same. The difference in this case is that some velocity-dependent resistance was eliminated, whereas in the two previous cases only constant or weight-dependent terms were eliminated, leaving the higher velocity resistance to be unchanged and dominated by aerodynamic drag.

These results, although slightly smaller than the previously reported figures[1] are reasonably consistent with them. It was to be expected that the reduction would be diminished by the weighting of the fuel consumption with the factors not considered during operation on level tangent track: energy dissipation during braking and fuel consumed during idling.

Reductions in train resistance attributable to better curving performance in an improved truck were not modeled. It is possible as a consequence that the above figures could be more favorable for certain types of improved trucks, but until definite information on the reduction of train resistance through the use of such trucks is available from the field, such additional gains must remain speculative.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This study was undertaken as a supplement to the previous examination of train resistance and possible savings in fuel consumption resulting from reductions thereto when the train is operated over level tangent track. It was realized that certain of the conclusions might be modified if train operation over normal track including grades and curves were simulated. Such was indeed the case, although the conclusions were not always modified to the expected extent nor did they necessarily reflect an intuitive prejudgement. However, since new information in the form of data from wind tunnel tests on wooden blocks simulating railroad vehicles was incorporated into the program at the same time, not all of the modifications to the previous results are attributable to simply the change in the nature of the track. Nevertheless, the conclusions drawn are based upon the latest information available and are related to normal train operation, and they should be valid within the limitations stated herein.

If there is a single conclusion which stands out from the results of this study, it is one which does not depend upon the type of track over which the simulated trip is made: speed is costly in terms of fuel consumption. A glance over the results of the runs summarized in Table IV shows consistently, on both an absolute basis and on a ton-mile basis, that a heavy price is paid in terms of fuel consumption when the average trip velocity is high. One must be careful for this reason to consider the average trip velocity and the operational speed limit when interpreting the fuel consumption figures. It is evident, moreover, that the impact of speed is far larger than the impact of any of the modifications discussed herein, although it was not specifically investigated as a separate means of reducing fuel consumption. There are, of course, innumerable repercussions from lowering the average freight train speed.

Another penalty is exacted by the complexity of the track. The more complex the track, the higher the fuel consumption per mile for a given train. This is illustrated clearly in Table VII; fuel consumption on level tangent track is 2.40 gallons per mile, while for the same train operating at approximately the same average velocity over the most complex track the fuel consumption is 5.87 gallons per mile.

A third general conclusion is that regardless of the nature of the track any improvement in equipment such as those investigated herein resulted in some fuel savings, however small. All of the modifications to equipment in operations examined in the context of this report reduced train resistance, which reduction in turn is reflected in diminished fuel consumption. The question is, as usual, whether the additional investment required is economically justifiable on the basis of the savings generated. A complete economic analysis of the impact of the fuel savings discussed herein is beyond the scope of this report, as additional benefits quite often accrue as a result of making the particular improvement in order to save fuel, but the economic implications of most of the fuel savings have been touched upon in the preceeding sections. An economic analysis of the benefits discussed herein will be the subject of a future report.

In Reference 1 it was noted that for operation over level tangent track the rewards for the lightening of equipment were not great. The reasons for this were that the weight saved was only a portion of the car weight, the car weight is only a small portion of the total weight if the train is fully loaded, and the portion of the resistance attributable to the weight of the train is, except at low velocities, only a small portion of the entire resistance, which is reflected in fuel consumption.

It was expected that the rewards for utilizing light weight equipment would be quite high when the train was operated over normal track, particularly when the track passed through mountainous terrain. Some of the reasons why the reductions in fuel consumption were not more dramatic were advanced in the previous section. Nevertheless, for the aluminum hopper cars in unit train service, compared with the $97 per car figure reported in Reference 1 for annual savings, the $161 and $321 per car saved are considerably larger. However, with the present price differential for aluminum cars, the payout period is still in the neighborhood of twenty-five or thirty years unless other indirect benefits are included, and such an investment decision would seem unwise based upon fuel savings alone. A good analysis of the additional economic implications of the use of aluminum cars is given in Reference 12.

The fuel savings on a percentage basis for the W1-W2-W1 TOFC/COFC round trips were only slightly larger than the modest reductions in train resistance reported in Reference 1. However, on the E1-E2-E1 round trip, the percentages were significantly larger. Some of the reasons for these results are given in the previous section and in Appendix D. High speed operations are less sensitive per se to reductions in weight because of the relative dominance of air drag, particularly with such equipment as TOFC/COFC. In addition, it is shown that higher speed extends the theoretical grade limit in excess of which rewards for lightening equipment are higher, so that for a certain train operating over a given track it might be beneficial to lighten the equipment if the operation were conducted at a low speed but not so beneficial if conducted at a high speed. The rewards are highly dependent upon the nature of the operation. Still, as before, while energy savings are always beneficial no matter how small, whether the additional investment in light weight equipment is justifiable economically is the question to be answered. Without the benefit of a detailed economic analysis, cost benefits from fuel savings alone appear meager on the comparatively high speed operation over the relatively uncomplicated W1-W2-W1 track; on the more complex E1-E2-E1 track where the average speed was lower, the fuel savings alone (up to 9 percent) appear more significant.

It was noted in the previous report that appropriate rearrangement of the consist could, in the higher speed ranges where aerodynamic drag assumes the dominant role, achieve very worthwhile reductions in train resistance when the train is operated over level tangent track. The results of the current investigation indicated that the percentage reduction in train resistance was smaller than the reduction reported previously, only 6.5 percent vs. 12.6 percent. This smaller reduction is directly attributable to new aerodynamic data from wind tunnel tests on blocks simulating railroad vehicles. These data place a heavier drag penalty on shorter gaps than formerly, and the smaller reduction is not related to any change in fuel consumption attributable to the different nature of the track. This means that consist rearrangement, which minimizes longer gaps but generally leaves shorter gaps unaffected, does not appear as favorably as formerly indicated in Reference 1. The percentage reduction in fuel consumption indicated by the results was 3.6 percent, less than the reduction in resistance. This is explained by the fact that fuel consumption is closely related to train resistance in a constant velocity operation over level tangent track but not as closely related in an ordinary operation over normal track. As a consequence, any savings in fuel consumption attributable to a single factor are diminished percentage-wise from what might be expected in the absence of the other factors. In addition, the difference in the number of locomotives undoubtedly affected fuel consumption to a limited degree. While these results tend to mitigate the previously reported impact of consist rearrangement, it must be noted that as the aerodynamic data on blocks are unverified at this time by field testing on full scale railroad vehicles, consist rearrangement may still offer meaningful fuel savings. Determination of the true aerodynamic drag of a particular arrangement of freight cars has yet to be finalized. However, as fuel consumption is not directly related to train resistance in normal operation, the diminution of the savings in fuel consumption from those over level tangent track was not unexpected.

The reductions in train resistance attributable to improved bearing seals and additional track rigidity are both independent of speed and represent a certain fixed reduction of resistance in pounds. The figures for each can be directly related to energy per car mile on a theoretical basis. In actuality, the theoretical figures represent a limit which is attainable only through operation on level track or tracks with less than a certain grade assuming round trip operation. On normal tracks the percentage reduction in fuel consumption is less than would be expected from purely theoretical considerations. Thus the expected reduction in fuel consumption will be larger as the operation more closely resembles operation over level track, and smaller as the track becomes more comprised of grades.

Improvements in truck design, as simulated in the program, showed reductions in fuel consumption of approximately 2.5 percent, better than that achieved through improved bearing seals, but less than for the other improvements. It must also be recognized that the figure is a limit for fuel savings from improved trucks in that all contributions from poor trucks have been eliminated. It would not be reasonable to expect an improved truck to achieve such perfection. Hence, of all the proposed improvements, this appears to have the most limited potential for fuel savings. However, again there are possibly certain benefits other than fuel savings, such as reduced maintenance of way expenditures, which might be accrued, but an examination of these is beyond the scope of this report.

In summary, it may be said that the study shows that fuel savings resulting from reduction of train resistance are highly sensitive to the operation being run: average velocity, train weight, type of train, and complexity of the track. These four factors mingle in a sometimes conflicting fashion to determine resulting fuel savings and a simple relationship of fuel savings to reduction in train resistance does not exist. An attempt has been made herein to probe the relationship of these factors and their influence upon fuel savings, but the picture has been shown to be too complex to be explained in a simple fashion. The most general conclusion that can be drawn is that the particular operation for which the design improvement or equipment modification is recommended be thoroughly analyzed by means of the computer program described herein or a train performance simulator with similar capability to determine the fuel savings which will accrue to the particular operation. The resulting fuel savings will not necessarily be applicable to a different operation.

The program developed as a part of this investigation has shown itself to be a useful tool for examination of fuel consumption and it is planned to utilize it to study in more detail certain aspects of train operation which could not be examined within the time frame of the current study or which appeared as a result of the study to need further examination.

Specifically, some effort will be devoted to a segregation of the effects of the track and the new aerodynamic data in the area of consist rearrangement. Although it appeared desirable at the beginning of the current investigation to make the most accurate assessment of fuel consumption that present knowledge would permit, after these assessments were made it was realized that in many cases the changes in fuel consumption could not be accurately attributed to either cause singly, and that it was difficult if not impossible to determine the effect of the track alone. It is planned that the additional aerodynamic data which will be forthcoming from current wind tunnel tests be incorporated into the program as it becomes available, and that at the same time the program be exercised in an appropriate fashion to segregate the effects of the new data from the effects of purely the track.

Time did not permit a detailed economic analysis of the cost-benefit of the fuel savings which can be expected by the improvements or modifications examined herein, although the economics of certain of them were briefly discussed. Since all these improvements or modifications result in some fuel savings and it is always the economic tradeoff which needs to be resolved, in the following phase of this work a detailed cost-benefit study supported by the data from additional program runs will be undertaken.

Close examination of certain features of train operation is desirable. At low speeds the first two terms of the resistance equation representing mechanical and fixed resistances predominate. Yet there is still considerable uncertainty concerning the accuracy of these terms. A better understanding of low speed resistance would be of value in predicting the behavior of freight cars in marshalling yards, for instance, and a study of the phenomenon will be conducted as part of related research at the Transportation Systems Center (TSC/DOT).

Another phenomenon worthy of a closer examination is truck hunting. The contributions of truck hunting to energy dissipation are presently not well understood, and it is planned that a theoretical examination of this phenomenon be undertaken as part of the next phase of this effort and that the results be correlated with field data from a specific test of the phenomenon performed as part of one of FRA's current research programs in freight car truck design.

While an effort was made during the current study to examine types of operations which would provide meaningful results from a limited number of runs, it became apparent that there are many features of train operation which can greatly affect fuel consumption but which could not be examined within the scope of the report. Some of these were touched upon and some were not. Locomotive assignment policy appears to be one aspect of train operation to which fuel consumption is particularly sensitive. The operational speed limit is another obvious constraint which affects fuel consumption. The extent to which the average speed of the operation and the average grade or track complexity affect the desirability of light weight equipment appears from the study to be an important area for further examination. Further use of the program will be made to explore these and other similar aspects of fuel consumption, and the results will be correlated with other on-going FRA programs.

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APPENDIX A

COMPUTER PROGRAM

1.0 GENERAL

This appendix describes the computer program which calculates the fuel consumption of a freight train operating over normal track. The mathematical background and some detailed discussions of various algorithms in the program are given. Program input and output and proper usage are described. The explanation of the program is not intended as a complete users' manual, but most persons familiar with Fortran programming will be able, with a little effort and the use of the text that follows, to use the program, understand its logic, and modify it or adapt it to their own use.

The program was devised to solve a specific problem, namely, to compute the fuel consumption of a freight train whose composition is known and which is made to move over a track with known characteristics. While every effort has been made to minimize changes that might be required in existing track data for use with the program, certain modifications may still be necessary in order to permit the satisfactory functioning of the program. Similarly, the train must be specified in a manner compatible with program needs. Other inputs to the program must be similarly formatted.

2.0 DESCRIPTION

The program basically consists of a "DO" loop, which repeatedly calculates for consecutive time intervals the values of a number of variables required to determine fuel consumption. The velocity of the train must be determined for each instant of time in order to determine train resistance, which in turn affects fuel consumption. In addition energy inputs into the train during acceleration periods must be determined, so that acceleration data is required. Hence, the program undertakes to compute the velocity profile for the entire trip, and from this information the fuel consumption is determined.

2.1 Mathematical Background

It has been assumed that the resistance of the train is governed by the modified Davis formula, which has the form

$$R \text{ (lbs)} = a + bv + cv^2 \tag{1}$$

in which "a" and "b" are functions of weight.

For a given notch position (approximately constant power), the tractive effort is a function of velocity, since

$$TE \cdot v = \text{Constant} \triangleq K_1 \tag{2}$$

Hence

$$TE = K_1/v \tag{3}$$

The net force accelerating the train will be the tractive effort minus the resistance so that, for Newton's law,

$$TE - R = m\frac{dv}{dt} \tag{4}$$

Combination of the above expressions results in:

$$mv \frac{dv}{dt} = K_1 - av - bv^2 - cv^3 \tag{5}$$

which is not integrable in closed form. The velocity can be found, however, by piecemeal integration, step-by-step. This is the procedure utilized in the program described herein.

At any given time the velocity of the train and its position along the track are known. A notch setting, determined by algorithms discussed in the following section, determines the constant power to be applied during the next time interval, which power, together with the velocity, determines the tractive effort. The resistance of the train is calculated, based upon the velocity of the train at the beginning of the time period, and in combination with the known tractive effort the train acceleration is determined for the next time interval.

From the known time interval and this calculated acceleration, the velocity at the end of the time period is calculated, and the distance traversed and the mean velocity over the period computed.

From these data the fuel consumption during that interval can be computed. The resistance based upon the mean velocity is computed and added to the force accelerating the train and the sum multiplied by the distance traversed and an appropriate dimensional factor. It is assumed that the time constants involved in a change of notch position are small enough to be ignored for the purpose of calculation of fuel consumption over a finite time interval considerably larger than the time constants. When the net tractive effort is less than zero, the engines are returned to the idle setting, and the fuel consumption reflects this idle rate.

An assumption of constant power during that interval will give a different value for fuel consumption than a calculation based upon average velocity, and hence average resistance, over the distance traversed, reflecting the work done by the locomotives. It can be shown (see Appendix B) that the difference is attributable to the change in resistance across the time interval and the difference between the initial velocity and the mean velocity during the time interval. The difference becomes zero for an infinitely small time interval. For finite intervals, the sum of the differential fuel consumption as calculated by the program tends to equal the sum as calculated for constant power, as there is equal likelihood that the mean velocity or the differential distance will be larger or smaller than the preceeding values and differences will tend to cancel. For some sample calculations, the differences were on the order of 1 percent.

Regardless of which calculation is chosen, an error will be incurred because of the finite length of the time interval and the approximation made in the calculation of resistance. Although the calculation used permits slightly different rates of fuel consumption at the same notch setting, it was felt it actually represented a truer calculation of fuel consumption for the particular velocity profile calculated. Had the other calculation been selected, a different method of calculating the velocity profile would have had to be used.

2.2 Program Inputs

The program is presently set up on an interactive basis. The program operator must specify the values of several parameters the values of which will affect the resulting fuel calculation, in addition to specifying file numbers which contain basic information concerning the train and the track over which a simulated trip is to be made. Figure A-1 shows the formatting of the inputs, in slightly abbreviated form to eliminate computer messages. Certain inputs are in "F" format, and others are in "I" format. The program may be examined for details. In general, the "I" format requires a certain number of integers to be entered, as noted. The program has not necessarily been optimized in these respects, but the numbers have been selected as reasonable values.

```
INPUT TRAIN FILE NUMBER
1
INPUT ORDER FILE NUMBER
1
INPUT TRACK FILE NUMBER
14



INPUT, NO. OF LOCOMOTIVES, ENTER A 1 DIGIT NO.
3
INPUT,NO. OF VEHICLES IN TRAIN, (INCL. LOCOMOTIVES),  ENTER A 3 DIGIT NO.
071
INPUT, NO. OF TRACK RECORDS IN TRACK FILE,            ENTER A 4 DIGIT NO.
0150
INPUT,TIME INTERVAL,SECONDS
10.0
INPUT,NO. OF INTERVALS, ENTER A 4 DIGIT NO.
2000
START PRINT AT I = (A 4 DIGIT NO.
0001
INPUT,VELOCITY TOLERANCE BAND, PLUS & MINUS MPH
2.5
INPUT,NOTCH CHANGE
2
INPUT,ACCELERATION WINDOW,SECONDS
10.0
IN-BAND MULTIPLICATION FACTOR
5.0
ENTER OPERATIONAL SPEED LIMIT,MPH
25.0
INPUT CUTOFF, ENTER A 4 DIGIT NO.
1000
INPUT,STD. DEVIATION
300.0
INPUT,MEAN
0.0
DATA PRINT OPTION, TYPE 1 FOR YES, 0 FOR NO


0
$
  INPUT A 9 DIGIT, ODD NUMBER FOR SEED
999999999
```

FIGURE A-1
PROGRAM INPUTS

2.2.1 Data File Inputs

The operator first specifies a train file number. No changes have been made in the train file from the format reported in Volume I (1), but a typical train file is repeated here in Figure A-2. The first column lists reference numbers. The second column describes the vehicle type by means of numbers; each number designates a line of data in another file corresponding to the vehicle type; this file is discussed subsequently. The third column lists the net load on each vehicle in tons.

The operator next specifies an order file number. For ordering the train in the sequence specified in the train file, the order file used is simply a listing of consecutive numbers the length of which equals the number of vehicles in the train. If a different order for the same train is desired, the same numbers are rearranged in a different order. Thus if it is desired to place in the number 4 position the vehicle which in the train file is in the number 32 position, in the new order file the number 32 is placed in the fourth row, and so on. The reader is referred to Volume I (1) for a more thorough discussion of these considerations.

The operator next specifies the file number identifying the track over which the simulated trip will be made. Some considerations with regard to track data are worth mentioning, as this subject was not discussed in Volume I (1), and track records may not necessarily be formatted in an identical fashion from user to user. As an example, the speed limit information for the tracks utilized in this report had to be manually interspersed among the other track data in order for it to be in an acceptable format, as such information had been separately listed previously. See Figure A-3 as an example of original track data and a sample of how the information was reformatted for use herein.

FILE: TRAIN1 DATA

101	1	0.0
102	1	0.0
103	1	0.0
104	14	61.5
105	3	61.5
106	3	0.0
107	3	61.5
108	3	0.0
109	16	0.0
110	3	0.0
111	4	61.5
112	16	0.0
113	3	61.5
114	2	0.0
115	3	0.0
116	2	0.0
117	2	61.5
118	2	61.5
119	2	0.0
120	3	61.5
121	4	0.0
122	4	61.5
123	3	61.5
124	2	0.0
125	3	0.0
126	2	61.5
127	16	61.5
128	4	0.0
129	4	61.5
130	2	0.0
131	3	61.5
132	5	0.0
133	16	0.0
134	3	0.0
135	2	0.0
136	2	0.0
137	3	61.5
138	2	0.0
139	2	61.5
140	2	61.5
141	2	61.5
142	14	61.5
143	2	0.0
144	2	0.0
145	5	0.0
146	14	61.5
147	3	61.5
148	3	0.0
149	3	0.0
150	3	0.0
151	3	61.5
152	3	61.5
153	3	0.0
154	16	61.5
155	2	61.5
156	2	61.5
157	2	61.5
158	3	0.0
159	2	0.0
160	3	0.0
161	2	61.5
162	4	0.0
163	3	61.5
164	16	0.0
165	16	61.5
166	4	0.0
167	3	61.5
168	2	0.0
169	2	61.5
170	5	61.5
171	17	0.0

FIGURE A-2
TYPICAL TRAIN FILE

	Milepost	Grade	G.E.C.
	4.30	-0.18	0.00
	4.70	.06	.00
	6.65	- .02	.06
	8.55	.16	.00
MP 10	9.30	.16	.00
	11.05	- .08	.00
	13.70	.22	.03
	17.20	- .08	.11
	18.15	.28	.09
MP 20	19.30	.28	.09
	19.90	.50	.06
	22.95	.48	.11
	27.35	.00	.04
MP 30	29.30	- .44	.04
	30.60	.32	.04
	33.10	.18	.00
	35.60	- .34	.00
MP 40	39.30	- .34	.00
	39.80	.02	.00
	42.70	.40	.00

Speed Limit	Milepost
20.	4.30
65.00	6.70
79.00	7.00
75.00	14.00
80.00	25.20
70.00	28.10
60.00	30.40
80.00	31.60
70.00	39.50

FIGURE A-3(a)
ORIGINAL TRACK DATA

FILE: TRACK21 DATA A

	Milepost	Grade	G.E.C.	Speed Limit
101	0.00	-.18	.00	10.0
102	0.40	.06	.00	20.0
103	2.35	-.02	.06	40.0
104	2.40	-.02	.06	65.0
105	2.70	-.02	.06	79.0
106	4.25	.16	.00	79.0
107	5.00	.16	.00	79.0
108	6.75	-.08	.00	79.0
109	9.40	.22	.03	79.0
110	9.70	.22	.03	75.0
111	12.90	-.08	.11	75.0
112	13.85	.28	.09	75.0
113	15.00	.28	.09	75.0
114	15.60	.50	.06	75.0
115	18.65	.48	.11	75.0
116	20.90	.48	.11	80.0
117	23.05	.00	.04	80.0
118	23.80	.00	.04	70.0
119	25.00	-.44	.04	70.0
120	26.10	-.44	.04	60.0

FIGURE A-3(b)
REFORMATTED TRACK DATA

In general, mileposts must be in numerical sequence, from the first at 0.0 miles to the final one at the destination where the final speed limit will be zero. No provision is made in the program for a simulated run in the opposite direction. This can be performed, however, by providing a second track file with the data appropriately modified for operation in the reverse direction. A short program which will perform this operation on track files formatted for use with the fuel calculation program is given in Appendix C. It also lists a short program which computes the rise in elevation between end points of the track file according to the data therein.

In addition, track records which include a zero speed limit, apparently to indicate a required stop, must be examined to ensure that the milepost following the one indicating zero speed is different from the previous; the program cannot accommodate the same milepost having different data associated with it, as happened to be the case in many track records examined during the development of the program. Track records used to generate the data reported herein have been consistently modified at such points to introduce an additional milepost 0.1 miles further along the track with the speed limit of the next track record. This permits the logic of the program, after a simulated stop has been made, to perceive a new requirement for speed even if the train happens to be stopped in the tenth of a mile where the speed limit is zero. Otherwise, the program would not permit the train to proceed.

In addition, certain liberties have been taken with regard to the speed limits in track sections adjacent to the origin and destination and around required stops. The adjacent section has been limited to 10 mph, the next to 20 mph, and the next to 40 mph if the track record itself did not impose such limitations. This has been done to bring the train to a halt more smoothly than would be the case if it were suddenly required to decelerate from 60 mph in a short distance. See Figure A-4 which shows a portion of the original track record and the

	92.45	-.06	.00
	96.05	-.20	.00
	97.50	-.10	.00
	98.95	-.40	.00
MP 100	99.30	-.40	.00
	100.35	-.12	.00
	103.55	.06	.00
	105.95	.16	.00
MP 110	109.30	.16	.00
	112.00	.08	.00
	114.60	.09	.00
MP 120	121.00	.09	.00
	122.05	.04	.00
	125.15	0.10	0.01
	129.29	0.09	0.00
	133.20	0.38	0.01
	134.05	0.09	0.00

Original Track Record near Station Stop

168	96.05	-.12	.00	65.0	
169	97.30	-.12	.00	80.0	
170	99.25	.06	.00	80.0	
171	101.65	.16	.00	40.0	
172	105.00	.16	.00	20.0	
173	106.70	.16	.00	10.0	
174	107.70	.08	.00	0.0	station stop
175	107.80	.09	.00	10.0	
176	110.30	.09	.00	20.0	
177	116.70	.09	.00	40.0	
178	117.75	.04	.00	80.0	
179	120.85	.10	.01	40.0	

Modified Track Record

Note: All mileposts in modified track record have been reduced by 4.3 miles.

FIGURE A-4
REFORMATTING OF TRACK RECORD NEAR STOP

associated speed limits and the corresponding portion of the track record modified to accommodate the needs of the program and actually used therein.

2.2.2 Numerical Inputs

The next inputs require only numbers to be entered by the operator. The number of locomotives is presently limited by format to nine or less. This could easily be modified. The number of vehicles in the train must be specified with a three-digit number and must correspond to the number in the train file being used. Similarly, the number of track records is specified by a four-digit number which must correspond to the number of track records in the file specified.

Because of the non-linear nature of the train resistance equations, it is necessary to perform the calculation of fuel consumption in small steps, each corresponding to a period during which the velocity changes only by a small increment. The selection of the time interval, in seconds, is left to the program operator. In order to avoid performing repetitious calculations when the velocity is approximately constant, the time interval is modified by the program during such periods if certain requirements are met. The fuel consumption calculations are sensitive to this choice of interval, and the implications are discussed in the section dealing with sensitivity and calibration.

The number of intervals which may be calculated is presently limited by dimension statements to 2000. From examination of various track records and program runs, then appears to be on the average one track record per mile or less, and the program averages around six or seven calculations per track record. Hence the program is presently limited to runs of 250 miles or less with about the same number of track records. This limitation was compatible with the needs of the runs for this report, but the program could readily be modified to expand its capability, at the cost of incurring additional computer charges when run. Since the program is set up to cease calculation after the train has arrived at its destination, no excessive computations are made by specifying the full 2000 intervals, but fewer may be specified if only early portions of the output are of interest.

Similarly, if only the latter portions of the trip are of interest, printing of the output may begin not at the origin, but after a certain number of iterations of the loop specified by the operator.

The next four inputs are discussed in detail in the section on sensitivity and calibration, as the values inserted will affect the resulting value of fuel consumption to a limited degree. The velocity tolerance band and the notch change instruction are restrictions upon the simulated engineer, but the acceleration window and multiplication factor are parameters internal to the program whose values are completely arbitrary. The choice of values was left open during the period of development of the program and could easily be standardized at this time. All of the results in this report were run using constant values for all four of these variables, the values shown in Figure A-1.

The cutoff value is related to a random stop algorithm designed into the program. The probability of making a stop at any given iteration of the "DO" loop is specified by this parameter, and is equal to (1000-inserted value)/2000. Specifying 1000 ensures that no random stops (intended to simulate unforeseen stops of any nature) will be incurred at all. The results in this report were all run with zero probability of random stopping.

The standard deviation specifies the standard deviation of a Poisson probability density function generated by the program describing the probable length of any intermediate stop made during the trip. If the decision is made (as above) to stop, the length of the stop is determined from this function. The choice of a Poisson function was made arbitrarily but it seemed to reflect reality more than other choices might have. The units are seconds, so that a value of 300 specifies that the most probable length of stop is three hundred seconds or five minutes. In the case of predetermined stops, the program is directed to make them of the same length as the standard deviation specified. The algorithm corresponding to the Poisson function utilizes a built-in subroutine for generating random numbers with a uniform probability density function. The Poisson distribution is approximated by a specially devised subroutine.

The mean is the mean value of the uniform probability density function above. It should be set at zero for the purposes of this program.

The data print option allows the program operator to avoid printing the value of all the variables for every iteration of the loop. If a "0" is selected, the program only prints the program inputs; the net and gross weights of the train and the final values for total fuel consumption; average fuel consumption rate; and average velocity for the trip. Before the last three items are printed, the program prints, as a check, the number of iterations, the final track record number, the distance travelled, and the cumulative time. If any stops have been made, the program also prints the value of I, the loop index, the value of two numbers used to generate the length of stop, the length of the stop, and the cumulative time in seconds spent idling the engines at stops.

2.2.3 Auxiliary Data File

Although not a specific input to the program, an auxiliary data file is required to be available to be read automatically by the program. This file (reproduced in its present size and form in Figure A-5) lists dimensional, aerodynamic, and weight data for various types of railroad equipment pertinent to the calculations in the program. The table of data is explained in detail in Volume I (1), and alterations

120.0	110.0	90.0	45.0	10.0	122.0
10.0	122.0	78.0	10.0	78.0	124.0
150.0	110.0	135.0	74.0	110.0	10.0
120.0	110.0	90.0	45.0	10.0	10.0
122.0	122.0	10.0	78.0	78.0	124.0
150.0	110.0	135.0	74.0	130.0	10.0
3.0	2.0	1.5	2.0	2.0	3.0
45.0	3.0	3.0	45.0	3.0	11.5
2.0	20.0	3.0	3.0	5.0	2.0
2.0	2.0	1.5	2.0	2.0	45.0
3.0	3.0	45.0	3.0	3.0	11.5
2.0	20.0	3.0	3.0	5.0	2.0
80.6	73.8	60.5	30.2	6.7	37.9
37.9	37.9	34.6	34.6	34.6	31.7
137.6	73.8	90.6	49.6	73.9	6.7
20.2	18.4	15.1	7.6	1.7	9.5
9.5	9.5	8.6	8.6	8.6	7.9
34.4	18.4	22.6	12.4	18.5	1.7
.0085	.0085	.0085	.0085	.0085	.0085
.0085	.0085	.0085	.0085	.0085	.0085
.018	.0085	.0085	.0085	.0085	.0085
34.0	32.0	28.0	19.0	12.0	25.0
25.0	38.0	20.0	20.0	28.0	29.0
40.0	22.0	37.0	30.0	32.0	12.0
62.0	50.0	45.0	54.0	60.0	85.0
85.0	85.0	85.0	85.0	85.0	60.0
85.0	60.0	88.0	60.0	40.0	85.0
368000.	60700.0	59600.0	68900.0	79500.0	76200.0
76200.0	76200.0	76200.0	76200.0	76200.0	51500.0
76200.0	79500.0	119200.0	77600.0	56600.0	76200.0

FIGURE A-5
AUXILIARY DATA FILE

and additions to the table should be made in conjunction with the methodology set forth in that volume. Additions beyond the present eighteen vehicle types would require format changes within the program.

2.3 Program Outputs

The program generates the value of fourteen variables during each iteration of the loop. These are printed with the corresponding value of the loop index "I" if the option "1" has been selected. The variables are as follows, in the order of printing across the page (see Figure A-6 for a typical data output; all values are the prevailing values for the particular iteration of the loop unless specified as cumulative):

I	The loop index
TE(I)	Tractive effort, lbs.
U	An indicator of throttle or braking effort (see following section)
TR(I)	Train resistance (dissipative), lbs.
VDD(I)	Acceleration, mph ps
V(I)	Velocity, mph
J	Track Record No.
DS(I)	Distance, miles
DT	Time interval, seconds
S(I)	Cumulative distance, miles
DFC(I)	Fuel consumption, gallons
CFC	Cumulative fuel consumption, gallons
CDT	Cumulative time, seconds
RFC(I)	Rate of fuel consumption (all locomotives combined), gallons/min.
CRFC	Cumulative rate of fuel consumption (for entire distance travelled), gallons/min.

The values of all variables are of some interest, even though the primary variables of interest are the instantaneous fuel rate and the fuel consumption. Some of these values are used as inputs to a plotting

```
FILE: FTFC8    CUTPUT    C                        CONVERSATIONAL MONITCR SYSTEM

 MORE TRACTIVE EFFORT NEEDED
 403  15.28E+04 17  50.50E+03  21.49E-02  21.45E+00   53  56.60E-03  10.00E+00
      67.23E+00     14.88E-01  32.94E+01                             10.05E+03
                    89.29E-01  19.67E-01


     394     688
 MORE TRACTIVE EFFORT NEEDED
 404  13.83E+04 17  51.15E+03  18.32E-02  23.28E+00   53  62.13E-03  10.00E+00
      67.29E+00     14.79E-01  33.09E+01                             10.06E+03
                    88.74E-01  19.74E-01


     577     275
 405  80.79E+03 15  51.51E+03  61.43E-03  23.59E+00   53  32.55E-03  50.00E-01
      67.32E+00     45.19E-02  33.13E+01                             10.06E+03
                    54.23E-01  19.75E-01


     463     300
 406  60.49E+03 14  51.60E+03  18.69E-03  23.78E+00   53  65.79E-03  10.00E+00
      67.39E+00     68.38E-02  33.20E+01                             10.07E+03
                    41.03E-01  19.77E-01


     638     130
 407  60.04E+03 14  51.89E+03  18.69E-03  25.21E+00   53  52.30E-02  76.85E+00
      67.91E+00     54.61E-01  33.75E+01                             10.15E+03
                    42.64E-01  19.95E-01
```

FIGURE A-6
TYPICAL DATA OUTPUT

routine, described in the main body of the text, which plots the velocity and the instantaneous fuel consumption rate as functions of time.

2.4 Acceleration and Braking Considerations

During the development of the computer program, several simplifying assumptions have been made on the basis that this is a fuel consumption calculation rather than a train performance simulator. To simulate every action of the train is not intended. Hence, some details of operating the braking system or throttle which could possibly affect the overall fuel consumption have been omitted in the interest of simplicity.

2.4.1 Speed Control

This section describes the rationale behind the various algorithms which prescribe the throttle notch setting or braking effort, or changes thereto. Since in the program diminishing the braking effort is logically equivalent to increasing the tractive effort, much of the discussion below is applicable to time intervals during which the brakes are being applied, as well as time intervals when the acceleration is positive or negative, with tractive effort being applied.

The fundamental rationale governing the selection of throttle position or braking effort in the program is that the selection is made upon observation of the velocity of the train and the desired velocity. The latter is normally the track speed limit but is subject to a limitation imposed by the program operator, who specifies the maximum desired velocity for the trip. The program effectively simulates a Type I velocity control loop.

A comparison is made and the tractive or braking effort is adjusted in a manner designed to move the train velocity into an acceptable band about the desired velocity. The adjustment takes place in a certain time interval dt selected by the program operator. Normally ten seconds is selected as reflecting the shortest time in which the engineer could be expected to check the train velocity and adjust the throttle on a continuous basis for an indefinite period. Under certain circumstances the time interval dt is halved to increase the rapidity of response.

No anticipation is designed into the program, and velocity errors (deviations from the speed limit) are required to produce a change in tractive or braking effort. Although this rationale may not be completely realistic, failure to include anticipation was felt not to affect fuel consumption sufficiently during the transient operations where its absence might be noticed to justify the additional complexity involved in including it. Its absence would be noticed only during the short periods when velocity was changing.

The rapidity with which the program changes the tractive or braking effort is analogous to the gain of the control loop. The algorithms governing the changes in throttle notch position or braking effort are intended to simulate a smooth operation of the train, rather than adjust the train velocity in necessarily the most optimal fashion. Thus normally when the train velocity is observed to lie outside the permissible velocity band the notch will be adjusted only by one step until the next time interval. Under certain limited circumstances, the notch is adjusted by a larger value selected by the operator. The algorithm governing this adjustment was inserted, like the halving of the time interval, to quicken the response.

Tractive and braking efforts are established by the program to correspond with a range of values for a parameter "U" of 1 through 17, inclusive. Values 1 through 8 correspond to levels of braking, ranging from 100 percent of maximum braking effort to 12.5 percent in even increments. A value of 9 corresponds to coasting, with neither tractive nor braking effort. Values from 10 to 17 correspond to the eight throttle notch positions at which various increased levels of tractive effort are applied.

The value of "U" is adjusted in accordance with the following rationale. The program attempts to calculate the velocity V(I) for the Ith iteration of the loop. It is first determined whether the previous velocity V(I-1) is within the permissible band or not. The following paragraphs discuss the subsequent decision process.

2.4.1.1 Within Band

If the previous velocity is within the band, the program examines the previous acceleration. If its absolute value is small enough, so that if it remains constant the velocity will not break out of the tolerance band within a predetermined time, as selected by the program operator, and conditions on the track ahead are identical to the ones in the previous interval, the acceleration and tractive efforts are held the same. The length of the next time interval is extended to the time when the velocity breaks out of the permissible band, or when new track conditions are encountered. This saves computer time so that the frequency of computation is highest when the velocity is changing most rapidly and lowest when the velocity is nearly constant.

Otherwise, the program examines the velocity two time intervals earlier, V(I-2), in order to determine in what fashion the velocity entered the band. It also examines the previous acceleration VDD(I-1). If V(I-2) had been out of band, the parameter "U" is adjusted in the appropriate direction by a value equal to NC, a parameter specified at the beginning of the program. A value of 2 appears to give performance that is adequately smooth without sacrificing rapidity of velocity correction. If V(I-2) had been in band also, the value of "U" is only adjusted by one.

2.4.1.2 Out of Band

An analogous adjustment of "U" occurs when the previous velocity V(I-1) was out of band, although the logic is somewhat different. The program determines whether V(I-1) was above or below band and whether the previous acceleration VDD(I-1) was positive or negative. The intent is again to return the velocity to within the band. If the sense of the previous acceleration was to increase the velocity error, the parameter "U" is adjusted by the value NC (see above discussion); if not, "U" is adjusted tentatively by a value of 1. With the tentative tractive or braking effort determined, a tentative acceleration is checked to determine if the velocity will return within band within a time period selected by the program operator. This is known as the acceleration "window." If the tentative acceleration lies within this window the value of "U" is not adjusted further. If it does not, the value of "U" is adjusted an additional unit and new values for the acceleration, tractive or braking effort, and other variables are calculated. The direction of adjustment is such as to drive the velocity more quickly into the permissible band. In all cases tractive effort is adhesion limited. Braking effort has been appropriately limited in advance so that wheel slip during braking will not occur.

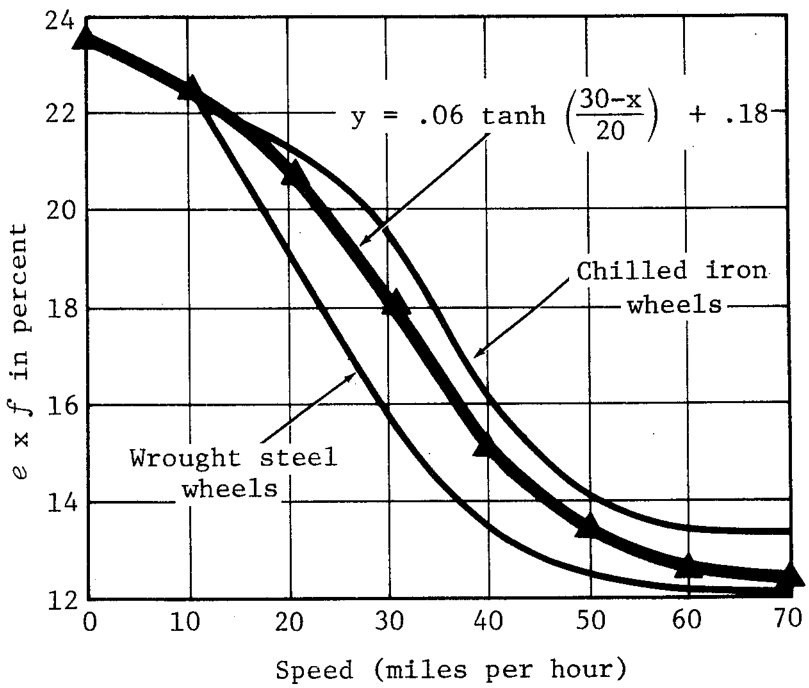
2.4.2 Braking System Operation

With regard to operation of the braking system, time delays have been ignored, and it is assumed that the restraining effect required by the algorithm takes place instantaneously and uniformly over the train length. A second assumption is that degrees of braking, varying uniformly from 0 percent to 100% of full braking, in discrete steps analogous to throttle positions, are applied. This assumption was made in order to make the program logic designed to adjust throttle position equally applicable to braking. This appears to differ from true braking in several respects. There appears to be a distinct minimum brake pressure above which pressure can be varied with infinite smoothness.[(4)] Thus, a minimum braking effort of about 6 psi would be required, or about 25% of full effort. A simulation of this was tried at first, but seemed to result in excessive jerkiness of train motion when the first level of braking was applied. This was subsequently abandoned and after some discussion with railroad personnel which revealed that the experienced engineer can control the deceleration rate of his train very effectively by sending "bubbles" of air down the train, the simulation was designed to provide eight levels of braking at .125, .25, .375, .5, .625, .75, .875, and 1.0 portions of full braking.

While it is recognized that this does not precisely duplicate actual braking operation, the difference in fuel consumption attributable to the small difference in simulation during the short periods when brakes will be applied is believed to be of second order magnitude.

A further consideration with regard to braking is the approximation of braking friction as a function of speed. Following the discussion in Hay [15] the cars have been braked at 60% of light weight (66,000 lbs.) and locomotives at 90%. Maximum braking is then between .18 and .24 of this value, depending upon velocity. A hyperbolic tangent curve has been used to approximate an average curve falling between the curves given for the friction factor as a function of velocity for chilled iron wheels and wrought steel wheels. See Figure A-7.

If the program logic calls for more braking than is available, the message "Inadequate Brakes" is received. As a final precautionary measure, execution of the program is halted if the train velocity exceeds 90 mph and the acceleration is positive.



Values of e x f at various speeds for chilled iron and wrought steel wheels.

(Original curves from Hay (15))

FIGURE A-7
BRAKING CURVE APPROXIMATION

3.0 PROGRAM LISTING

The program is listed in Figure A-8. Although the program seems long, it is not formidable. The resistance of the train is calculated by the methodology developed earlier and reported in Volume I (1). The program developed at that time for that purpose was incorporated with appropriate modifications directly into a second program, developed under a later phase of the same task, designed to calculate fuel consumption. For that reason, only a cursory description is given to those lines extracted from the original program. The reader is referred to Volume I for the explanation of and the method behind the train resistance calculation.

Lines 10-180

These lines list requirements for computer storage space for variables used in the program and define real and integer variables.

Lines 190-300

These lines initialize certain variables to zero and define certain constraints used in the program.

Lines 310-320

These lines read the data from the data file describing the characteristics of railroad rolling stock.

Lines 330-1200

These lines request the inputs to the program and direct the information to the appropriate places.

Lines 1210-1930

These lines essentially repeat the program previously developed for computing train resistance.

```
      DIMENSION V(2000),TE(2000),VDD(2000),DV(2000),MV(2000),
     1 TRACK(500,4)
      DIMENSION DS(2000),S(2000),TR(2000),DFC(2000),TEH(2000),
     1 TEL(2000),RR(2000)
      DIMENSION VAR(2000),RC(2000),RL(2000),RFC(2000),R(2000)
      DIMENSION NUM(2),N1(12),N2(12)
      DIMENSION A(200),B(200),FF(200),FA(200)
      DIMENSION CAA(200),CBB(200),CC(200),DD(200),UC(200)
      DIMENSION D(200),E(200),F(200),G(200)
      DIMENSION GA(200),GF(200),CFF(200),CFA(200),AFF(200),AFA(200)
      DIMENSION NET(200),TARE(200),GROSS(200)
      DIMENSION ARRAY(200),DATA(200,2),COEFF(18,10),ORDER(200)
      EQUIVALENCE (ARRAY,DATA)
      INTEGER ARRAY,FILE,ORDER,OPTN1
      INTEGER P,Q,FILE,U,PP,VAR,VV,PPP
      INTEGER W,X,Y,Z,CUTOFF,ZX,ZSL
      REAL MV,MF,LIMIT,N3,N4
      REAL KD,KE,KF,MN,NET,OSL
      CDT = 0.0
      CFC = 0.0
      CRFC = 0.0
      CIT=0.0
      Z = 0
      ZX = 0
      ZSL = 0
      KD = .0763*88.0**2/(32.2*60.0**2*2.0)
      KE = KD
      KF = KD
      CF = 5280.0*5.05E-7*.0644
      CF2 = 88.0*.0644/(550.0*60.0*3600.0)
      READ(4,50)((COEFF(I,J),I=1,18),J=1,10)
   50 FORMAT(6F11.4)
      WRITE(6,12)
      WRITE(7,12)
   12 FORMAT(1X,' INPUT, NO. OF LOCOMOTIVES, ENTER A 1 DIGIT NO.')
      READ(5,13)NL
      WRITE(7,13)NL
   13 FORMAT(I1)
      WRITE(6,14)
      WRITE(7,14)
   14 FORMAT(1X,' INPUT,NO. OF VEHICLES IN TRAIN, (INCL. LOCOMOTIVES),
     1 ENTER A 3 DIGIT NO.')
      READ(5,33)NV
      WRITE(7,33)NV
   33 FORMAT(I3)
      READ (1,51) ((DATA(N,L),L=1,2),N=1,NV)
   51 FORMAT (4X,I3,F6.1)
      READ (2,52)(ORDER(N),N=1,NV)
   52 FORMAT (5X,I3)
      WRITE(6,116)
      WRITE(7,116)
  116 FORMAT(1X,' INPUT, NO. OF TRACK RECORDS IN TRACK FILE,
     1 ENTER A 4 DIGIT NO.')
      READ(5,17)NTR
      WRITE(7,17)NTR
```

FIGURE A-8
PROGRAM LISTING

```
 17    FORMAT(I4)
       WRITE(6,18)
       WRITE(7,18)
 18    FORMAT(1X,' INPUT,TIME INTERVAL,SECONDS')
       READ(5,19)DT
       WRITE(7,19)DT
 19    FORMAT(F5.1)
       WRITE(6,245)
       WRITE(7,245)
 245    FORMAT(1X,' INPUT,NO. OF INTERVALS, ENTER A 4 DIGIT NO.')
       READ(5,17)NI
       WRITE(7,17)NI
       WRITE(6,22)
       WRITE(7,22)
 22    FORMAT(1X,' START PRINT AT I = (A 4 DIGIT NO.')
       READ(5,17)INDEX
       WRITE(7,17)INDEX
       WRITE(6,240)
       WRITE(7,240)
 240    FORMAT(1X,' INPUT,VELOCITY TOLERANCE BAND, PLUS & MINUS MPH')
       READ(5,250) TOL
       WRITE(7,250)TOL
 250   FORMAT(F4.1)
       WRITE(6,26)
       WRITE(7,26)
 26    FORMAT(1X,' INPUT,NOTCH CHANGE')
       READ(5,13) NC
       WRITE(7,13)NC
       WRITE(6,28)
       WRITE(7,28)
 28    FORMAT(1X,' INPUT,ACCELERATION WINDOW,SECONDS')
       READ(5,250)TIME
       WRITE(7,250)TIME
       WRITE(6,311)
       WRITE(7,311)
 311    FORMAT(1X,' IN-BAND MULTIPLICATION FACTOR')
       READ(5,250) MF
       WRITE(7,250)MF
       WRITE (6,27)
       WRITE (7,27)
  27   FORMAT (1X,' ENTER OPERATIONAL SPEED LIMIT,MPH')
       READ (5,250) OSL
       WRITE (7,250) OSL
       WRITE(6,32)
       WRITE(7,32)
 32    FORMAT(1X,' INPUT CUTOFF, ENTER A 4 DIGIT NO.')
       READ(5,17)CUTOFF
       WRITE(7,17)CUTOFF
       WRITE(6,34)
       WRITE(7,34)
 34    FORMAT(1X,' INPUT,STD. DEVIATION')
       READ(5,19)SIGMA
       WRITE(7,19)SIGMA
       WRITE(6,36)
       WRITE(7,36)
```

FIGURE A-8
PROGRAM LISTING
(CONTINUED)

```
 36   FORMAT(1X,' INPUT,MEAN')
      READ(5,250)AM
      WRITE(7,250)AM
      WRITE(6,16)
      WRITE(7,16)
 16   FORMAT(1X,'DATA PRINT OPTION, TYPE 1 FOR YES, 0 FOR NO')
      READ(5,55)OPTN1
      WRITE(7,55)OPTN1
 55   FORMAT(I1)
      WRITE(7,41)
      SUM4 = 0.0
      DO 337 K = 1,NV
 337  SUM4 = SUM4+DATA(K,2)
      WRITE(7,338)SUM4
 338  FORMAT (1X,'    NET TRAIN WEIGHT, TONS:', F10.2)
      WRITE(7,41)
      DO 341 K = 1,NV
 341  GROSS(K) = DATA(ORDER(K),2)+COEFF(ARRAY(ORDER(K)),10)/2000.0
      SUM5 = 0.0
      DO 339 K = 1,NV
 339  SUM5 = SUM5+GROSS(K)
      WT = SUM5
      WRITE(7,344)SUM5
 344  FORMAT (1X,'    GROSS TRAIN WEIGHT,TONS',F10.2)
      WRITE(7,41)
      DO 24 I = 1,NV
      IF (I.GT.1) GO TO 42
      DO 25 K = 1,NV
      NET(K) = DATA(ORDER(K),2)
      TARE(K) = COEFF(ARRAY(ORDER(K)),10)
      IF (K.LE.NL) A(K) = (NET(K)+TARE(K)/2000.0)*.6+120.0
      IF (K.GT.NL) A(K) = (NET(K)+TARE(K)/2000.0)*.6+80.0
      B(K) = .01*(NET(K)+TARE(K)/2000.0)
      IF (K.EQ.1) GO TO 37
      GF(K) = COEFF(ARRAY(ORDER(K)),3)+COEFF(ARRAY(ORDER(K-1)),4)
      GO TO 38
 37   GF(K) = 1000.0
 38   IF (K.EQ.NV) GO TO 39
      GA(K) = COEFF(ARRAY(ORDER(K)),4)+COEFF(ARRAY(ORDER(K+1)),3)
      GO TO 25
 39   GA(K) = 1000.0
 25   CONTINUE
      SUM1L = 0.0
      SUM1C = 0.0
      DO 87 M = 1,NL
 87   SUM1L = SUM1L+A(M)
      NL2 = NL+1
      DO 88 M = NL2,NV
 88   SUM1C = SUM1C+A(M)
 41   FORMAT (/)
 42   CONTINUE
      IF (I.EQ.1) CFF(I) = 1.0
      IF (I.GT.1) CFF(I) = .5*TANH(.5*(ALOG(GF(I)/10.0)-1.4))+.5
      IF (I.EQ.NV) CFA(I) = 1.0
      IF (I.LT.NV) CFA(I) = .5*TANH(1.1*(ALOG(GA(I)/10.0)-1.4))+.5
```

FIGURE A-8
PROGRAM LISTING
(CONTINUED)

```
      IF (I.EQ.1) GO TO 160
      CAA(I) = COEFF(ARRAY(ORDER(I)),1)
      CBB(I) = COEFF(ARRAY(ORDER(I-1)),2)
      IF (CAA(I)-CBB(I))251,252,252
  251 AFF(I) = 0.0
      GO TO 170
  252 AFF (I) = (CAA(I)-CBB(I))/CAA(I)
      GO TO 170
  160 AFF(I) = 1.0
  170 IF (I.EQ.NV) GO TO 140
      CC(I) = COEFF(ARRAY(ORDER(I)),2)
      DD(I) = COEFF(ARRAY(ORDER(I+1)),1)
      IF (CC(I)-DD(I)) 253,254,254
  253 AFA(I) = -4.0*EXP(-.173*GA(I))*(1.0-EXP(-.173*GA(I)))
      GO TO 402
  254 AFA(I) = (CC(I)-DD(I))/CC(I)
      GO TO 402
  140 AFA(I) = 1.0
  402 CONTINUE
      FF(I) = 1.0-(1.0-CFF(I))*(1.0-AFF(I))
      FA(I) = 1.0-(1.0-CFA(I))*(1.0-AFA(I))
      D(I) = KD*COEFF(ARRAY(ORDER(I)),5)*FF(I)
      E(I) = KE*COEFF(ARRAY(ORDER(I)),7)*COEFF(ARRAY(ORDER(I)),8)*
     1 COEFF(ARRAY(ORDER(I)),9)
      F(I) = KF*COEFF(ARRAY(ORDER(I)),6)*FA(I)
      UC(I) = 2.0*.272*16.0*KD+.003*KD*COEFF(ARRAY(ORDER(I)),9)*10.0
      G(I) = D(I)+E(I)+F(I)+UC(I)
   24 CONTINUE
      WL = (COEFF(1,10))/2000.0
      LIMIT = .23*NL*WL*2000.0
      IF (LIMIT.GT.250000.0) LIMIT = 250000.0
      READ (3,10)((TRACK(M,N),N=1,4),M=1,NTR)
   10 FORMAT (4X,3F9.2,F9.1)
      DO 79 M = 1,NTR
      IF (TRACK(M,4).GT.OSL) TRACK(M,4) = OSL
   79 CONTINUE
      DTO = DT
      CFC = 0.0
      WRITE(6,2)
      WRITE(7,2)
    2 FORMAT(1X,'  INPUT A 9 DIGIT, ODD NUMBER FOR SEED ')
      READ(5,3)IX
      WRITE(7,3)IX
    3 FORMAT(I9)
      WRITE(7,41)
      CALL RANDU(IX,IY,RN)
      IF(OPTN1.EQ.1) WRITE(7,66)RN
   66 FORMAT(3X,' RN = ',F8.6,/)
      DO 90 I = 1,NI
      DT = DTO
      P = 0
      PP = 0
      PPP = 0
      IF (I.EQ.1) GO TO 100
      GO TO 110
```

FIGURE A-8
PROGRAM LISTING
(CONTINUED)

```
100   TE(I) = NL*75000.0
      IF (TE(I).GT.LIMIT) TE(I) = LIMIT
      S(1) = 0.0
      L = 13
      U = 1
      DO 15 J = 1,20
      K = J+1
      IF (TRACK(K,1).GT.S(I)) GO TO 20
15    CONTINUE
20    J = K-1
      VAR(I) = J
      VDD(I) = (TE(I)-(SUMIL+SUMIC+20.0*WT*TRACK(J,3)+20.0*WT*TRACK
     1 (J,2)))/(100.0*WT)
      DV(I) = VDD(I)*DT
      V(I) = DV(I)
      MV(I) = V(I)/2.0
      DS(I) = V(I)*DT/(2.0*3600.0)
      S(I) = DS(I)
      RFC(I) = TE(I)*MV(I)*CF2*60.0
      CRFC = RFC(I)
      IF ((V(I).GT.90.0).AND.(VDD(I).GT.0.0)) GO TO 620
      GO TO 135
110   Q = K-1
      IF (Z.NE.0) GO TO 726
      DO 725 W = 1,2
      CALL RANDU(IY,IY,RN)
      BASE = 1000.0*RN
      NUM(W) = BASE+1.0
725   CONTINUE
      IF (I.GE.INDEX.AND.OPTN1.EQ.1) WRITE(7,67)NUM(1),NUM(2)
67    FORMAT(2X,2(3X,I4))
726   CONTINUE
      DO 30 J = Q,NTR
      K = J+1
      IF (TRACK(K,1).GT.S(I-1)) GO TO 40
30    CONTINUE
40    J = K-1
      VAR(I) = J
      VV = VAR(I-1)
      IF (I.GT.1.AND.J.NE.NTR.AND.V(I-1).EQ.0.0.AND.TRACK(J,4).EQ.0.0)
     1 TRACK(J,4) = TRACK((J+1),4)
      IF (ZSL.EQ.1) GO TO 700
      IF (TRACK(J,4).EQ.0.0.AND.Z.NE.2) ZSL = 1
      IF (TRACK(J,4).EQ.0.0.AND.Z.NE.2) GO TO 700
      DIF = (V(I-1)-TRACK(J,4))
      IF(ABS(ABS(DIF)-TOL).LE.1.0E-3)DIF=TOL
      IF (ABS(DIF).LT.TOL.AND.J.EQ.NTR) GO TO 95
      IF (NUM(1).GT.CUTOFF.AND.Z.NE.2) GO TO 700
      IF (Z.EQ.2) GO TO 750
      IF (ABS(DIF).LT.TOL) GO TO 300
      IF (ABS(DIF).GE.TOL) GO TO 400
300   IF (I.EQ.2) GO TO 302
      GO TO 304
302   DIF2 = -TRACK(J,4)
      GO TO 301
```

FIGURE A-8
PROGRAM LISTING
(CONTINUED)

```
 304  IF (ABS(VDD(I-1)).LE.TOL/(MF*DT)) GO TO 351
      GO TO 303
 351  IF (TRACK(VV,2).EQ.TRACK(J,2).AND.TRACK(VV,3).EQ.TRACK(J,3)
     1 .AND.TRACK(VV,4).EQ.TRACK(J,4)) GO TO 352
 303  DIF2 = V(I-2)-TRACK(J,4)
 301  IF (VDD(I-1).GT.0.0.AND.ABS(DIF2).GT.TOL) P = 3
      IF (VDD(I-1).GT.0.0.AND.ABS(DIF2).LE.TOL) P = 2
      IF (VDD(I-1).EQ.0.0) GO TO 305
      IF (VDD(I-1).LT.0.0.AND.ABS(DIF2).LE.TOL) P = 4
      IF (VDD(I-1).LT.0.0.AND.ABS(DIF2).GT.TOL) P = 5
      GO TO 900
 400  IF (V(I-1)-TRACK(J,4)) 600,600,500
 600  IF(VDD(I-1).GE.0.0) P = 1
      PPP = 1
      IF (VDD(I-1).LT.0.0) P = 5
      GO TO 900
 500  IF (VDD(I-1) .GE.0.0) P = 3
      IF (VDD(I-1).LT.0.0) P = 1
      PPP = 2
 900  IF (P.EQ.2) L = L-1
      IF (P.EQ.3) L = L-NC
      IF (P.EQ.4) L = L+1
      IF (P.EQ.5) L = L+NC
      PP = 1
      GO TO 930
 910  IF (PPP.EQ.1.AND.VDD(I).GE.0.0.AND.ABS(DIF/VDD(I)).LT.TIME)
     1 GO TO 120
      IF (PPP.EQ.2.AND.VDD(I).LT.0.0.AND.ABS(DIF/VDD(I)).LT.TIME)
     1  GO TO 120
 920  IF (PPP.EQ.1) L = L+1
      IF (PPP.EQ.2) L = L-1
 305  PP = 2
 930  U = L
      IF (U.LE.0) GO TO 320
      IF (U.GT.17) GO TO 330
      GO TO 310
 320  IF(OPTN1.EQ.1) WRITE(7,322)
 322  FORMAT(1X,' INADEQUATE BRAKES')
      U = 1
      L = 1
      PPP = 3
      GO TO 310
 330  IF (I.LT.INDEX) GO TO 367
      IF(OPTN1.EQ.1)WRITE(7,340)
 340  FORMAT(1X,' MORE TRACTIVE EFFORT NEEDED')
 367  U = 17
      L = 17
      PPP = 3
      GO TO 310
 700  Z = 1
      L = L-NC
      IF (L.LE.0) L = 1
      U = L
 310  BETA = (30.0-V(I-1))/20.0
      FRF = .06*(EXP(BETA)-EXP(-BETA))/(EXP(BETA)+EXP(-BETA))+.18
```

FIGURE A-8
PROGRAM LISTING
(CONTINUED)

```
      BFC = (NV-NL)*.60*66000.0*FRF
      BFL = NL*.90*WL*2000.0*FRF
      FB = BFC+BFL
  313 GO TO (201,202,203,204,205,206,207,208,209,210,
     1 211,212,213,214,215,216,217), U
  201 TE(I) = -1.0*FB
      GO TO 225
  202 TE(I) = -.875*FB
      GO TO 225
  203 TE(I) = -.750*FB
      GO TO 225
  204 TE(I) = -.625*FB
      GO TO 225
  205 TE(I) = -.500*FB
      GO TO 225
  206 TE(I) = -.375*FB
      GO TO 225
  207 TE(I) = -.250*FB
      GO TO 225
  208 TE(I) = -.125*FB
      GO TO 225
  209 TE(I) = 0.0
      GO TO 225
  210 TEH(I) = NL*12500.0/(V(I-1)-5.0)
      TEL(I) = NL*(-950.0*V(I-1)+12000.0)
      GO TO 218
  211 TEH(I) = NL*63158.0/(V(I-1)-5.2632)
      TEL(I) = NL*(-2700.0*V(I-1)+39000.0)
      GO TO 218
  212 TEH(I) = NL*233333.0/(V(I-1)+1.1111)
      TEL(I) = NL*(-3400.0*V(I-1)+55000.0)
      GO TO 218
  213 TEH(I) = NL*335238.0/(V(I-1)+.4762)
      TEL(I) = NL*(-4300.0*V(I-1)+75000.0)
      GO TO 218
  214 TEH(I) = NL*496556.0/(V(I-1)+1.0345)
      TEL(I) = NL*(-4900.0*V(I-1)+94000.0)
      GO TO 218
  215 TEH(I) = NL*640500.0/(V(I-1)+.500)
      TEL(I) = NL*(-6400.0*V(I-1)+125000.0)
      GO TO 218
  216 TEH(I) = NL*933332.0/(V(I-1)+1.1111)
      TEL(I) = NL*(-6100.0*V(I-1)+145000.0)
      GO TO 218
  217 TEH(I) = NL*1047227.0/(V(I-1)+1.2605)
      TEL(I) = NL*(-8600.0*V(I-1)+179000.0)
      GO TO 218
  218 IF (V(I-1)-10.0) 219,219,220
  219 TE(I) = TEL(I)
      GO TO 221
  220 TE(I) = TEH(I)
  221 IF (TE(I)) 225,225,224
  224 IF (TE(I).GT.LIMIT) GO TO 230
      GO TO 225
  230 IF (I.LT.INDEX) GO TO 368
```

FIGURE A-8
PROGRAM LISTING
(CONTINUED)

```
      IF(OPTN1.EQ.1) WRITE(7,68)
 68   FORMAT(1X,' ADHESION LIMITED')
 368  U = U-1
      L = U
      PP = 2
      IF (U.LT.1) U = 1
      GO TO 313
 225  IF(ZX.EQ.1)GO TO 805
 237  CR = 0.0
      DO 226 X = 1,NV
      CR = CR+A(X)+B(X)*V(I-1)+G(X)*V(I-1)**2
 226  CONTINUE
      R(I) = CR
      TR(I) = R(I)+20.0*WT*TRACK(J,3)+20.0*WT*TRACK(J,2)
      VDD(I) = (TE(I)-TR(I))/(100.0*WT)
      IF(ABS(VDD(I))-1.0E-3) 790,791,791
 790  IF (VDD(I)) 792,793,793
 792  VDD(I) = -1.0E-3
      GO TO 791
 793  VDD(I) = 1.0E-3
      GO TO 791
 791  IF((P.EQ.1).AND.(PP.EQ.1)) GO TO 910
      IF (ABS(VDD(I)).LE.1.0E-2.AND.U.EQ.17) GO TO 799
 120  IF ((P.EQ.3.OR.P.EQ.5).AND.PPP.NE.3) DT = DT/2.0
      IF (Z.EQ.1) DT = DT/2.0
      DV(I) = VDD(I)*DT
      V(I) = V(I-1)+DV(I)
      IF (V(I).LT.0.0) V(I) = 0.0
      IF (Z.EQ.1.AND.V(I).EQ.0) GO TO 730
      GO TO 800
 730  DT = -V(I-1)/VDD(I-1)
      Z = 2
      IF (ZSL.EQ.1) ZSL = 2
      GO TO 800
 352  VDD(I) = VDD(I-1)
      DST = TRACK((J+1),1)-S(I-1)
      DSC = V(I-1)**2+2.0*VDD(I)*DST*3600.0
      IF(VDD(I)) 353,354,355
 353  DT1 = -(TOL+DIF)/VDD(I)
      IF (DSC) 356,357,357
 356  DT = DT1
      GO TO 804
 357  DT2 = (-V(I-1)+SQRT(DSC))/VDD(I)
      GO TO 358
 355  DT1 = (TOL-DIF)/VDD(I)
      DT2 = (-V(I-1)+SQRT(DSC))/VDD(I)
      GO TO 358
 354  TE(I) = TE(I-1)
      V(I) = V(I-1)
      DS(I) = TRACK((J+1),1)-S(I-1)
      DT = (DS(I)/V(I))*3600.0
      MV(I) = V(I)
      GO TO 810
 358  IF (DT1-DT2) 359,361,361
 359  DT = DT1
```

FIGURE A-8
PROGRAM LISTING
(CONTINUED)

```
      GO TO 804
 361  DT = DT2
      GO TO 804
 804  ZX=1
      GO TO 313
 805  DV(I) = VDD(I)*DT
      ZX=0
      V(I) = V(I-1)+DV(I)
      GO TO 800
 750  IF (ZSL.EQ.2) GO TO 756
      N3 = 0.0
      N4 = 0.0
      DO 751 X = 1,12
      CALL RANDU(IY,IY,RN)
      BASE1 = 100.0*RN
      N1(X) = BASE1+1.0
 751  CONTINUE
      IF (I.GE.INDEX) WRITE(7,69)X,N1(X)
      DO 752 Y = 1,12
      CALL RANDU(IY,IY,RN)
      BASE2 = 100.0*RN
      N2(Y) = BASE2+1.0
 752  CONTINUE
      IF(I.GE.INDEX) WRITE (6,770)Y,N2(Y)
      DO 753 Z = 1,12
      N3 = N3+.01*N1(Z)
 753  N4 = N4+.01*N2(Z)
      WRITE(7,69)N3,N4
 69   FORMAT(6X,'N3 = ',F6.3,5X,'N4 = ',F6.3,/)
 770  FORMAT (  1H ,2X,I2,5X,I3)
      G1 = (N3-6.0)*SIGMA+AM
      G2 = (N4-6.0)*SIGMA+AM
      DT = SQRT(G1**2+G2**2)
 756  IF (ZSL.EQ.2) DT = SIGMA
      CIT = CIT+DT
      WRITE(7,71)I,G1,G2,DT,CIT
 71   FORMAT(1X,5(3X,F6.1))
      DFC(I) = NL*DT*5.5/3600.0
      Z = 0
      ZSL = 0
      L = 13
      S(I) = S(I-1)
      GO TO 754
 799  V(I) = V(I-1)
      DT = 3600.0*(TRACK((J+1),1)-S(I-1))/V(I-1)
      DV(I) = VDD(I)*DT
 800  MV(I) = (V(I)+V(I-1))/2.0
      DS(I) = MV(I)*DT/3600.0
 810  S(I) = S(I-1)+DS(I)
      IF (TRACK((J+1),1)-S(I).LE.1.0E-3.AND.J.NE.NTR)
     1 S(I) = TRACK((J+1),1)
      IF ((V(I).GT.90.0).AND.(VDD(I).GT.0.0)) GO TO 620
      IF (I.GT.3.AND.V(I).EQ.0.0.AND.V(I-1).EQ.0.0
     1 .AND.V(I-2).EQ.0.0) GO TO 95
 130  CR = 0.0
```

FIGURE A-8
PROGRAM LISTING
(CONTINUED)

```
      DO 131 X = 1,NV
      CR = CR+A(X)+B(X)*MV(I)+G(X)*MV(I)**2
  131 CONTINUE
      R(I) = CR
      TR(I) = R(I)+20.0*WT*TRACK(J,3)+20.0*WT*TRACK(J,2)
      RR(I) = TR(I)+100.0*WT*VDD(I)
      DFC(I) = CF*RR(I)*DS(I)
      IF (RR(I).LE.0.0.OR.U.LE.9) DFC(I) = NL*DT*5.5/3600.0
  754 CONTINUE
      CFC = CFC+DFC(I)
      CDT = CDT+DT
      IF (I.EQ.1) GO TO 98
      RFC(I) = 60.0*DFC(I)/DT
      CRFC = 60.0*CFC/CDT
   98 IF (I.GE.INDEX.OR.NUM(I).GT.CUTOFF) GO TO 97
      IF (J.EQ.NTR) GO TO 97
      GO TO 90
   97 WRITE(8,58)CDT,V(I),RFC(I)
   58 FORMAT(F7.0,2(5X,F5.2))
      IF(OPTN1.EQ.1) WRITE(7,190)I,TE(I),U,TR(I),
     1 VDD(I),V(I),J,DS(I),DT,S(I),DFC(I),CFC,CDT,RFC(I),CRFC
   90 CONTINUE
  190 FORMAT (  1H ,I4,2PE11.2,I3,3(2PE11.2),2X,I3,2PE11.2,2PE11.2,
     1 /,5X,2PE11.2,3X,2(2PE11.2),27X,2PE11.2,/,19X,2(2PE11.2),//)
      GO TO 95
  620 WRITE(7,622)
  622 FORMAT(1X,' RUNAWAY')
      WRITE(7,621)I,L,P,VDD(I),V(I)
  621 FORMAT (  1H ,1X,I3,2X,I2,2X,I2,2X,2(2PE11.2))
      GO TO 625
   95 SUM6 = 0.0
      WRITE(9,81)I
   81 FORMAT(I4)
      III=I-1
      IF(OPTN1.EQ.0) WRITE(7,94)III,J,S(III),CDT
   94 FORMAT(  1H ,2X,I4,2X,I3,4X,F8.1,3X,F8.1)
      INT = I-1
      DO 91 M = 1,INT
   91 SUM6 = SUM6+DFC(M)
      WRITE(7,92)M,SUM6
   92 FORMAT (  1H ,I4,2X,' TOTAL TRAIN FUEL CONSUMPTION',
     1 F8.2,' GALLONS')
      WRITE(7,154) CRFC
  154 FORMAT ('          AVERAGE RATE OF FUEL CONSUMPTION FOR TRIP = ',
     1 F8.2,' GAL./MIN')
      AV=S(I-1)*3600.0/CDT
      WRITE(7,99)AV
   99 FORMAT(  1H ,6X,' AVERAGE VELOCITY FOR TRIP  =  ',
     1 F8.2,' MPH')
  625 STOP
      END
      SUBROUTINE RANDU(IX,IY,YFL)
      IY=IX*65539
      IF(IY)5,6,6
    5 IY=IY+2147483647+1
```

FIGURE A-8
PROGRAM LISTING
(CONTINUED)

```
  6     YFL=IY                                                  FTF05510
        YFL=YFL*.4656613E-9                                     FTF05520
        RETURN                                                  FTF05530
        END                                                     FTF05540
```

FIGURE A-8
PROGRAM LISTING
(CONTINUED)

Lines 1940-2030

These lines establish the adhesion limit and limit the tractive effort to a maximum of 250,000 lbs. from a consideration of drawbar pull. The speed limits of the track records are limited by the operational speed limit imposed by the program operator. Two variables are initialized.

Lines 2040-2130

These lines request a seed number for the random number routine.

Lines 2140-2200

These lines are the beginning of the "DO" loop which calculates velocity and fuel consumption. It is necessary to have a separate calculation for the first time interval because the previous velocity, upon which the calculation depends, is zero. These lines direct the program to the appropriate calculation.

Lines 2210-2420

These lines make the initial calculation. The initial starting notch has been arbitrarily selected as #4 (U=13), and the initial tractive effort corresponds to such a notch setting. The tractive effort is adhesion-limited at .23 times the locomotive weight. A value of J is established by a small loop which enables subsequent calculations to examine the track data file and extract the speed limit, grade, and curvature for the present location of the train. A value for the initial acceleration of the train is calculated from the mass of the train and the net force on the train, the other being the tractive effort less the resistance at zero velocity. The resistance includes both that of the locomotives and that of the trailing cars. From the initial acceleration and the time interval selected, the distance traversed in the time interval, the final velocity, the mean velocity over the period, and the rate of fuel consumption during that period are computed. The program then jumps to a later point in the loop where the remaining variables are calculated. A provision for a runaway train, in case the velocity exceeds the specified value and the acceleration is positive, stops the program under such circumstances.

Lines 2430-2640

These lines begin the normal calculation of velocity and fuel consumption after the initial calculation. A short loop establishes a value for J, which is used as a parameter locating the train so that subsequent calculations may extract pertinent data from the track data file. Two random numbers are generated for later use in the program, and certain decisions directing the program calculation are made on the basis of the value of several logical and other parameters. Lines 2600-2610 ensure that if the train has been stopped by the logic of the program on a piece of track where the track record states that the speed limit is zero, the train will be made to proceed by the adjusted logic of the program after it has completed the appointed length of the stop. The statement is necessary to avoid the train attempting to start in the face of a zero speed limit requirement. It was added late during the development of the program to accommodate track records which include sections within which the speed limit is zero.

Lines 2650-3280

These lines contain the heart of the notch selection process and the rationale for expanding the time interval between calculations. The previous velocity is examined to determine whether it was in-band or out-of-band. If in-band, if the absolute value of the acceleration is small enough, the time interval is extended to the time at which the velocity breaks out of the permissible band or to the time when a change in track characteristics appears. If out-of-band, the notch position is adjusted in a regular fashion, depending upon the previous acceleration as well to return the velocity to within this band. For more discussion, see the section entitled "Acceleration and Braking Considerations."

Lines 3290-3330

These lines merely define certain braking constants used subsequently.

Lines 3340-3810

The first line selects the equations used for calculating tractive efforts, based upon the value of the parameter "U". "U" is assigned values from 1 to 17, corresponding consecutively to eight values of braking, one value of coasting (no braking and no tractive effort) and eight values of tractive effort corresponding to the eight notch positions. The equations calculating tractive effort reflect curves approximating the characteristics of the GM EMD SD-40 locomotive. The equations calculating braking effort reflect certain assumptions and theoretical considerations derived from Hay (15) and other sources. The tractive effort curves above 10 mph represent approximately constant power curves; the braking effort equations represent a fraction of the available braking force. For further discussion see the section entitled "Acceleration and Braking Considerations."

Lines 3820-3920

These lines, if the tractive effort is adhesion-limited, serve to reduce the notch setting called for by the previous algorithms to a level so that the wheels are not spinning and so that the fuel consumption rate is appropriately reduced.

Lines 3930-3990

These lines calculate the resistance of the locomotives and the trailing cars based upon variables calculated in lines 1210-1930.

Line 4000

This line computes the acceleration of the train from the tractive effort selected and the resistance computed above.

Lines 4010-4190

The first of these lines requires a check of the time required to return the velocity to within the permissible band; if the acceleration is inadequate, the notch is again modified by one position; the process is not thereafter repeated. Subsequent lines divide the selected time interval in half under certain circumstances when the velocity and acceleration seem to demand more prompt adjustment of the throttle setting. Line 4090 was inserted later in the development of the program to avert a digital problem associated with the acceleration nearing zero as the train approaches its limiting velocity at full-throttle.

Lines 4200-4430

These lines are entered if the program has already determined that conditions of the track remain constant for the next interval and that the acceleration is such that the velocity tolerance band will not be violated for a period longer than the time interval selected if the acceleration remains constant for that period. These lines compute the time at the computed acceleration to either (1) break out of the velocity band or (2) arrive at a point on the track where conditions are different. The program selects the shorter time and computes the distance travelled over that time interval.

Lines 4440-4450

These lines direct the program to readjust the tractive effort based upon the newly-calculated mean velocity for the purposes of subsequent fuel consumption calculation.

Lines 4460-4860

These lines incorporate the stopping routine determining the length of stop. Random numbers having a uniform probability density function are generated by the subroutine. These are subsequently used to generate a quasi-Poisson distribution from which the random length of stop is extracted. The values of several other variables pertinent to the length of stop are computed.

Lines 4870-5770

These lines conclude the calculation by recomputing the train resistance based upon the mean velocity. From that value and the acceleration of the train the fuel consumption and the rate of fuel consumption are computed.

Lines 5780-End

The remaining lines merely calculate the values of certain additional variables of interest and direct the printing of the program variables.

APPENDIX B

FUEL CONSUMPTION CALCULATION

It can be noted in line 5020 of the program that the differential fuel consumption for the given time interval it is given by:

$$DFC(I) = DF \cdot RR(I) \cdot DS(I)$$

This is essentially a work calculation, in which energy consumption is measured by the product of differential distance travelled and force exerted in accelerating the train and against dissipative forces. The result of the calculation is only approximately a constant value for the same notch setting, although a given notch setting is supposed to represent constant power operation. The reason the fuel consumption rate is not constant in the output of the program for the same notch setting is because the calculation is a linear approximation of the solution to a non-linear problem.

Refer to Figure B-1. As any instant of time t_o, the velocity v_o is known, having been previously calculated. Based upon this velocity v_o, the notch setting for the next succeeding time interval is selected by the program algorithms. The tractive effort for this time period is determined from the velocity v_o and the tractive effort curve corresponding to the notch. The train resistance is computed, based on this velocity v_o. Grade and curve resistance are added, and the remaining tractive effort determines the train's acceleration (a_1).

The acceleration over the time period dt determines the velocity at the end of the time period and the mean velocity during the period. The dissipative resistance is recalculated, based upon this mean velocity, but the acceleration is held constant at the previously determined value. Total resistive force (RR(I)), including grade and curve resistance and acceleration force, is computed. The

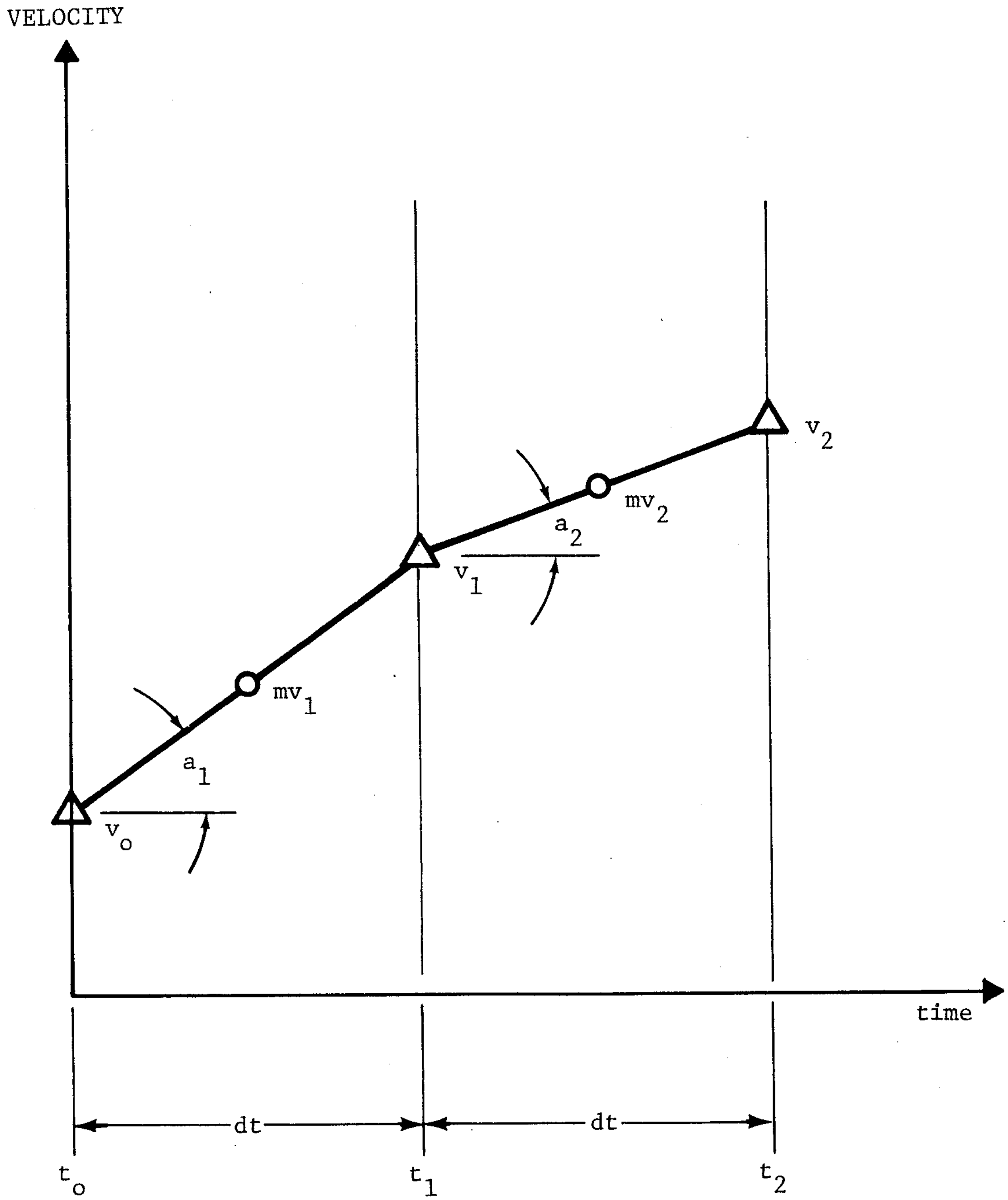


FIGURE B-1
FUEL CONSUMPTION CALCULATION

distance travelled during the time interval is computed from the mean velocity and the length of time. These two factors are multiplied and by means of an appropriate conversion factor (CF) converted to differential fuel consumption. The rate of fuel consumption is obtained by dividing by the length of the time interval.

It follows from the program and the explanation above that the rates of fuel consumption in the first and second intervals shown on the figure RFC_1 and RFC_2 are given by the following expressions:

$$RFC_2 = mv_2 \left[TE(v_1) + R(mv_2) - R(v_1)\right]$$

$$RFC_1 = mv_1 \left[TE(v_o) + R(mv_1) - R(v_o)\right]$$

in which the velocities in parentheses indicate at which velocity the tractive effort (TE) and dissipative resistance (R) have been evaluated. (It is assumed in these expressions and those following that dimensions are compatible without the need of conversion factors).

These expressions are not equal, but can be shown to be equal under certain circumstances which in fact do not prevail. Dissipative resistance is a function of velocity. If resistance were constant, the expression would reduce to:

$$RFC_2 = mv_2 \ (TE(v_1))$$

$$RFC_1 = mv_1 \ (TE(v_o))$$

For a given notch setting, power is not exactly constant, either in reality or in the approximation of the tractive effort curves in the program. If power were constant

$$P = TE(v) \cdot v$$

whence

$$TE(v) = \frac{P}{v}$$

If the tractive effort $TE(v_o)$ at velocity v_o is used to evaluate P, then

$$P = TE(v_o) \cdot v_o = \text{Constant}$$

and the tractive effort at any velocity is given by

$$TE(v) = \frac{TE(v_o) \cdot v_o}{v}$$

whence

$$TE(v_1) = \frac{TE(v_o) \cdot v_o}{v_1}$$

$$TE(v_o) = \frac{TE(v_o) \cdot v_o}{v_o} = TE(v_o)$$

and by substitution the expressions reduce to:

$$RFC_2 = mv_2 \cdot TE(v_o) \left(\frac{v_o}{v_1} \right)$$

$$RFC_1 = mv_1 \cdot TE(v_o)$$

The ratio is seen to be

$$\frac{RFC_2}{RFC_1} = \left(\frac{mv_2}{mv_1} \right) \left(\frac{v_o}{v_1} \right)$$

If the fuel rate had been evaluated at the initial velocities instead of the mean, the ratio would be:

$$\frac{RFC_2}{RFC_1} = \left(\frac{v_1}{v_o} \right) \left(\frac{v_o}{v_1} \right) = 1$$

It was felt that evaluation of the fuel rate at the mean velocity during the period was for this computation a more accurate representation of the fuel rate than an evaluation at the initial velocity, especially in view of the approximate nature of the linearized calculation.

An alternative fuel consumption calculation would use the known fuel rates for the particular locomotive in a given notch setting. This would have the advantage of displaying a constant fuel rate for a given notch, particularly noticeable on the plots of velocity profile and fuel consumption rate vs. time. However, although some consideration was given to this idea, again it was felt that the method used probably reflected fuel consumption more accurately for the type of calculation made.

APPENDIX C

AUXILIARY PROGRAMS

For the record, all "TRAIN" files used in making the simulated runs reported in Table II of the main body of the report are listed in their entirety immediately below. The "TRAIN" files list, in the order of original composition of the consist, the type of vehicle and the net load carried in tons. The "ORDER" files are used for arranging the consist. Of the "ORDER" files, only "ORDER 1," corresponding to standard order for the 71 car train, and "ORDER 7," corresponding to the order of the re-arranged 71 car train, are listed. The remaining trains were all arranged in the order of the train file, and consequently their "ORDER" files are simply sequences of consecutive numbers with length corresponding to the number of vehicles in the train.

"TRACK" files contain significant information but are lengthy. However, complete information on the "TRACK" files used in making the same simulated runs is contained in this report. The "TRACK" files, as modified for use with this program, list the milepost and distance in miles, and the grade, grade equivalent of curvature, and speed limit for the next track section. The western W1-W2 track (TRACK 21) and the eastern E1-E2 track (TRACK 32) are listed in their entirety as slightly modified for use with the computer program. The statistical track (TRACK 13) generated from overall track statistics was listed as an example in the main body of the report. These three can be reversed by means of the "RVSL 1" program listed below to obtain the W2-W1 track (TRACK 26), the E2-E1 track (TRACK 37), and the reversed statistical track (TRACK 14), respectively. The tracks used to calibrate the program are not included.

Also listed below are the program "RISE 1," used to calculate the change in altitude between end points on the "TRACK" files, and "RVSL 1," used to create a new "TRACK" file in the opposite direction for use with the program, as mentioned above.

FILE: TRAIN1 DATA

101	1	0.0	137	3	61.5
102	1	0.0	138	2	0.0
103	1	0.0	139	2	61.5
104	14	61.5	140	2	61.5
105	3	61.5	141	2	61.5
106	3	0.0	142	14	61.5
107	3	61.5	143	2	0.0
108	3	0.0	144	2	0.0
109	16	0.0	145	5	0.0
110	3	0.0	146	14	61.5
111	4	61.5	147	3	61.5
112	16	0.0	148	3	0.0
113	3	61.5	149	3	0.0
114	2	0.0	150	3	0.0
115	3	0.0	151	3	61.5
116	2	0.0	152	3	61.5
117	2	61.5	153	3	0.0
118	2	61.5	154	16	61.5
119	2	0.0	155	2	61.5
120	3	61.5	156	2	61.5
121	4	0.0	157	2	61.5
122	4	61.5	158	3	0.0
123	3	61.5	159	2	0.0
124	2	0.0	160	3	0.0
125	3	0.0	161	2	61.5
126	2	61.5	162	4	0.0
127	16	61.5	163	3	61.5
128	4	0.0	164	16	0.0
129	4	61.5	165	16	61.5
130	2	0.0	166	4	0.0
131	3	61.5	167	3	61.5
132	5	0.0	168	2	0.0
133	16	0.0	169	2	61.5
134	3	0.0	170	5	61.5
135	2	0.0	171	17	0.0
136	2	0.0			

FIGURE C-1
TRAIN 1 DATA

FILE: TRAIN3 DATA

101	1	0.0
102	1	0.0
103	1	0.0
104	3	101.7
105	3	101.7
106	3	101.7
107	3	101.7
108	3	101.7
109	3	101.7
110	3	101.7
111	3	101.7
112	3	101.7
113	3	101.7
114	3	101.7
115	3	101.7
116	3	101.7
117	3	101.7
118	3	101.7
119	3	101.7
120	3	101.7
121	3	101.7
122	3	101.7
123	3	101.7
124	3	101.7
125	3	101.7
126	3	101.7
127	3	101.7
128	3	101.7
129	3	101.7
130	3	101.7
131	3	101.7
132	3	101.7
133	3	101.7
134	3	101.7
135	3	101.7
136	3	101.7
137	3	101.7
138	3	101.7
139	3	101.7
140	3	101.7
141	3	101.7
142	3	101.7
143	3	101.7
144	3	101.7
145	3	101.7
146	3	101.7
147	3	101.7
148	3	101.7
149	3	101.7
150	3	101.7
151	3	101.7
152	3	101.7
153	3	101.7
154	3	101.7
155	3	101.7
156	3	101.7
157	3	101.7
158	3	101.7
159	3	101.7
160	3	101.7
161	3	101.7
162	3	101.7
163	3	101.7
164	3	101.7
165	3	101.7
166	3	101.7
167	3	101.7
168	3	101.7
169	3	101.7
170	3	101.7
171	17	0.0

FIGURE C-2
TRAIN 3 DATA

FILE: TRAIN4 DATA

101	1	0.0
102	1	0.0
103	1	0.0
104	3	0.0
105	3	0.0
106	3	0.0
107	3	0.0
108	3	0.0
109	3	0.0
110	3	0.0
111	3	0.0
112	3	0.0
113	3	0.0
114	3	0.0
115	3	0.0
116	3	0.0
117	3	0.0
118	3	0.0
119	3	0.0
120	3	0.0
121	3	0.0
122	3	0.0
123	3	0.0
124	3	0.0
125	3	0.0
126	3	0.0
127	3	0.0
128	3	0.0
129	3	0.0
130	3	0.0
131	3	0.0
132	3	0.0
133	3	0.0
134	3	0.0
135	3	0.0
136	3	0.0
137	3	0.0
138	3	0.0
139	3	0.0
140	3	0.0
141	3	0.0
142	3	0.0
143	3	0.0
144	3	0.0
145	3	0.0
146	3	0.0
147	3	0.0
148	3	0.0
149	3	0.0
150	3	0.0
151	3	0.0
152	3	0.0
153	3	0.0
154	3	0.0
155	3	0.0
156	3	0.0
157	3	0.0
158	3	0.0
159	3	0.0
160	3	0.0
161	3	0.0
162	3	0.0
163	3	0.0
164	3	0.0
165	3	0.0
166	3	0.0
167	3	0.0
168	3	0.0
169	3	0.0
170	3	0.0
171	17	0.0

FIGURE C-3
TRAIN 4 DATA

FILE: TRAIN6 DATA

101	1	0.0
102	1	0.0
103	1	0.0
104	1	0.0
105	1	0.0
106	8	27.8
107	8	27.8
108	8	27.8
109	8	27.8
110	8	27.8
111	8	27.8
112	6	13.9
113	8	27.8
114	8	27.8
115	8	27.8
116	8	27.8
117	8	27.8
118	8	27.8
119	8	27.8
120	8	27.8
121	8	27.8
122	8	27.8
123	8	27.8
124	8	27.8
125	8	27.8
126	8	27.8
127	7	13.9
128	6	13.9
129	8	27.8
130	8	27.8
131	8	27.8
132	8	27.8
133	8	27.8
134	8	27.8
135	8	27.8
136	8	27.8
137	7	13.9
138	8	27.8
139	8	27.8
140	8	27.8
141	8	27.8
142	8	27.8
143	8	27.8
144	6	13.9
145	8	27.8
146	8	27.8
147	8	27.8
148	8	27.8
149	8	27.8
150	8	27.8
151	8	27.8
152	8	27.8
153	8	27.8
154	8	27.8
155	8	27.8
156	8	27.8
157	8	27.8
158	8	27.8
159	8	27.8
160	8	27.8
161	7	13.9
162	8	27.8
163	6	13.9
164	8	27.8
165	8	27.8
166	8	27.8
167	8	27.8
168	8	27.8
169	8	27.8
170	8	27.8
171	8	27.8
172	8	27.8
173	17	0.0

FIGURE C-4
TRAIN 6 DATA

FILE: TRAIN14 DATA

101	1	0.0
102	1	0.0
103	1	0.0
104	1	0.0
105	1	0.0
106	11	33.0
107	11	33.0
108	11	33.0
109	11	33.0
110	9	16.5
111	11	33.0
112	11	33.0
113	11	33.0
114	11	33.0
115	11	33.0
116	11	33.0
117	11	33.0
118	11	33.0
119	11	33.0
120	11	33.0
121	10	16.5
122	11	33.0
123	11	33.0
124	9	16.5
125	11	33.0
126	11	33.0
127	11	33.0
128	11	33.0
129	11	33.0
130	11	33.0
131	11	33.0
132	11	33.0
133	11	33.0
134	11	33.0
135	11	33.0
136	11	33.0
137	11	33.0
138	10	16.5
139	11	33.0
140	11	33.0
141	11	33.0
142	11	33.0
143	11	33.0
144	11	33.0
145	11	33.0
146	9	16.5
147	11	33.0
148	11	33.0
149	11	33.0
150	11	33.0
151	11	33.0
152	10	16.5
153	11	33.0
154	11	33.0
155	11	33.0
156	11	33.0
157	11	33.0
158	11	33.0
159	11	33.0
160	11	33.0
161	11	33.0
162	11	33.0
163	11	33.0
164	11	33.0
165	11	33.0
166	11	33.0
167	9	16.5
168	11	33.0
169	11	33.0
170	11	33.0
171	11	33.0
172	11	33.0
173	17	0.0

FIGURE C-5
TRAIN 14 DATA

FILE: TRAIN21 DATA

101	1	0.0
102	1	0.0
103	1	0.0
104	3	108.0
105	3	108.0
106	3	108.0
107	3	108.0
108	3	108.0
109	3	108.0
110	3	108.0
111	3	108.0
112	3	108.0
113	3	108.0
114	3	108.0
115	3	108.0
116	3	108.0
117	3	108.0
118	3	108.0
119	3	108.0
120	3	108.0
121	3	108.0
122	3	108.0
123	3	108.0
124	3	108.0
125	3	108.0
126	3	108.0
127	3	108.0
128	3	108.0
129	3	108.0
130	3	108.0
131	3	108.0
132	3	108.0
133	3	108.0
134	3	108.0
135	3	108.0
136	3	108.0
137	3	108.0
138	3	108.0
139	3	108.0
140	3	108.0
141	3	108.0
142	3	108.0
143	3	108.0
144	3	108.0
145	3	108.0
146	3	108.0
147	3	108.0
148	3	108.0
149	3	108.0
150	3	108.0
151	3	108.0
152	3	108.0
153	3	108.0
154	3	108.0
155	3	108.0
156	3	108.0
157	3	108.0
158	3	108.0
159	3	108.0
160	3	108.0
161	3	108.0
162	3	108.0
163	3	108.0
164	3	108.0
165	3	108.0
166	3	108.0
167	17	0.0

FIGURE C-6
TRAIN 21 DATA

FILE: TRAIN22 DATA

101	1	0.0
102	1	0.0
103	1	0.0
104	3	0.0
105	3	0.0
106	3	0.0
107	3	0.0
108	3	0.0
109	3	0.0
110	3	0.0
111	3	0.0
112	3	0.0
113	3	0.0
114	3	0.0
115	3	0.0
116	3	0.0
117	3	0.0
118	3	0.0
119	3	0.0
120	3	0.0
121	3	0.0
122	3	0.0
123	3	0.0
124	3	0.0
125	3	0.0
126	3	0.0
127	3	0.0
128	3	0.0
129	3	0.0
130	3	0.0
131	3	0.0
132	3	0.0
133	3	0.0
134	3	0.0
135	3	0.0
136	3	0.0
137	3	0.0
138	3	0.0
139	3	0.0
140	3	0.0
141	3	0.0
142	3	0.0
143	3	0.0
144	3	0.0
145	3	0.0
146	3	0.0
147	3	0.0
148	3	0.0
149	3	0.0
150	3	0.0
151	3	0.0
152	3	0.0
153	3	0.0
154	3	0.0
155	3	0.0
156	3	0.0
157	3	0.0
158	3	0.0
159	3	0.0
160	3	0.0
161	3	0.0
162	3	0.0
163	3	0.0
164	3	0.0
165	3	0.0
166	3	0.0
167	17	0.0

FIGURE C-7
TRAIN 22 DATA

FILE: TRAIN23 DATA

101	1	0.0
102	1	0.0
103	1	0.0
104	1	0.0
105	3	101.7
106	3	101.7
107	3	101.7
108	3	101.7
109	3	101.7
110	3	101.7
111	3	101.7
112	3	101.7
113	3	101.7
114	3	101.7
115	3	101.7
116	3	101.7
117	3	101.7
118	3	101.7
119	3	101.7
120	3	101.7
121	3	101.7
122	3	101.7
123	3	101.7
124	3	101.7
125	3	101.7
126	3	101.7
127	3	101.7
128	3	101.7
129	3	101.7
130	3	101.7
131	3	101.7
132	3	101.7
133	3	101.7
134	3	101.7
135	3	101.7
136	3	101.7
137	3	101.7
138	3	101.7
139	3	101.7
140	3	101.7
141	3	101.7
142	3	101.7
143	3	101.7
144	3	101.7
145	3	101.7
146	3	101.7
147	3	101.7
148	3	101.7
149	3	101.7
150	3	101.7
151	3	101.7
152	3	101.7
153	3	101.7
154	3	101.7
155	3	101.7
156	3	101.7
157	3	101.7
158	3	101.7
159	3	101.7
160	3	101.7
161	3	101.7
162	3	101.7
163	3	101.7
164	3	101.7
165	17	0.0

FIGURE C-8
TRAIN 23 DATA

FILE: TRAIN24 DATA

101	1	0.0
102	1	0.0
103	1	0.0
104	1	0.0
105	3	0.0
106	3	0.0
107	3	0.0
108	3	0.0
109	3	0.0
110	3	0.0
111	3	0.0
112	3	0.0
113	3	0.0
114	3	0.0
115	3	0.0
116	3	0.0
117	3	0.0
118	3	0.0
119	3	0.0
120	3	0.0
121	3	0.0
122	3	0.0
123	3	0.0
124	3	0.0
125	3	0.0
126	3	0.0
127	3	0.0
128	3	0.0
129	3	0.0
130	3	0.0
131	3	0.0
132	3	0.0
133	3	0.0
134	3	0.0
135	3	0.0
136	3	0.0
137	3	0.0
138	3	0.0
139	3	0.0
140	3	0.0
141	3	0.0
142	3	0.0
143	3	0.0
144	3	0.0
145	3	0.0
146	3	0.0
147	3	0.0
148	3	0.0
149	3	0.0
150	3	0.0
151	3	0.0
152	3	0.0
153	3	0.0
154	3	0.0
155	3	0.0
156	3	0.0
157	3	0.0
158	3	0.0
159	3	0.0
160	3	0.0
161	3	0.0
162	3	0.0
163	3	0.0
164	3	0.0
165	17	0.0

FIGURE C-9
TRAIN 24 DATA

FILE: TRAIN25 DATA

101	1	0.0
102	1	0.0
103	1	0.0
104	1	0.0
105	3	108.0
106	3	108.0
107	3	108.0
108	3	108.0
109	3	108.0
110	3	108.0
111	3	108.0
112	3	108.0
113	3	108.0
114	3	108.0
115	3	108.0
116	3	108.0
117	3	108.0
118	3	108.0
119	3	108.0
120	3	108.0
121	3	108.0
122	3	108.0
123	3	108.0
124	3	108.0
125	3	108.0
126	3	108.0
127	3	108.0
128	3	108.0
129	3	108.0
130	3	108.0
131	3	108.0
132	3	108.0
133	3	108.0
134	3	108.0
135	3	108.0
136	3	108.0
137	3	108.0
138	3	108.0
139	3	108.0
140	3	108.0
141	3	108.0
142	3	108.0
143	3	108.0
144	3	108.0
145	3	108.0
146	3	108.0
147	3	108.0
148	3	108.0
149	3	108.0
150	3	108.0
151	3	108.0
152	3	108.0
153	3	108.0
154	3	108.0
155	3	108.0
156	3	108.0
157	3	108.0
158	3	108.0
159	3	108.0
160	3	108.0
161	3	108.0
162	17	0.0

FIGURE C-10
TRAIN 25 DATA

FILE: TRAIN26 DATA

101	1	0.0
102	1	0.0
103	1	0.0
104	1	0.0
105	3	0.0
106	3	0.0
107	3	0.0
108	3	0.0
109	3	0.0
110	3	0.0
111	3	0.0
112	3	0.0
113	3	0.0
114	3	0.0
115	3	0.0
116	3	0.0
117	3	0.0
118	3	0.0
119	3	0.0
120	3	0.0
121	3	0.0
122	3	0.0
123	3	0.0
124	3	0.0
125	3	0.0
126	3	0.0
127	3	0.0
128	3	0.0
129	3	0.0
130	3	0.0
131	3	0.0
132	3	0.0
133	3	0.0
134	3	0.0
135	3	0.0
136	3	0.0
137	3	0.0
138	3	0.0
139	3	0.0
140	3	0.0
141	3	0.0
142	3	0.0
143	3	0.0
144	3	0.0
145	3	0.0
146	3	0.0
147	3	0.0
148	3	0.0
149	3	0.0
150	3	0.0
151	3	0.0
152	3	0.0
153	3	0.0
154	3	0.0
155	3	0.0
156	3	0.0
157	3	0.0
158	3	0.0
159	3	0.0
160	3	0.0
161	3	0.0
162	17	0.0

FIGURE C-11
TRAIN 26 DATA

FILE: ORDER1 DATA

101	1	135	35
102	2	136	36
103	3	137	37
104	4	138	38
105	5	139	39
106	6	140	40
107	7	141	41
108	8	142	42
109	9	143	43
110	10	144	44
111	11	145	45
112	12	146	46
113	13	147	47
114	14	148	48
115	15	149	49
116	16	150	50
117	17	151	51
118	18	152	52
119	19	153	53
120	20	154	54
121	21	155	55
122	22	156	56
123	23	157	57
124	24	158	58
125	25	159	59
126	26	160	60
127	27	161	61
128	28	162	62
129	29	163	63
130	30	164	64
131	31	165	65
132	32	166	66
133	33	167	67
134	34	168	68
		169	69
		170	70
		171	71

FIGURE C-12
ORDER 1 DATA

FILE: ORDER7 DATA

101	1
102	2
103	3
104	14
105	16
106	17
107	18
108	19
109	24
110	26
111	30
112	35
113	36
114	38
115	39
116	40
117	41
118	43
119	44
120	55
121	56
122	57
123	59
124	61
125	68
126	69
127	5
128	6
129	7
130	8
131	10
132	13
133	15
134	20
135	23
136	25
137	31
138	34
139	37
140	47
141	48
142	49
143	50
144	51
145	52
146	53
147	58
148	60
149	63
150	67
151	11
152	21
153	22
154	28
155	29
156	62
157	66
158	32
159	45
160	70
161	4
162	42
163	46
164	9
165	12
166	27
167	33
168	54
169	64
170	65
171	71

FIGURE C-13
ORDER 7 DATA

FILE: TRACK21 DATA A

101	0.00	-.18	.00	10.0
102	0.40	.06	.00	20.0
103	2.35	-.02	.06	40.0
104	2.40	-.02	.06	65.0
105	2.70	-.02	.06	79.0
106	4.25	.16	.00	79.0
107	5.00	.16	.00	79.0
108	6.75	-.08	.00	79.0
109	9.40	.22	.03	79.0
110	9.70	.22	.03	75.0
111	12.90	-.08	.11	75.0
112	13.85	.28	.09	75.0
113	15.00	.28	.09	75.0
114	15.60	.50	.06	75.0
115	18.65	.48	.11	75.0
116	20.90	.48	.11	80.0
117	23.05	.00	.04	80.0
118	23.80	.00	.04	70.0
119	25.00	-.44	.04	70.0
120	26.10	-.44	.04	60.0
121	26.30	.32	.04	60.0
122	27.30	.32	.04	80.0
123	28.80	.18	.00	80.0
124	31.30	-.34	.00	80.0
125	35.00	-.34	.00	80.0
126	35.20	-.34	.00	70.0
127	35.50	.02	.00	70.0
128	35.70	.02	.00	80.0
129	38.40	.40	.00	80.0
130	40.50	-.36	.03	80.0
131	41.70	.52	.00	80.0
132	42.60	-.44	.00	80.0
133	45.00	-.44	.00	70.0
134	45.50	-.44	.00	80.0
135	46.00	-.20	.00	80.0
136	47.95	.18	.00	80.0
137	49.45	-.16	.00	80.0
138	52.55	.02	.00	80.0
139	52.90	.02	.00	70.0
140	53.40	.02	.00	80.0
141	55.00	.02	.00	80.0
142	55.30	.08	.00	80.0
143	58.95	.06	.00	80.0
144	64.65	.06	.00	80.0
145	65.00	.06	.00	80.0
146	69.30	.16	.00	80.0
147	71.65	-.16	.03	80.0
148	72.55	.28	.00	80.0
149	74.50	.48	.00	80.0
150	75.00	.48	.00	80.0
151	75.30	.48	.00	55.0
152	75.80	.48	.00	80.0
153	79.10	.48	.00	55.0
154	79.50	.48	.00	70.0
155	79.60	.12	.00	70.0

FILE: TRACK21 DATA A

156	81.40	.12	.00	65.0
157	81.90	.12	.00	80.0
158	83.60	-.56	.00	80.0
159	84.50	.38	.00	80.0
160	85.00	.38	.00	80.0
161	87.20	-.46	.03	80.0
162	88.15	-.06	.00	80.0
163	91.75	-.20	.00	80.0
164	93.20	-.10	.00	80.0
165	93.70	-.10	.00	65.0
166	94.65	-.40	.00	65.0
167	95.00	-.40	.00	65.0
168	96.05	-.12	.00	65.0
169	97.30	-.12	.00	80.0
170	99.25	.06	.00	80.0
171	101.65	.16	.00	40.0
172	105.00	.16	.00	20.0
173	106.70	.16	.00	10.0
174	107.70	.08	.00	0.0
175	107.80	.09	.00	10.0
176	110.30	.09	.00	20.0
177	116.70	.09	.00	40.0
178	117.75	.04	.00	80.0
179	120.85	.10	.01	40.0
180	121.70	.10	.01	70.0
181	124.99	.09	.00	70.0
182	128.90	.38	.01	70.0
183	129.75	.09	.00	70.0
184	132.40	.21	.01	70.0
185	134.73	.38	.02	70.0
186	138.00	.38	.02	60.0
187	139.20	.21	.04	60.0
188	140.78	.37	.03	60.0
189	145.30	.37	.03	70.0
190	146.88	.17	.00	70.0
191	148.29	-.35	.00	70.0
192	149.63	.10	.00	70.0
193	151.75	-.16	.00	70.0
194	155.80	-.40	.00	70.0
195	160.40	-.18	.00	70.0
196	163.06	.02	.00	70.0
197	167.59	-.28	.02	70.0
198	169.20	-.28	.02	30.0
199	169.83	-.25	.01	30.0
200	170.20	-.25	.01	70.0
201	171.94	-.10	.00	70.0
202	175.30	-.10	.00	65.0
203	175.50	-.10	.00	70.0
204	175.68	-.03	.00	70.0
205	179.80	-.28	.00	70.0
206	181.00	-.28	.00	30.0
207	181.32	.11	.01	30.0
208	182.30	.11	.00	60.0
209	182.47	-.07	.01	60.0
210	183.70	-.07	.01	50.0

FILE: TRACK21 DATA A

211	183.90	-.07	.01	70.0
212	184.19	.52	.02	70.0
213	185.25	-.37	.00	70.0
214	185.95	.55	.02	70.0
215	186.20	.55	.02	50.0
216	186.60	.55	.02	60.0
217	187.90	.55	.02	70.0
218	189.23	-.40	.01	70.0
219	191.40	-.40	.01	65.0
220	191.53	.56	.00	65.0
221	191.60	.56	.00	70.0
222	193.40	-.39	.00	70.0
223	195.07	.40	.00	70.0
224	196.33	-.20	.01	70.0
225	197.50	-.20	.01	50.0
226	197.90	-.20	.01	70.0
227	200.09	-.22	.01	70.0
228	201.30	-.22	.01	30.0
229	202.36	-.19	.02	30.0
230	202.80	-.19	.02	40.0
231	203.90	-.19	.02	79.0
232	204.68	-.04	.00	79.0
233	206.85	.00	.00	79.0
234	207.60	.00	.00	60.0
235	207.70	.00	.00	79.0
236	208.16	.15	.00	79.0
237	209.10	.15	.00	60.0
238	209.30	.15	.00	79.0
239	210.28	.59	.00	79.0
240	210.30	.59	.00	70.0
241	210.50	.59	.00	79.0
242	213.44	-.43	.01	79.0
243	215.08	-.18	.00	79.0
244	218.50	-.18	.00	40.0
245	218.90	-.30	.00	20.0
246	220.25	.12	.00	10.0
247	220.81	.12	.00	0.0

Note: Col. 1, milepost ID no.; Col. 2, milepost; Col. 3, percent grade; Col. 4, grade equivalent of curvature; Col. 5, speed limit, mph.

FIGURE C-14
TRACK 21 DATA

FILE: TRACK32 DATA A

101	0.00	0.00	.00	10.0
102	2.00	1.16	.05	20.0
103	2.70	.01	.00	20.0
104	3.00	.01	.00	25.0
105	3.19	.01	.00	45.0
106	3.25	1.08	.01	45.0
107	5.04	1.08	.01	40.0
108	5.25	1.08	.01	60.0
109	5.79	1.08	.01	30.0
110	6.65	1.08	.01	45.0
111	8.00	1.08	.01	60.0
112	9.52	.12	.00	60.0
113	10.00	-.50	.05	60.0
114	11.33	.47	.06	60.0
115	13.50	.18	.00	60.0
116	15.05	-.20	.00	60.0
117	15.95	.52	.05	60.0
118	16.40	-.47	.02	60.0
119	17.47	.15	.01	60.0
120	18.58	.50	.05	60.0
121	19.52	-.47	.03	60.0
122	20.00	-.47	.03	60.0
123	21.90	.27	.02	60.0
124	24.30	-.14	.01	60.0
125	27.38	.42	.07	60.0
126	28.28	-.36	.05	60.0
127	29.05	.08	.08	60.0
128	30.00	.08	.08	60.0
129	30.50	.50	.05	60.0
130	31.25	.07	.03	60.0
131	37.20	-.26	.06	60.0
132	39.35	.38	.02	60.0
133	40.00	.38	.02	50.0
134	40.36	-.30	.01	50.0
135	41.60	-.09	.05	50.0
136	44.10	.18	.05	50.0
137	45.59	.18	.05	60.0
138	48.63	-.30	.04	60.0
139	48.50	.40	.04	60.0
140	50.00	.40	.04	60.0
141	50.83	-.30	.08	60.0
142	51.00	-.30	.08	55.0
143	51.79	-.30	.08	60.0
144	52.00	.00	.05	60.0
145	52.90	-.49	.06	60.0
146	54.00	-.49	.06	50.0
147	56.30	.00	.03	50.0
148	56.59	.00	.03	60.0
149	57.05	.52	.05	60.0
150	59.60	-.16	.03	60.0
151	60.00	-.16	.03	60.0
152	62.77	.25	.01	60.0
153	63.70	-.77	.04	60.0
154	66.73	-.07	.04	60.0
155	69.10	.50	.04	60.0

FILE: TRACK32 DATA A

156	69.50	.50	.04	55.0
157	69.80	.50	.04	60.0
158	70.00	.50	.04	60.0
159	70.20	.50	.04	60.0
160	71.60	-.51	.03	60.0
161	73.30	.38	.00	60.0
162	78.47	-.48	.04	60.0
163	79.30	.17	.01	60.0
164	80.00	.17	.01	60.0
165	81.19	.17	.01	40.0
166	81.70	.17	.01	40.0
167	82.00	.17	.01	60.0
168	83.25	.59	.04	60.0
169	84.80	-.22	.00	60.0
170	85.57	.27	.00	60.0
171	87.43	-.46	.00	60.0
182	89.70	.52	.03	60.0
173	90.00	.52	.03	60.0
174	91.00	-.54	.03	60.0
175	95.55	.23	.02	60.0
176	96.55	-.30	.04	60.0
177	97.65	.33	.02	60.0
178	98.85	-.41	.05	60.0
179	100.00	-.41	.05	60.0
180	101.59	-.41	.05	55.0
181	103.20	.34	.04	55.0
182	103.89	.34	.04	60.0
183	110.00	.34	.04	60.0
184	110.63	-.50	.01	60.0
185	113.10	.00	.05	60.0
186	113.30	.00	.05	40.0
187	114.15	.60	.02	20.0
188	115.89	.60	.02	6.0
189	116.10	-.87	.03	6.0
190	116.40	-.87	.03	0.0
191	116.50	.81	.03	10.0
192	117.39	.81	.03	20.0
193	117.50	.81	.03	40.0
194	119.00	.81	.03	60.0
195	120.00	-1.47	.03	60.0
196	120.70	-.47	.00	60.0
197	122.00	.54	.02	60.0
198	126.95	-.79	.05	60.0
199	130.00	.71	.02	60.0
200	130.10	.71	.02	55.0
201	130.50	.71	.02	60.0
202	131.65	-.63	.03	60.0
203	133.90	.76	.10	60.0
204	134.30	.76	.10	50.0
205	135.19	.76	.10	45.0
206	136.00	.76	.10	50.0
207	136.85	1.00	.10	50.0
208	138.19	1.00	.10	55.0
209	139.15	.90	.04	55.0
210	140.00	.90	.04	55.0

Note: Col. 1, milepost ID no.; Col. 2, milepost; Col. 3, percent grade; Col. 4, grade equivalent of curvature; Col. 5, speed limit, mph.

FIGURE C-15
TRACK 32 DATA

FILE: TRACK32 DATA A

211	141.50	-.06	.01	55.0
212	142.19	-.06	.01	60.0
213	144.53	-.75	.03	60.0
214	147.10	1.00	.00	60.0
215	147.70	-.65	.00	60.0
216	148.90	.78	.00	60.0
217	150.00	.78	.00	60.0
218	150.15	-.90	.05	60.0
219	151.10	.68	.02	60.0
220	151.95	-.50	.07	60.0
221	152.39	-.50	.07	50.0
222	153.47	.60	.05	50.0
223	154.57	-.50	.00	50.0
224	155.45	-.75	.06	50.0
225	156.30	-1.00	.06	50.0
226	160.00	-1.00	.06	45.0
227	160.28	.24	.01	45.0
228	160.50	.24	.01	50.0
229	160.90	.37	.03	50.0
230	161.68	-.20	.00	50.0
231	161.89	-.20	.00	60.0
232	162.14	-.80	.02	60.0
233	163.19	-.80	.02	50.0
234	163.44	.84	.08	50.0
235	163.69	.84	.08	55.0
236	164.13	.00	.03	55.0
237	165.13	-.58	.06	55.0
238	166.13	.56	.07	55.0
239	166.19	.56	.07	50.0
240	167.39	.56	.07	45.0
241	168.83	-.50	.09	45.0
242	169.00	-.50	.09	55.0
243	170.16	.75	.06	55.0
244	176.71	.48	.00	55.0
245	178.01	.75	.06	55.0
246	179.00	.75	.06	45.0
247	179.09	.80	.10	45.0
248	180.15	-1.00	.09	45.0
249	181.15	1.20	.05	45.0
250	181.39	1.20	.05	55.0
251	181.65	.37	.06	55.0
252	182.45	.25	.05	55.0
253	184.80	.00	.03	55.0
254	185.19	.00	.03	60.0
255	185.50	-.47	.03	60.0
256	186.90	.12	.10	60.0
257	187.19	.12	.10	50.0
258	187.50	.12	.10	60.0
259	188.08	.93	.04	60.0
260	189.11	.00	.05	60.0
261	190.11	.22	.01	60.0
262	190.98	-1.33	.05	60.0
263	191.26	.20	.09	60.0
264	191.30	.20	.09	50.0
265	194.19	.20	.09	55.0

FILE: TRACK32 DATA A

266	195.30	.20	.09	60.0
267	196.07	-.30	.04	60.0
268	197.64	.14	.04	60.0
269	199.69	-1.05	.01	60.0
270	200.09	-1.05	.01	60.0
271	200.77	.25	.00	60.0
272	201.53	-.66	.04	60.0
273	202.53	.44	.04	60.0
274	204.05	.91	.04	60.0
275	205.00	.91	.04	50.0
276	206.39	.91	.04	60.0
277	207.30	.91	.04	50.0
278	207.60	-.55	.04	50.0
279	208.30	-.55	.04	60.0
280	210.02	1.00	.03	60.0
281	210.29	1.00	.03	60.0
282	210.87	.30	.01	60.0
283	211.50	.30	.01	55.0
284	212.30	.30	.01	60.0
285	212.43	-.95	.02	60.0
286	214.33	-.21	.02	60.0
287	215.39	-.21	.02	55.0
288	215.65	.00	.05	55.0
289	218.00	.00	.05	60.0
290	218.74	.55	.05	60.0
291	219.64	-.20	.03	60.0
292	220.64	-.84	.00	60.0
293	221.91	-.54	.10	60.0
294	222.00	-.54	.10	45.0
295	222.44	.72	.14	45.0
296	222.60	.72	.14	40.0
297	223.60	.72	.14	45.0
298	223.88	-1.19	.10	45.0
299	226.13	.40	.10	45.0
300	226.86	1.23	.10	45.0
301	229.03	-1.18	.11	45.0
302	229.15	1.11	.08	45.0
303	229.50	1.11	.08	50.0
304	229.89	1.11	.08	55.0
305	230.34	1.11	.08	55.0
306	230.61	-1.05	.05	55.0
307	231.95	1.11	.05	55.0
308	232.60	1.11	.05	50.0
309	233.56	-1.21	.07	50.0
310	234.89	-1.21	.07	45.0
311	236.80	.41	.07	45.0
312	238.66	-1.17	.12	45.0
313	240.12	.00	.00	45.0
314	240.37	.00	.00	45.0
315	240.65	1.07	.08	45.0
316	241.18	-1.15	.14	45.0
317	241.50	-1.15	.14	40.0
318	244.00	-1.15	.14	45.0
319	244.63	-1.21	.10	45.0
320	245.81	-.51	.00	45.0

FILE: TRACK32 DATA A

321	246.29	-.51	.00	55.0
322	246.55	-.40	.02	55.0
323	246.78	-.57	.05	55.0
324	248.19	-.57	.05	60.0
325	249.12	-.07	.03	60.0
326	250.43	-.18	.08	40.0
327	251.00	-.18	.08	20.0
328	253.92	-.18	.08	6.0
329	254.43	.12	.14	0.0

FIGURE C-15
TRACK 32 DATA
(CONTINUED)

```
FILE: RISE1    FORTRAN  A                    CONVERSATIONAL MONITOR SYSTEM

      DIMENSION TRACK(500,4),DR(500)
      RISE = 0.0
      WRITE(6,12)
      WRITE(7,12)
   12 FORMAT (1X,' INPUT, NO. OF TRACK RECORDS (3 DIGITS)')
      READ (5,13)NTR
      WRITE(7,13)NTR
   13 FORMAT (I3)
      READ (3,10)((TRACK(M,N),N=1,4),M=1,NTR)
   10 FORMAT (4X,3F9.2,F9.1)
      NTRA = NTR-1
      DO 20 I = 1,NTRA
      DR(I) = (TRACK((I+1),1)-TRACK(I,1))*52.80*TRACK(I,2)
      RISE = RISE+DR(I)
   20 CONTINUE
      WRITE (7,15) RISE
   15 FORMAT (5X,' TOTAL RISE BETWEEN END POINTS',F8.2,' FEET')
      STOP
      END
```

FIGURE C-16
LISTING OF "RISE 1" PROGRAM

```
      DIMENSION TRACK(500,5),TRUCK(500,5)
      WRITE(6,12)
      WRITE(7,12)
   12 FORMAT (1X,' INPUT, NO. OF TRACK RECORDS (3 DIGITS)')
      READ (5,13)NTR
      WRITE(7,13)NTR
   13 FORMAT (I3)
      READ (3,10)((TRACK(M,N),N=1,5),M=1,NTR)
   10 FORMAT (I3,1X,3F9.2,F9.1)
      DO 20 I = 1,NTR
      TRUCK(I,1) = TRACK(I,1)
      IF (I.EQ.NTR) GO TO 30
      TRUCK(I,5) = TRACK((NTR-I),5)
      TRUCK(I,4) = TRACK((NTR-I),4)
      TRUCK(I,3) = -TRACK((NTR-I),3)
      GO TO 40
   30 TRUCK(I,5) = 0.0
      TRUCK(I,4) = 0.0
      TRUCK(I,3) = 0.0
   40 CONTINUE
      IF (I.EQ.1) GO TO 15
      TRUCK(I,2) = TRACK((NTR+2-I),2)-TRACK((NTR+1-I),2)+TRUCK((I-1),2)
      GO TO 20
   15 TRUCK(I,2) = 0.0
   20 CONTINUE
      WRITE (7,25)((TRUCK(K,L),L=1,5),K=1,NTR)
   25 FORMAT ( I3,1X,3F9.2,F9.1)
      STOP
      END
```

FIGURE C-17
LISTING OF "RVSL 1" PROGRAM

APPENDIX D

FURTHER CONSIDERATIONS OF LIGHT WEIGHT EQUIPMENT

It has been noted in the main text of the report that certain design improvements or equipment modifications result in a reduction in train resistance which is constant and independent of velocity, if the modified Davis formula can be taken as a true representation of train resistance and if the simulation of these improvements or modifications has been correctly reflected in the adjustment of certain terms in that equation. These specific improvements and modifications are improved bearing seals, which is simulated by reducing the fixed drag per car, and rigidization of the track, which is simulated by reducing to zero, in the limit, the weight-dependent term of the mechanical (non-velocity-dependent) resistance. Reduction in either of these values theoretically results in a fixed reduction of energy per car-mile, independent of the velocity of operation, and the text of the report discusses under what circumstances the full portion of the theoretical savings can be attained and the reasons why under normal circumstances something less than that is actually attained.

It is apparent from examination of the modified Davis formula that weight reduction bears a certain resemblance to reduction in mechanical resistance and should at least partially have analogous impact upon fuel consumption; algebraically, reduction of the coefficient of the weight-dependent term of the mechanical resistance is equivalent to reduction of the term itself. If the velocity-dependent and also weight-dependent middle term of the modified Davis formula is ignored, and it was shown in Reference 1 to be the smallest of the components of train resistance and to amount for the average train to less than 10 percent of total resistance at speed around 40 mph, the analogy should be complete. Nevertheless, one feels intuitively that there must be a distinction between the effects despite the algebraic similarities, as work done against train resistance is always dissipative, while work done against gravity is at least partially available for later use. Work done against gravity is not specifically considered in the formula and must be separately taken into account. In the following paragraphs some discussion is given of various considerations with regard to the circumstances under which the use of light weight equipment becomes more favorable than merely achieving a slight reduction in mechanical drag. Figure D-1 shows these circumstances and limitations in graphical form in a form analogous to Figure 8, which illustrated the same constraint with regard to mechanical drag reduction achieved by improved bearing seals and rigidization of the track.

The figure is drawn, as with Figure 8, for a simple up-down operation as shown in Figure 7. As noted in the main body of the report, roundtrip operation is reasonably analogous to such a simplification; the only distinctions are that all grades are not the same on a real track and there are sections of level tangent track interspersed. Nevertheless, consideration of the figure, even though it is predicated on these considerations above and those assumptions mentioned in the first paragraph of this appendix, is worthwhile. While the particular points at which the curves break or intersect the axes are dependent upon the particular train and the particular operational velocity assumed, the general configuration will remain unchanged for any train and any velocity.

This figure is drawn in general terms only. For the up-down operation of Figure 7, the fuel consumption for zero grade is proportional to R, the train resistance at the velocity. For the light

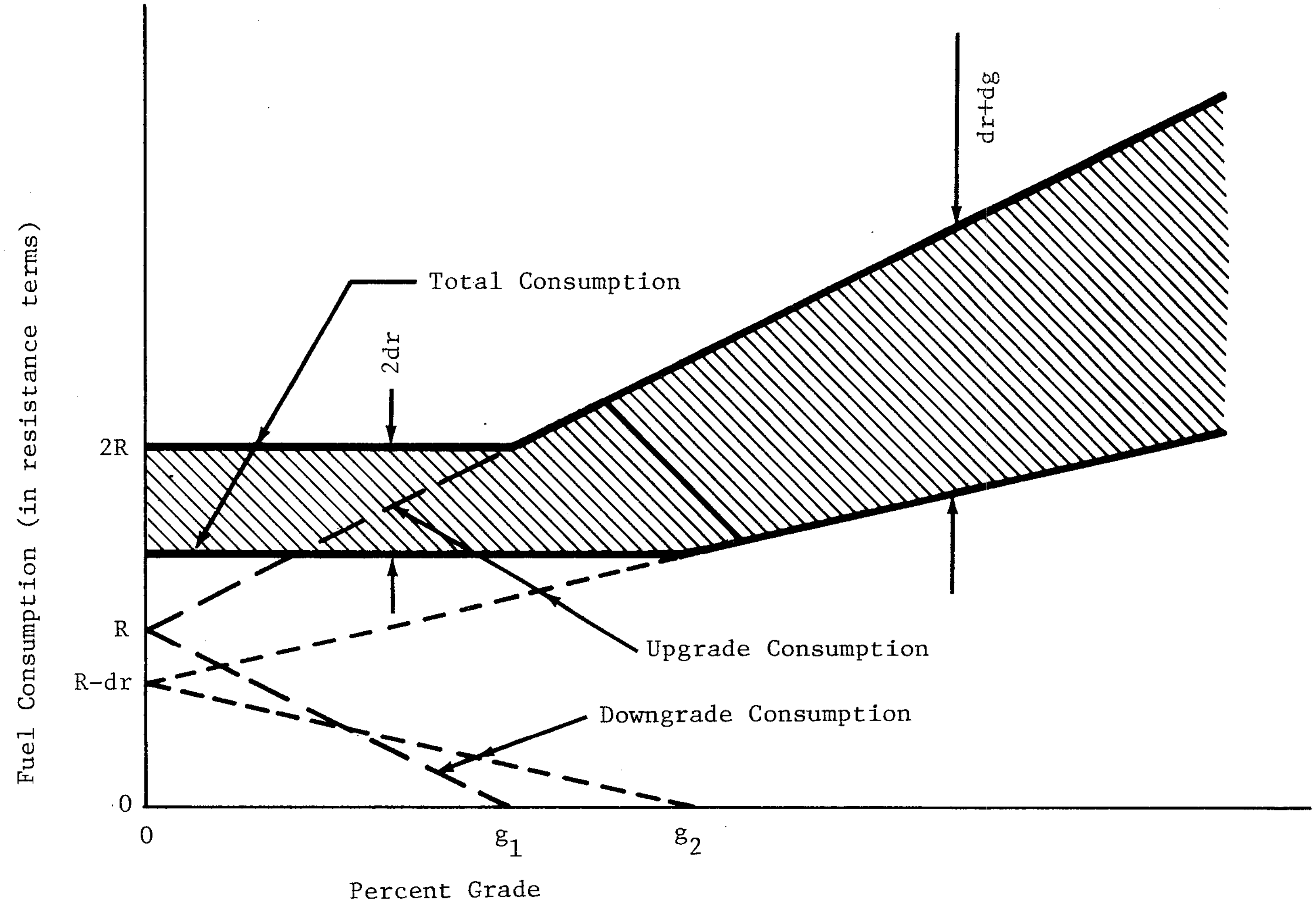


FIGURE D-1
FUEL SAVINGS FOR LIGHT WEIGHT EQUIPMENT

weight train, the corresponding point is R-dr. The term "dr" is the reduction of the mechanical resistance attributable to weight reduction. The grade g_1 is the grade at which the gravity pull downward in the train equals the resistance of the train. For the light weight train the corresponding point is g_2. The dashed lines indicate the fuel consumption on each slope of the hill for the standard train and the upper solid line the total consumption for the operation for the same train. The dotted lines indicate the fuel consumption on each slope of the hill for the light weight train and the lower solid line the total consumption for the operation for the light weight train.

This figure differs from the previous figure (Figure 8) in only one respect, that the lines emanating from the points on the ordinate R and R-dr are no longer parallel. This is attributable to the fact that the slope is dependent upon the magnitude of the gravity component of drawbar pull: for a lighter train the term is smaller, and the included angle at R-dr is smaller than at R. It can be proven that g_2 will always be larger than g_1 for a weight reduction; thus the configuration of lines will always resemble what presently appears in the figure.

For the portions of the curves where the grade is less than g_1, the difference can be shown both algebraically and geometrically to be equal to 2dr; this is the same value as that for Figure 8 if the same general terms were used there. It can be seen that beyond g_2 the lines diverge, and the difference grows as the grade on the hill increases. This is in contrast to the result of Figure 8, which shows that after a certain limiting grade is reached, the savings are limited to dr, or only 50 percent of the figure for smaller grades. It can be shown that the result in Figure D-1 for grades above g_2 is equal to dr+dg, where dg is the magnitude of the reduction in drawbar pull attributable to lightening the train and is a function of the grade. Thus as the grade increases, although dr remains constant, dg grows, and the potential savings are higher. In fact, it can be easily observed that the potential savings are always higher than 2dr.

The curves can be explained qualitatively as follows. The point g_2 is the grade at which gravity pull equals train resistance for the lighter train. Up to this grade, fuel consumption for the assumed operation is constant and all work done against gravity during the climb up the hill is recoverable on the downside, as the potential energy of the train is converted to work against train resistance. At grades larger than g_2, only a portion of this potential energy is recoverable; the rest must be dissipated in braking. It can be seen from the figure that an increase in g_2 is favorable in that the savings between g_1 and g_2 increase, rather than decrease, as in Figure 8. An increase of g_2 means that for the portion of fuel savings attributable to reduction of mechanical drag, the extent of the grades over which 100 percent of the theoretically attainable fuel savings are attainable is enlarged. Thus, between g_1 and g_2, additional savings are available which are not available to the standard train.

Below g_1, no gravitational effects are observable, and all work done against gravity is recovered on the downslope. In this area, lightening the train serves only to reduce mechanical drag. It has been noted in Reference 1 and in the text of this report that fuel savings from the use of light weight equipment are small. Still, with a light weight train, 100 percent of these potential savings are theoretically available up to the grade g_2; in addition, some additional savings in gravitational potential energy are achieved if the grade lies between g_1 and g_2 which were not available to the standard train. Although even with the light weight train the potential fuel savings from the reduction of train resistance drop to 50 percent of the full potential if the grade exceeds g_2, the entire savings continue to increase because of the term dg, which is a function of the grade.

In summary, it can be said with regard to the use of light weight equipment, that for the up-down type operation, for small grades (below g_1) only savings resulting from reduction in mechanical resistance will be effected, and it has been noted that these are small. However, the full potential savings are available, as the savings are effected on both the upslope and downslope. For large grades (greater than g_2) only 50 percent of the full potential savings attributable to reduction in mechanical resistance are available, and no savings are effected on the downslope, but additional savings are made on the upslope which are proportional to the grade, so that as the grade increases, the total possible savings from the use of light weight equipment increase. The advantages of weight reduction are therefore plainly dependent upon the grade g_1, below which the savings effected are only those attributable to reduction in mechanical resistance, which has been noted is small. Only above this grade does light weight equipment start showing a great potential. This grade, in turn, is dependent upon the velocity at which the train is to be operated and the resistance of the train at that speed.

This simplistic illustration of the effects of the use of light weight equipment in order to save fuel was offered to provide some rationale behind the figures presented in the main text of this report. The actual case is substantially more complicated, and the theoretical savings shown in Figure D-1 are clouded heavily by other factors discarded in the interests of simplicity. Operation over normal track, evan when considered in a round trip context so that for every up grade there is a corresponding down grade of equal length, is considerably more complex, as operation over level tangent track will be interspersed randomly with the up-down type operation illustrated here. Moreover, rather than a single grade to which particular savings from the figure might be applicable, many different grades occur in real track, so that over some of them only the savings attributable to reduction in mechanical resistance are effected. Even the "average" grade for the journey is not a particularly representative value, as the relationship of potential fuel savings to grade is non-linear.

In addition, velocity on the trip is not constant as assumed in the example, and as noted before, the particular point of intersection of the curves with the axes as well as the break points of the curves are speed-dependent. Also, at least one stop is made during the simulated trips reported in the text, and probably more during a real journey. And, at the risk of being repetitious, the rationale reflected in Figure D-1 is dependent upon the discarding of the middle term of the modified Davis equation as representing a negligible portion of resistance. In actuality, whether this is realistic depends again upon the particular type of operation; as the train becomes heavier and the velocity higher, the resistance attributable to this term becomes more consequential, and will act to enhance the savings reported here. The whole analysis in the report, of course, is predicated on the validity of the modified Davis equation and the proper simulation of the several effects. Finally, it must be noted that the existence of other parasitic resistances which consume fuel cloud the picture further, and that the savings in weight which can be made are still, as noted before, only a portion of the tare weight, which is in turn generally only a small portion of the gross weight.

Despite the above limitations, it is felt that the rationale offered explains to a certain degree what happens to fuel consumption when light weight equipment is utilized. To the extent that the operation resembles the simple up-down operation used as an example, the parallel will be valid. Unfortunately, as noted, real operation involves so many factors conflicting with this simple concept that the analogy is somewhat strained. Nevertheless, it is hoped that it sheds some light on what actually happens.

Because of the large deviation of real operation from such a simple example, and the dependence of the results upon the particular operation, it is felt that the results of the program are far more representative of the impact of utilizing light weight equipment in a particular operation than any other method might indicate, and the reader is urged to utilize the program to analyze the impact upon his own operation.

APPENDIX E

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