

BB 81 195810
tape 81/199556

Resistance of a Freight Train To Forward Motion - Volume IV, Users' Manual for Freight Train Fuel Consumption Program



February 1981

FINAL REPORT

Document is available to the U.S. public through
the National Technical Information Service
Springfield, Virginia 22161

Prepared for
U.S. Department of Transportation
Federal Railroad Administration
Office of Research and Development
Washington, D.C. 20590

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

NOTICE

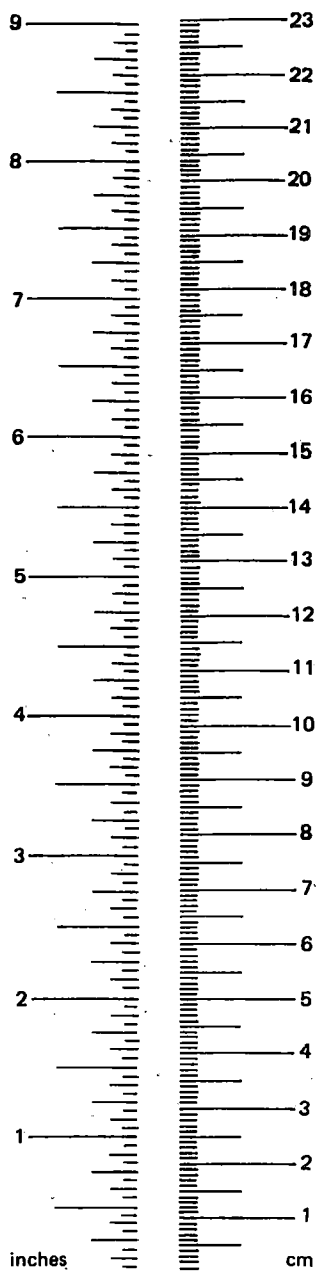
The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

1. Report No. FRA/ORD-78/04.IV		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Resistance of a Freight Train to Forward Motion - Volume IV, Users' Manual for Freight Train Fuel Consumption Program				5. Report Date February 1981	
				6. Performing Organization Code	
7. Author(s) John D. Muhlenberg				8. Performing Organization Report No. MTR-80W00127	
9. Performing Organization Name and Address The MITRE Corporation 1820 Dolley Madison Boulevard McLean, Virginia 22102				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No. DOT-FR-54090	
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Railroad Administration 400 Seventh Street, S.W. Washington, D. C. 20590				13. Type of Report and Period Covered Final Report Feb. 1979-July 1980	
				14. Sponsoring Agency Code	
15. Supplementary Notes See also FRA/ORD-78/04.I, Volume I, Methodology and Evaluation, April 1978; FRA/ORD-78/04.II, Implementation and Assessment, April 1978; and FRA/ORD-78/04.III, Volume III, Freight Train Fuel Consumption: Economic Analysis and Correlation of Predictions with Field Data, September 1980					
16. Abstract <p>This document provides information concerning a computer program devised to predict fuel consumption of a freight train operated over a track with known characteristics. The information is of value to both the user who wants merely to utilize the capabilities of the program and the programmers who need to understand its inner workings. The program is listed in its entirety in the document.</p> <p>Computer program available on magnetic tape, see FRA/ORD/MT-78/04.IV.</p>					
17. Key Words Train Resistance Fuel Consumption Train Fuel Consumption Prediction			18. Distribution Statement Available to the Public through the National Technical Information Service, Springfield, Virginia 22161.		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 62	22. Price

METRIC CONVERSION FACTORS

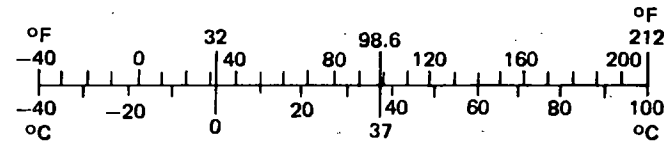
Approximate Conversions to Metric Measures

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



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	36	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



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

TABLE OF CONTENTS

	<u>Page</u>
LIST OF ILLUSTRATIONS	iv
LIST OF TABLES	iv
1.0 INTRODUCTION	1
2.0 USERS' GUIDE	3
2.1 Information Requirements	3
2.1.1 General Data Files	3
2.1.2 Stored Data Files	8
2.1.3 Operator Input Data	13
2.1.4 Subroutines	16
2.1.4.1 Subroutine RANDU	17
2.1.4.2 Subroutine TRCKRD	17
2.1.4.3 Subroutine LOCO2	17
2.2 Output	18
2.3 Summary	22
3.0 PROGRAM GUIDE	23
3.1 Introduction	23
3.2 General	23
3.3 Symbols and Definitions	37
3.4 Mathematical Rationale	40
3.4.1 Resistance Calculation	40
3.4.2 Velocity Determination	41
3.5 Acceleration and Braking Considerations	43
3.5.1 Speed Control	43
3.5.1.1 Within Band	45
3.5.1.2 Out of Band	46
3.5.2 Braking System Operation	47
3.6 Random Stop Algorithm	48
3.7 Program	51
REFERENCES	57

LIST OF ILLUSTRATIONS

<u>Figure Number</u>		<u>Page</u>
1	General Data Files	4
2	Train File	9
3	Order File	9
4	Typical Track File	11
5	Program for Track Data Reversal	12
6	Program for Elevation Rise Calculation	13
7	Operator Input Data	15
8	"Exec" File	19
9	Typical Data Output from Main Loop Interations	21
10	Listing of Main Program	24
11	Subroutine for Reading Track Data	34
12	Subroutine for Locomotive Characteristics	35
13	Braking Curve Approximation	49

LIST OF TABLES

<u>Table Number</u>		<u>Page</u>
I	Identification of Vehicle Types	6

1.0 INTRODUCTION

This manual describes a computer program which was specifically designed to calculate the fuel consumption of a freight train operated over a track the characteristics of which are known. Incidental to the calculation are the values of other parameters needed to perform the calculation, some of which contribute to a certain resemblance of the calculation to a complete simulation of the operation. The program, however, does not purport to be a train operation simulator.

The material herein should be useful to both the user who wants merely to utilize the capabilities of the program in its present form and the programmers who need to understand its inner workings. The logic of the program, in particular the notch selection process, is described in some detail, but complete logic flow diagrams are not provided. Some of the descriptive material herein has appeared before in reports of efforts utilizing the program; however, in the interest of progress the program has been steadily improved from the standpoint of accuracy and was finally revised carefully from the earlier versions from a programming standpoint to eliminate the previous need for large storage capacity and to place the characteristic tractive effort curves of various types of locomotives in a separate subroutine.

While attempts at validation of the program have been made with comparative success, and the program would be expected to predict actual fuel consumption within +0% and -10%, the prediction of fuel consumption cannot be expected to be precise. Like any other mathematical model, the program is a tool to be used with appropriate regard for its idiosyncrasies and its shortcomings. It is felt that the program will in actuality produce results more accurate than most existing train performance simulators, but

the fact remains that in the real world there are effects having considerable impact upon fuel consumption virtually impossible to predict or model in an accurate way. The results of the validation attempts were that the program consistently underpredicted the fuel consumption by a small percentage. It is believed that this underprediction is not attributable to defects in the program itself but rather to effects in the real world which are not being modelled, such as the manner in which the train is handled (for example, train stretching) or the effects of cross winds. The reader is referred to the three-volume series of reports which discuss, among other things, the development of this program, the methodology behind the calculation, and considerations with regard to accuracy.

2.0 USERS' GUIDE

The program requires only that information necessary to make a meaningful calculation of fuel consumption be either available for use by the program in stored form or be introduced into the program at the beginning of the interactive session with the operator. At the present time the program remains set up on an interactive basis, with the operator communicating with the computer through a terminal of some type. Only modest changes in the program, which should be obvious to anyone with minimal programming experience, would be necessary to eliminate this feature and convert it to the introduction of data from punched cards. Nevertheless the requirements for the information will remain. In addition, the information must be formatted correctly for compatibility with the needs of the program. As with any program, intelligent usage is the key to a satisfactory result.

2.1 Information Requirements

Information required for operation of this program, after the program has been read into the user's system, falls generally into four categories, each of which is discussed below. As the factors which affect fuel consumption are many, the information requirements might be considered to be large; however, it is felt that a reasonable compromise has been struck between information requirements and accuracy, not to mention computing time.

2.1.1 General Data Files

The program presently uses two general data files which are considered to be part of the program, so basic is the information. Neither file requires further action in order to be utilized by the program other than to have them read into the user's system. With appropriate changes in the program, however, they may be subsequently expanded to include more data. The present versions of both data files are illustrated in Figure 1.

CAR & LOCOMOTIVE DATA TABLE

124.0	124.0	3.0	3.0	60.7	23.3	.0100	34.8	65.8	410000.0
124.0	124.0	3.0	3.0	60.7	23.3	.0100	34.8	65.7	392000.0
122.0	122.0	3.0	3.0	59.4	22.8	.0100	34.4	59.2	277500.0
110.0	110.0	2.0	2.0	31.0	10.0	.0061	32.0	50.0	60700.0
90.0	90.0	1.5	1.5	32.5	12.5	.0238	28.0	45.0	58000.0
90.0	90.0	1.5	1.5	22.8	8.7	.0166	28.0	45.0	58000.0
45.0	45.0	2.0	2.0	19.5	7.5	.0241	19.0	54.0	68900.0
10.0	10.0	2.0	2.0	0.0	0.0	.0104	12.0	60.0	79500.0
122.0	10.0	3.0	45.0	37.9	9.5	.0085	25.0	85.0	76200.0
10.0	122.0	45.0	3.0	37.9	9.5	.0085	25.0	85.0	76200.0
122.0	122.0	3.0	3.0	8.5	8.5	.0170	38.0	85.0	69000.0
78.0	10.0	3.0	45.0	34.6	8.6	.0085	20.0	85.0	76200.0
10.0	78.0	45.0	3.0	34.6	8.6	.0085	20.0	85.0	76200.0
78.0	78.0	3.0	3.0	34.6	8.6	.0085	28.0	85.0	76200.0
124.0	124.0	11.5	11.5	31.7	7.9	.0085	29.0	60.0	51500.0
150.0	150.0	2.0	2.0	137.6	34.4	.0180	40.0	85.0	76200.0
135.0	135.0	2.0	2.0	90.6	22.6	.0085	37.0	79.0	180000.0
135.0	135.0	3.0	3.0	39.0	13.0	.0051	37.0	88.0	119200.0
74.0	74.0	3.0	3.0	8.5	4.5	.0108	30.0	60.0	77600.0
110.0	130.0	5.0	5.0	73.9	18.5	.0085	32.0	40.0	60000.0
10.0	10.0	2.0	2.0	6.7	1.7	.0085	12.0	85.0	76200.0

ADDITIONAL LOCOMOTIVE PARAMETERS

3.0	75000.0	10.0	10.0	5.5	25.0
3.0	47000.0	15.0	17.5	5.5	25.0
2.0	27900.0	10.0	10.0	5.5	25.0

FIGURE 1
GENERAL DATA FILES

The first contains general information about various types of rolling stock, including locomotives, which might be used in a train—mostly dimensional, but some non-dimensional coefficients and the tare weights are included. The list presently comprises twenty-one types of rolling stock, including such standard types as a typical boxcar, hopper car, tank car, gondola, and flat car. A loaded or covered hopper car is included as a separate item. Data on three different locomotive types are included. The list may be expanded by adding lines to the file, but certain format requirements in the program would require changes for compatibility. The data are required for calculating the mechanical, velocity dependent, and aerodynamic resistances of the items of rolling stock considered in the program. The twenty-one types of vehicles presently listed are identified in Table I.

A short explanation of each item of data in the file seems worthy of inclusion here. The user is referred to References (1), (2), and (3) for a complete explanation of the rationale behind the choice of parameters and their values. When the program is used, if the option to print data other than the result is used, the complete file is printed with the title "Car and Locomotive Data Table", as shown in the figure. The file consists of ten items of data for each of twenty-one vehicle types presently tested.

- (a) Column (1) shows the approximate cross sectional area of the vehicle, in ft^2 , at the section including the largest and most prominent area at the front of the car. Column (2) shows the same at the rear of the car. It is obvious that there is considerable subjectivity in the choice of values for these two and the location of the cross section to be taken. However, as most trains are fairly lengthy, errors in the selection of either above will tend to cancel each other out. The choices given seem to have produced satisfactory results, and the results of the program will be found to be comparatively insensitive to a variation in the magnitude of any particular datum in this table.

TABLE I
IDENTIFICATION OF VEHICLE TYPES

TYPE	DESCRIPTION
1	GM EMD SD-40 Locomotive
2	GM EMD SD-45 Locomotive
3	GM EMD GP-38 Locomotive
4	Boxcar
5	Hopper Car, empty
6	Hopper Car, covered or loaded
7	Gondola
8	Flat Car
9	TOFC, trailer in front
10	TOFC, trailer in rear
11	TOFC, twin trailer
12	COFC, container in front
13	COFC, container in rear
14	COFC, twin trailer
15	Container Well Car
16	Auto Rack Car
17	Instrument Car
18	Stack-Pak Car
19	Tank Car
20	Caboose
21	TTX Special Flat Car

NOTE: Type numbers identify the line numbers in the Car and Locomotive Data Table incorporating the characteristics of the particular vehicle in a format suitable for use with the program. They are also used in the first column of the "Train" and "Order" files. They are included in the data file for identification purposes but are neither read per se by the main program nor printed with the output data.

- (b) Column (3) shows the distance in feet from the coupling point at the forward end of the vehicle to the area of major cross-sectional prominence in (1) and (2) above. Column (4) shows the same for the rear end of the vehicle.
- (c) Column (5) shows the drag area ($C_D A$) in ft^2 for the forward end of the car. Column (6) shows the drag area in ft^2 for the rear end of the car. Column (7) shows the dimensionless adjusted skin friction coefficient C_S for the surface area of the car. The user is referred to References (1), (2) and (3) for the rationale behind the choice of values.
- (d) Column (8) shows the adjusted surface perimeter in ft. for use with the above C_S . Column (9) shows the length of the car in feet between the major cross sectional areas selected in (1) and (2) above. Column (10) lists the tare weight of each vehicle in lbs.

The second file contains additional data relevant to locomotives and necessary for fuel consumption calculations. At present, six items of data are listed for each of three types of locomotives. The data were culled from Reference (4), made available to the author by manufacturers or found in the literature, or estimated if not readily available. The data as shown reflect the EMD SD-40, SD-45, and GP-38 locomotives respectively.

- (a) Column (1) gives the number of axles per truck.
- (b) Column (2) gives the initial tractive effort in lbs. It corresponds with the value from the tractive effort curves for operation at zero velocity in the fifth notch.
- (c) Column (3) gives the velocity in mph below which the approximations to the tractive effort curves in the program are straight lines; for certain locomotives, that point is different for the higher notches and is given in the fourth column.
- (d) Column (5) gives the fuel consumption rate at idle in gpm. Other figures not being available to the author at time of writing, the figure reported in Reference (5) for the SD-40 was used for all locomotives.
- (e) An estimated value for fuel consumption in gpm during periods of dynamic braking appears in column (6).

While the second file presently lists values for certain characteristics of three locomotives, with appropriate changes in format statements in the program to accommodate an expanded file, as with the first file (above), the characteristics of additional vehicles may be appended when needed.

2.1.2 Stored Data Files

These are data files containing lengthy information applicable to a particular operation. Two of these apply to the train, one to the track. Once prepared, they may naturally be used over again, but they must generally be prepared specially for this program and must be on file in the user's system so that the program may read them when called upon. When the program is run, the first questions asked of the operator are which of these three files he wishes to use. The operator simply inserts a number referring to the particular file.

- (a) The train file (see Figure 2) lists in the second column the vehicle types in the train in the initial order. Locomotives must be at the head of the list, one behind the other; no provision has been made for locating locomotives elsewhere in the train. The numbers refer to the rows of data in the Car and Locomotive Data Table previously referred to. The third column gives the net weight of the vehicle load in tons; for locomotives, cabooses, and empty vehicles, this is zero. Format requirements are I3, lX, I3, F6.1. Numbers in the first column are reference numbers only and are not read by the program.

- (b) The order file (see Figure 3) 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 and a new file created. Thus if it is desired to place in the number 4 position the vehicle which in the train file is in the number 7 position, in the new order file the number 7 is placed in the fourth row, and so on, as

Ref.	Type	Net
101	2	0.0
102	2	0.0
103	8	34.1
104	9	34.1
105	4	34.1
106	14	34.1
107	7	34.1
108	12	34.1
109	11	34.1
110	8	34.1
111	20	0.0

**FIGURE 2
TRAIN FILE**

101	1
102	2
103	3
104	4
105	5
106	6
107	7
108	8
109	9
110	10
111	11

a) Original Order.

101	1
102	2
103	6
104	7
105	10
106	5
107	9
108	4
109	8
110	3
111	11

b) Rearranged Order

**FIGURE 3
ORDER FILE**

illustrated. Note that in the rearranged train the two locomotives remain at the front of the train. The reader is referred to Reference (1) for a more thorough discussion of these considerations. Format requirements are I3, 2X, I3. As with the train file (above), numbers in the first column are reference numbers only and are not read by the program.

- (c) The track file (see Figure 4) characterizes the track over which the simulated trip will be made. It contains information identifying milepost number, milepost, grade, grade equivalent of curvature, and speed limit, all in a single file. Format requirements are I3, 1X, 3F9.2, F9.1. Milepost numbers in the first column are not read by the program. Mileposts are in miles, grade in percent, curvature in percent grade equivalent, and speed limits in mph. Track records must be used with discretion as they may not necessarily be formatted in an identical fashion from user to user. In particular, track records for use with this program must be forward looking, i.e., the records at a particular milepost must reflect the conditions in the next section ahead of the milepost. Quite often, speed limit information is available only in a separate file and must be appropriately interspersed with the other data. Curvature information is often less detailed and less accurate than a manual extraction of data directly from track charts would reveal and may contribute to an underestimate of true fuel consumption.

Some specific comments regarding the track file formatting are necessary. 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 Figure 5. A short program which computes the rise in

Milepost	Distance	Grade	GFC	Speed Limit
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	20.0
119	23.58	.38	.02	10.0
120	24.58	.12	.02	0.0
121	24.68	.12	.02	10.0
122	26.93	-.12	.02	20.0
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	40.0
133	41.92	.12	.02	30.0
134	43.11	-.12	.02	20.0
135	44.59	-.63	.02	10.0
136	45.93	-.12	.10	0.0

FIGURE 4
TYPICAL TRACK FILE

FILE: RVSL1 FORTRAN A

```

      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
```

12

FIGURE 5
PROGRAM FOR TRACK DATA REVERSAL

elevation between end points of the track file according to the data therein is given in Figure 6.

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. A suggested modification at such points is 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. See Mileposts 120 and 121, Fig. 4, supra.

In addition, speed limits in track sections adjacent to the origin and destination and around required stops should be modified to require gradual stopping and starting about those points, as the program attempts to match the train speed with the speed limit. The adjacent section should be 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.

2.1.3 Operator Input

The program is presently set up on an interactive basis. The operator must first specify the file numbers of the train, order, and track files (above) to be used to simulate the operation. The format requirement is simply I2 or I3. In addition, the operator is required to supply answers to seven additional questions discussed below. Input questions and typical answers are illustrated in Figure 7.

FILE: RISE1 FORTRAN A

```

      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
```

14

FIGURE 6
PROGRAM FOR ELEVATION RISE CALCULATION

OUTPUT FILE ERASED
INPUT TRAIN FILE NUMBER
79
INPUT ORDER FILE NUMBER
11
INPUT TRACK FILE NUMBER
13

DMSLIO740I EXECUTION BEGINS...

INPUT, NO. OF LOCOMOTIVES, ENTER A 1 DIGIT NO.

2

INPUT, NO. OF VEHICLES IN TRAIN, (INCL. LOCOMOTIVES), ENTER A 3 DIGIT NO.

011

INPUT, NO. OF TRACK RECORDS IN TRACK FILE, ENTER A 4 DIGIT NO.

0036

START PRINT AT I = (A 4 DIGIT NO.

0001

ENTER OPERATIONAL SPEED LIMIT, MPH

79.0

INPUT, ESTIMATED HEADWIND, MPH

00.0

DATA PRINT OPTION, TYPE 1 FOR YES, 0 FOR NO

1

FIGURE 7
OPERATOR INPUT DATA

- (a) No. of locomotives: Enter the number of locomotives in the train the operation of which is being simulated. Enter only a one digit number from one to nine.
- (b) No. of vehicles in train: Enter the number of vehicles in the same train. The figure includes the number of locomotives as well as the trailing vehicles. Format requires that a three digit number be entered, i.e., if the number is 88, enter 088.
- (c) No. of Track Records: Enter the number of track records in the track file corresponding to the track over which operation is being simulated. Format requires that a four digit number be entered, i.e., if there are only 95 records, enter 0095.
- (d) Start Print at I = : If asked, the program will print data from every iteration of the loop. Format requires the entering of a four digit number. If all such data is desired, the print should begin with I=0001. If only portions subsequent to I=56, for example, are needed, enter 0056. If only the result is needed, the answer to this question, apart from format, is immaterial, as the last question (below) overrides.
- (e) Operational Speed Limit, mph: The answer to this question imposes a maximum speed limit for the simulated trip which overrides information from the track records. Format is F4.1.
- (f) Estimated Headwind, mph: If a headwind for the trip is expected, enter the estimated velocity in mph. Format is F4.1.
- (g) Data Print Option: The program generates ten items of information at each iteration of the loop (see Section 2.2 below). If the operator wishes to have this information printed for the iterations specified above, the average trip velocity, and average rate of fuel consumption are needed, enter the digit 0.

2.1.4 Subroutines

The program utilizes three subroutines, each of which performs a particular function in the program. The first requires nothing to be done in connection with its operation, the second requires only that it be read into the user's system, and the third requires only that it be read into the user's system and expanded if desired

when additional information becomes available or is essential to accurate simulation. The subroutines are listed in Section 3.

2.1.4.1 Subroutine RANDU

This subroutine generates random numbers in connection with a stopping algorithm. As it comprises only seven lines, it is attached directly to the main program.

2.1.4.2 Subroutine TRCKRD

This subroutine inspects the track file and determines the track record corresponding with the location of the train. The main program retains and uses only data from three track records: those used in the previous time step, those used in the present time step, and those in the track record directly ahead of the train's current position. The subroutine readjusts all of these values in an appropriate fashion as the train passes into the next track section. The subroutine must, of course, be read into the user's system so that it is available for calling.

2.1.4.3 Subroutine LOC02

This subroutine incorporates the tractive effort characteristics of various locomotives and, when called upon, calculates the tractive effort exerted by the locomotive at a particular notch setting and speed. At the present time, the characteristics of the GP-38, SD-40, and SD-45 locomotives of the Electromotive Division, General Motors, are given. The characteristics were in one instance supplied by the manufacturer. For the other two locomotives, a single tractive effort curve from the Car and Locomotive Cyclopedia was utilized and curves for the other notch positions were estimated from that curve.

The curves only approximate the true characteristics. It is not essential to the accuracy of the program that any better approximation be made. Above a certain velocity, usually 10 mph but occasionally higher, the curves have been approximated by a hyperbolic function; below this velocity, a straight-line approximation has been made. The straight line portions are truncated above a certain tractive effort level. It is possible, of course, that the curves could be approximated in a different fashion, but modifications to the subroutine would be required.

The subroutine simply selects a particular set of equations determined by the value of LT, corresponding to locomotive type, and a pair of equations, determined by the value of the parameter UU, corresponding to the notch setting. One equation (TEH) reflects the hyperbolic approximation above a certain velocity, the second equation (TEL) the straight line approximation. Which result of the two equations is used is determined by the main program, based upon the train velocity.

2.2 Output

The user has three choices of output, permitting the minimization of printing costs, if desired. Complete information is available under the first option below. The second and third options print only selected portions of the sometimes lengthy output. Selection of the options is described in Section 2.1.3.

The identification numbers of the train, order, and track data files used to make the run are presently printed along with other data selected. This has been arranged in an "EXEC" file (see Figure 8) in conjunction with the IBM 370 system for which the program is presently formatted. The printing of these data, although recommended for the user regardless of system, does not form a portion of the program in the form listed.

FILE: FTFC52 EXEC A

```
&CONTROL ERROR
ERASE FTFC52 OUTPUT C
ERASE XYDATA DATA A
ERASE IPLOT DATA A
&TYPE OUTPUT FILE ERASED
&TYPE INPUT TRAIN FILE NUMBER
&READ VARS &T
FILEDEF FT01F001 DISK TRAIN&T DATA A
&TYPE INPUT ORDER FILE NUMBER
&READ VARS &O
FILEDEF FT02F001 DISK ORDER&O DATA A
&TYPE INPUT TRACK FILE NUMBER
&READ VARS &TK
FILEDEF FT03F001 DISK TRACK&TK DATA A
FILEDEF FT04F001 DISK COEFF DATA A
FILEDEF FT10F001 DISK LOCO1 DATA A
EXEC DEFT CYL 10 MODE C ADDR 300
ACC 300 C
DESBUF
&STACK HT
&STACK I *****
&STACK I * TRAIN&T DATA FILE WAS USED FOR THIS RUN *
&STACK I * ORDER&O DATA FILE WAS USED FOR THIS RUN *
&STACK I * TRACK&TK DATA FILE WAS USED FOR THIS RUN *
&STACK I *****
&STACK FILE
FEDIT FTFC52 OUTPUT C
&STACK RT
FILEDEF FT07F001 DISK FTFC52 OUTPUT C (DISP MOD)
FILEDEF FT08F001 DISK XYDATA DATA A
FILEDEF FT09FC01 DISK IPLOT DATA A
LOAD FTFC52 (CLEAR START
&END
```

FIGURE 8
"EXEC" FILE

In addition to the above, the following are printed under the option for complete printing of data:

1. A duplicate of the questions asked of operator at the initiation of the program and the operator's response.
2. The Car and Locomotive Data Table.
3. The Table of Additional Locomotive Parameters.
4. Net Train Load and Gross Train Weight, in tons.
5. Locomotive and car mechanical drag, pounds.
6. The equation for the resistance of the train.
7. An initial random number, associated with the random stop routine, which is presently not being used.
8. A complete set of data for every iteration of the main loop, as follows (see Figure 9):

- a. Two random numbers associated with the length of the random stop routine, which is presently not being used. (The length of station stops has been arbitrarily set at five minutes.)
- b. In consecutive order, from left to right, across the page in three lines

I	The loop index
TE	Tractive effort, pounds
U	An indicator of throttle position or braking effort (value ranges from 1 to 17)
TR	Train resistance (dissipative), pounds
VDD	Acceleration, mphps
V	Velocity, mph
J	Track Record Number
DS	Distance, miles
DT	Time interval, seconds
S	Cumulative distance, miles
DFC	Fuel consumption, gallons
CFC	Cumulative fuel consumption, gallons
CDT	Cumulative time, seconds

	696	521						
23	53.03E+03	15	35.72E+02	50.35E-02	35.02E+00	3	90.27E-03	10.00E+00
	23.18E-01		82.64E-02	53.68E-01				62.24E+01
			49.58E-01	51.75E-02				
	866	502						
24	57.90E+03	16	42.17E+02	54.69E-02	40.49E+00	3	10.49E-02	10.00E+00
	24.23E-01		10.49E-01	64.17E-01				63.24E+01
			62.93E-01	60.88E-02				
	225	832						
25	28.70E+03	14	46.74E+02	24.41E-02	41.71E+00	3	57.08E-03	50.00E-01
	24.80E-01		28.21E-02	66.99E-01				63.74E+01
			33.85E-01	63.06E-02				

21

FIGURE 9
TYPICAL DATA OUTPUT FROM MAIN LOOP ITERATIONS

RFC Rate of fuel consumption (all locomotives
 combined), gallons/minutes

CRFC Cumulative rate of fuel consumption (for
 entire distance traveled)

9. The total train fuel consumption, the average rate of fuel consumption for the entire trip, and the average velocity for the trip.

A second option permits the printing of all of the above except for the values of the 15 variables above during the early iterations of the loop. The value of these 15 variables is printed for only the iterations of the loop equal or subsequent to a value selected at the time the program was initiated. This option is selected by entering a number other than 0001 in answer to the question posed (see Section 2.1.3(d)).

A third option permits the printing and identification of only the final three values (see 9 above). This option is selected by entering a zero in response to the question on data print option (see 2.1.3(g) above).

2.3 Summary

The above should constitute sufficient information for an intelligent user to utilize the program to calculate the fuel consumption of a freight train operated over a specific route. The user is referred to the programmer's guide (following section) if modifications to the program are needed or if problems in its operation are encountered. A listing of the program is provided there for reference.

3.0 PROGRAM GUIDE

3.1 Introduction

This section provides general information about the program in its present form which should be useful to a programmer if modifications or additions to the program or its subroutines are contemplated. Program symbols are defined and the mathematical background behind the calculation of the train's fuel consumption and the determination of the train's velocity is given. A general discussion of the logic behind acceleration and braking, as determined by the program, is given. The random stop algorithm, although not presently in use in the program, is described. Finally, commentary on individual sections of the program itself is given.

Some of the material herein, as with some of the material in the previous section, has been previously published in reports documenting the results of simulations of freight train operations. The material, however, has been revised to reflect program upgrading.

3.2 General

The program is written in FORTRAN and in its present form is compatible with an IBM 370 system. A complete listing of the final version of the program is given in Figure 10. Subroutines used in conjunction with the main program are illustrated in Figures 11 and 12. Since appearance of an earlier version of the program in one of the three volumes of a series of reports on the fuel consumption of freight trains (Reference 2), the program has been substantially modified: several changes have been made in the computation itself to improve the accuracy of the simulation, and the program itself has been revised in order to eliminate previous requirements for excessive data storage capacity (768K). For a discussion of modifications to the program made subsequent to the publication of

```

DIMENSION NUM(2),N1(12),N2(12),LOCO1(3,6),TRACK(3,4)
DIMENSION ARRAY(200),DATA(200,2),COEFF(21,10),ORDER(200)
EQUIVALENCE (ARRAY,DATA)
INTEGER ARRAY,CUTOFF,ORDER,OPTM1
INTEGER P,PP,PPP,Q,U,JU,W,X,Y,Z,ZX,ZSL
REAL MV,MF,LIMIT,N3,N4,MDFC,LOCO1,KD,KE,KF,MN,NET,OSL,MPH

```

C-----INITIALIZATION

```

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)
DT = 10.0
NI = 2000
TOL = 2.5
NC = 2
TIME = 10.0
MF = 5.0
CUTOFF = 1000
SIGMA = 300.0
AM = 0.0
WT = 0.0
SUM1L = 0.0
SUM1C = 0.0
SUM1 = 0.0
SUM2 = 0.0
SUM3 = 0.0
SUM4 = 0.0
SUM5 = 0.0
SUM6 = 0.0
CFC = 0.0
J = 1
V1 = 0.0
VDD = 0.0
IX = 999999999

```

C-----READ INPUTS AND DATA FILES:

```

50 READ(4,50)((COEFF(I,J),J=1,10),I=1,21)
   FORMAT (5X,F5.1,2X,F5.1,2X,F4.1,2X,F4.1,2X,F5.1,2X,F5.1,
1 2X,F5.4,2X,F4.1,2X,F5.1,2X,F8.1)
53 READ (10,53)((LOCO1(K,L),L=1,6),K=1,3)
   FORMAT (5X,F3.1,3X,F7.1,3X,F4.1,3X,F4.1,3X,F3.1,3X,F4.1)
   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)

```

FIGURE 10
LISTING OF MAIN PROGRAM

```

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
17  FORMAT(I4)
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, 27)
WRITE (7, 27)
27  FORMAT (1X, ' ENTER OPERATIONAL SPEED LIMIT, MPH')
READ (5, 19) OSL
WRITE (7, 19) OSL
19  FORMAT (F4. 1)
WRITE (6, 18)
WRITE (7, 18)
18  FORMAT (1X, ' INPUT, ESTIMATED HEADWIND, MPH')
READ (5, 19) HW
WRITE (7, 19) HW
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)
IF (OPTN1.EQ.0) GO TO 115
WRITE (7, 114)
114 FORMAT (12X, ' CAR & LOCOMOTIVE DATA TABLE')
WRITE (7, 41)
WRITE (7, 50) ((COEFF(I, J), J=1, 10), I=1, 21)
WRITE (7, 41)
WRITE (7, 113)
113 FORMAT (12X, ' ADDITIONAL LOCOMOTIVE PARAMETERS')
WRITE (7, 41)
WRITE (7, 53) ((LOCO1(K, L), L=1, 6), K=1, 3)
WRITE (7, 41)
115 CONTINUE
C-----CALCULATE TRAIN WEIGHTS
DO 337 K = 1, NV
NET = NET+DATA (ORDER(K), 2)

```

FIGURE-10 (Continued)
LISTING OF MAIN PROGRAM

```

337  GROSS = GROSS+DATA(ORDER(K),2)+COEFF(ARRAY(ORDER(K)),10)/2000.0
      WRITE(7,338) NET
338  FORMAT (1X,'      NET TRAIN LOAD, TONS:',F10.2)
      WRITE(7,41)
      WRITE(7,344) GROSS
344  FORMAT (1X,'      GROSS TRAIN WEIGHT, TONS:',F10.2)
      WRITE(7,41)
C-----*****
C
C-----CALCULATE RESISTANCES OF EACH VEHICLE AND ADD
C
C-----*****
      DO 24 I = 1,NV
      IF (I.GT.1) GO TO 43
      DO 25 K = 1,NV
      NET = DATA(ORDER(K),2)
      TARE = (COEFF(ARRAY(ORDER(K)),10))/2000.0
      GROSS = NET+TARE
      WT = WT+GROSS
      IF (K.LE.NL) SUM1L = SUM1L+GROSS*.6+40.0*LOCO1(ARRAY(1),1)
      IF (K.GT.NL) SUM1C = SUM1C+GROSS*.6+80.0
      SUM2 = SUM2+.01*GROSS
25  CONTINUE
      SUM1 = SUM1L+SUM1C
      IF (OPTN1.EQ.0) GO TO 43
      WRITE (7,89) SUM1L,SUM1C
89  FORMAT (10X,' LOCO. MECH. DRAG, LBS.:',F8.2,
1 4X,' CAR MECH. DRAG, LBS.:',F8.2)
43  CONTINUE
      IF (I.EQ.1) GO TO 37
      GF = COEFF(ARRAY(ORDER(I)),3)+COEFF(ARRAY(ORDER(I-1)),4)
      GO TO 38
37  GF = 1000.0
38  IF (I.EQ.NV) GO TO 39
      GA = COEFF(ARRAY(ORDER(I)),4)+COEFF(ARRAY(ORDER(I+1)),3)
      GO TO 42
39  GA = 1000.0
41  FORMAT (/)
42  CONTINUE
      IF (I.EQ.1) CFF = 1.0
      IF (I.GT.1) CFF = .5*TANH(.5*(ALOG(GF/10.0)-1.4))+.5
      IF (I.EQ.NV) CFA = 1.0
      IF (I.LT.NV) CFA = .5*TANH(1.1*(ALOG(GA/10.0)-1.4))+.5
      IF (I.EQ.1) GO TO 160
      CAA = COEFF(ARRAY(ORDER(I)),1)
      CBB = COEFF(ARRAY(ORDER(I-1)),2)
      IF (CAA-CBB) 251,252,252
251  AFF = 0.0
      GO TO 170
252  AFF = (CAA-CBB)/CAA
      GO TO 170
160  AFF = 1.0
170  IF (I.EQ.NV) GO TO 140
      CC = COEFF(ARRAY(ORDER(I)),2)
      DD = COEFF(ARRAY(ORDER(I+1)),1)

```

FIGURE 10 (Continued)
LISTING OF MAIN PROGRAM


```

IF (CC-DD) 253,254,254
253 AFA = -4.0*EXP(-.173*GA)*(1.0-EXP(-.173*GA))
GO TO 402
254 AFA = (CC-DD)/CC
GO TO 402
140 AFA = 1.0
402 CONTINUE
FF = 1.0-(1.0-CFF)*(1.0-AFF)
FA = 1.0-(1.0-CFA)*(1.0-AFA)
D = KD*COEFF(ARRAY(ORDER(I)),5)*FF
E = KE*COEFF(ARRAY(ORDER(I)),7)*COEFF(ARRAY(ORDER(I)),8)*
1 COEFF(ARRAY(ORDER(I)),9)
F = KF*COEFF(ARRAY(ORDER(I)),6)*FA
IF (ARRAY(ORDER(I)).LE.NL) CDA = 8.0*LOCO1(ARRAY(1),1)
IF (ARRAY(ORDER(I)).GT.NL) CDA = 16.0
UC = 2.0*.272*CDA*KD+.003*KD*COEFF(ARRAY(ORDER(I)),9)*10.0
G = D+E+F+UC
SUM6 = SUM6+G
24 CONTINUE
SUM3 = SUM6/NV
WRITE (7,41)
WRITE (7,458) SUM1,SUM2,SUM3
458 FORMAT (4X,' EQUATION FOR THE RESISTANCE OF THIS TRAIN IN LBS. IS
1 :',/,/,4X,' R = ',F10.2,' + ',F10.4,'*V + ',F10.4,
1 '*NV*V**2',/,/,10X,' WHERE NV IS THE TOTAL NO. OF VEHICLES')
C-----END OF CALCULATION OF RESISTANCE COEFFICIENTS
C-----EXAMINE TRACK AND SPEED LIMIT RESTRICTIONS:
WL = COEFF(ARRAY(ORDER(1)),10)/2000.0
LIMIT = .23*NL*WL*2000.0
READ (3,10)((TRACK(M,N),N=1,4),M=2,3)
10 FORMAT (4X,3F9.2,F9.1)
IF (TRACK(2,4).GT.OSL) TRACK(2,4) = OSL
IF (TRACK(3,4).GT.OSL) TRACK(3,4) = OSL
DO 79 M = 1,4
TRACK(1,M) = TRACK(2,M)
79 CONTINUE
DTC = DT
WRITE (7,41)
CALL RANDU(IX,IY,RN)
IF (OPTN1.EQ.1) WRITE (7,66) RN
66 FORMAT (3X,' RN = ',F8.6,/)
C-----*****
C
C-----START SIMULATION OF TRIP -- MAIN LOOP
C
C-----*****
DO 90 I = 1,NI
DT = DTC
49 FORMAT (F10.2)
P = 0
PP = 0
PPP = 0
IF (I.NE.1) GO TO 110
C-----INITIAL STEP OF MAIN LOOP
TE = NL*LOCO1(ARRAY(1),2)

```

FIGURE 10 (Continued)
LISTING OF MAIN PROGRAM

```

IF (TE.GT.LIMIT) TE = LIMIT
S = 0.0
S1 = 0.0
L = 13
U = L
J = 1
K = 2
CALL TRCKRD (S1,NTR,OSL,J,TRACK)
VDD=(TE-(SUM1+20.0*WT*(TRACK(2,3)+TRACK(2,2))))/(100.0*WT)
DV = VDD*DT
V = DV
MV = V/2.0
DS = V*DT/(2.0*3600.0)
S = DS
RFC = TE*MV*CF2*60.0
CRFC = RFC
IF ((V.GT.90.0).AND.(VDD.GT.0.0)) GO TO 620
GO TO 130
C-----ALL SUBSEQUENT STEPS OF MAIN LOOP
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
CALL TRCKRD (S1,NTR,OSL,J,TRACK)
IF (I.GT.1.AND.J.NE.NTR.AND.V1.EQ.0.0.AND.TRACK(2,4).EQ.0.0)
1 TRACK(2,4) = TRACK(3,4)
IF (ZSL.EQ.1) GO TO 700
IF (TRACK(2,4).EQ.0.0.AND.Z.NE.2) ZSL = 1
IF (TRACK(2,4).EQ.0.0.AND.Z.NE.2) GO TO 700
DIF = (V1-TRACK(2,4))
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(2,4)
GO TO 301
304 IF (ABS(VDD1).LE.TOL/(MF*DT)) GO TO 351
GO TO 303
351 IF (TRACK(1,2).EQ.TRACK(2,2).AND.TRACK(1,3).EQ.TRACK(2,3)
1 .AND.TRACK(1,4).EQ.TRACK(2,4)) GO TO 352
303 DIF2 = V2-TRACK(2,4)
301 IF (VDD1.GT.0.0.AND.ABS(DIF2).GT.TOL) P = 3
IF (VDD1.GT.0.0.AND.ABS(DIF2).LE.TOL) P = 2
IF (VDD1.EQ.0.0) GO TO 305
IF (VDD1.LT.0.0.AND.ABS(DIF2).LE.TOL) P = 4

```

FIGURE 10 (Continued)
LISTING OF MAIN PROGRAM

```

      IF (VDD1.LT.0.0.AND.ABS(DIF2).GT.TOL) P = 5
      GO TO 900
400  IF (V1-TRACK(2,4)) 600,600,500
600  IF(VDD1.GE.0.0) P = 1
      PPP = 1
      IF (VDD1.LT.0.0) P = 5
      GO TO 900
500  IF (VDD1 .GE.0.0) P = 3
      IF (VDD1.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.GE.0.0.AND.ABS(DIF/VDD) .LT.TIME)
1    GO TO 120
      IF (PPP.EQ.2.AND.VDD.LT.0.0.AND.ABS(DIF/VDD) .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-V1)/20.0
      FRF = .06*(EXP(BETA)-EXP(-BETA))/(EXP(BETA)+EXP(-BETA))+.18
      BFC = (NV-NL)*.60*66000.0*FRF
      BFL = NL*.90*WL*2000.0*FRF
      FB = BFC+BFL
313  IF (U.LE.9) GO TO 314
      LT = ARRAY(ORDER(1))
      VP = V1
      CALL LOCC2 (U,NL,LT,VP,TEH,TEL)
      GO TO 218
314  GC TO (201,202,203,204,205,206,207,208,209),U

```

FIGURE 10 (Continued)
LISTING OF MAIN PROGRAM

```

201  TE = -1.0*FB
      GO TO 225
202  TE = -.875*FB
      GO TO 225
203  TE = -.750*FB
      GO TO 225
204  TE = -.625*FB
      GO TO 225
205  TE = -.500*FB
      GO TO 225
206  TE = -.375*FB
      GO TO 225
207  TE = -.250*FB
      GO TO 225
208  TE = -.125*FB
      GO TO 225
209  TE = 0.0
      GO TO 225
218  MPH = LOCO1 (ARRAY (1), 3)
      IF (U.EQ.17.OR.U.EQ.16) MPH = LOCO1 (ARRAY (1), 4)
      IF (V1-MPH) 219,219,220
219  TE = TEL
      GO TO 221
220  TE = TEH
221  IF (TE) 225,225,224
224  IF (TE.GT.LIMIT) GO TO 230
      GO TO 225
230  IF (I.LT.INDEX) GO TO 368
      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
      CR = SUM1+SUM2*V1+SUM6*(V1+HW)**2
      R = CR
      TR = R+20.0*WT*TRACK (2,3)+20.0*WT*TRACK (2,2)
      VDD = (TE-TR)/(100.0*WT)
      IF (ABS (VDD)-1.0E-3) 790,791,791
790  IF (VDD) 792,793,793
792  VDD = -1.0E-3
      GO TO 791
793  VDD = 1.0E-3
      GO TO 791
791  IF ((P.EQ.1).AND.(PP.EQ.1)) GO TO 910
      IF (ABS (VDD).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 = VDD*DT
      V = V1+DV
      IF (V.LT.0.0) V = 0.0
      IF (Z.EQ.1.AND.V.EQ.0) GO TO 730

```

FIGURE 10 (Continued)
LISTING OF MAIN PROGRAM

```

GO TO 300
730 DT = -V1/VDD1
    Z = 2
    IF (ZSL.EQ.1) ZSL = 2
    GO TO 800
352 VDD = VDD1
    DST = TRACK(3,1)-S1
    DSC = V1**2+2.0*VDD*DST*3600.0
    IF(VDD) 353,354,355
353 DT1 = -(TOL+DIF)/VDD
    IF (DSC) 356,357,357
356 DT = DT1
    GO TO 804
357 DT2 = (-V1+SQRT(DSC))/VDD
    GO TO 358
355 DT1 = (TOL-DIF)/VDD
    DT2 = (-V1+SQRT(DSC))/VDD
    GO TO 358
354 TE = TE1
    V = V1
    DS = TRACK(3,1)-S1
    DT = (DS/V)*3600.0
    MV = V
    GO TO 810
358 IF (DT1-DT2) 359,361,361
359 DT = DT1
    GO TO 804
361 DT = DT2
    GO TO 804
804 ZX=1
    GO TO 313
805 DV = VDD*DT
    ZX=0
    V = V1+DV
    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,/)

```

FIGURE 10 (Continued)
LISTING OF MAIN PROGRAM

```

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 (2X,I4,4(3X,F6.1))
      DFC = NL*DT*LOCO1(ARRAY(1),5)/3600.0
      Z = 0
      ZSL = 0
      TE = 0.0
      TR = 0.0
      VDD = 0.0
      DS = 0.0
      L = 13
      S = S1
      GO TO 754
799  V = V1
      DT = 3600.0*(TRACK(3,1)-S1)/V1
      DV = VDD*DT
800  MV = (V+V1)/2.0
      DS = MV*DT/3600.0
810  S = S1+DS
      IF (TRACK(3,1)-S.LE.1.0E-3.AND.J.NE.NTR)
1    S = TRACK(3,1)
      IF ((V.GT.90.0).AND.(VDD.GT.0.0)) GO TO 620
      IF (I.GT.3.AND.V.EQ.0.0.AND-V1.EQ.0.0
1    .AND-V2.EQ.0.0) GO TO 95
130  CR = 0.0
      CR = SUM1+SUM2*MV+SUM6*(MV+HW)**2
      R = CR
      TR = R+20.0*WT*TRACK(2,3)+20.0*WT*TRACK(2,2)
      RR = TR+100.0*WT*VDD
      DFC = CF*RR*DS
      MDFC = NL*DT*LOCO1(ARRAY(1),5)/3600.0
      IF (DFC.LT.MDFC) DFC = MDFC
      IF (U.LE.8.AND.V1.GE.15.0) DFC = NL*
1    DT*LOCO1(ARRAY(1),6)/3600.0
754  CONTINUE
      CFC = CFC+DFC
      CDT = CDT+DT
      IF (I.EQ.1) GO TO 98
      RFC = 60.0*DFC/DT
      CRFC = 60.0*CFC/CDT
98   IF (I.GE.INDEX.OR.NUM(1).GT.CUTOFF) GO TO 97
      IF (J.EQ.NTR) GO TO 97
      GO TO 90
97   WRITE(8,58) CDT,V,RFC
58   FORMAT(F7.0,2(5X,F5.2))
      IF(OPTN1.EQ.1) WRITE(7,190) I,TE,U,TR,
1    VDD,V,J,DS,DT,S,DFC,CFC,CDT,RFC,CRFC.
      V2 = V1
      V1 = V
      TE1 = TE

```

FIGURE 10 (Continued)
LISTING OF MAIN PROGRAM

```

VDD1 = VDD
S1 = S
90 CONTINUE
C-----END OF MAIN LOOP
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,V
621 FORMAT ( 1H ,1X,I3,2X,I2,2X,I2,2X,2(2PE11.2))
GO TO 625
95 CONTINUE
WRITE(9,81) I
81 FORMAT(I4)
IF(OPTN1.EQ.0) WRITE(7,94)III,J,S1,CDT
94 FORMAT( 1H ,2X,I4,2X,I3,4X,F8.1,3X,F8.1)
WRITE(7,92)I,CFC
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=S1*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
6 YFL=IY
YFL=YFL*.4656613E-9
RETURN
END

```

FIGURE 10 (Concluded)
LISTING OF MAIN PROGRAM

FILE: TRCKRD FORTRAN A

34

```
SUBROUTINE TRCKRD (S,NTR,OSL,J,TRACK)
REAL OSL,TRACK(3,4)
DO 100 N = 1,4
TRACK(1,N) = TRACK(2,N)
100 CONTINUE
IF (TRACK(3,1).GT.S.OR.J.EQ.NTR) GO TO 999
DO 300 N = 1,4
TRACK(2,N) = TRACK(3,N)
300 CONTINUE
J = J+1
IF(J.EQ.NTR) GO TO 999
READ(3,15) (TRACK(3,N),N=1,4)
15 FORMAT(4X,3F9.2,F9.1)
IF (TRACK(3,4).GT.OSL) TRACK(3,4) = OSL
GO TO 100
999 RETURN
END
```

FIGURE 11
SUBROUTINE FOR READING TRACK DATA

FILE: LOCO2 FORTRAN A

```
SUBROUTINE LOCO2 (U,NL,LT,VP,TEH,TEL)
INTEGER UU,U
UU = U-9
GO TO (940,960,980),LT
940 GO TO (950,951,952,953,954,955,956,957),UU
950 TEH = NL*12500.0/(VP-5.0)
TEL = NL*(-950.0*VP+12000.0)
GO TO 999
951 TEH = NL*63158.0/(VP-5.2632)
TEL = NL*(-2700.0*VP+39000.0)
GO TO 999
952 TEH = NL*233333.0/(VP+1.1111)
TEL = NL*(-3400.0*VP+55000.0)
GO TO 999
953 TEH = NL*335238.0/(VP+.4762)
TEL = NL*(-4300.0*VP+75000.0)
GO TO 999
954 TEH = NL*496556.0/(VP+1.0345)
TEL = NL*(-4900.0*VP+94000.0)
GO TO 999
955 TEH = NL*640500.0/(VP+.500)
TEL = NL*(-6400.0*VP+125000.0)
GO TO 999
956 TEH = NL*933332.0/(VP+1.1111)
TEL = NL*(-6100.0*VP+145000.0)
GO TO 999
957 TEH = NL*1047227.0/(VP+1.2605)
TEL = NL*(-8600.0*VP+179000.0)
GO TO 999
960 GO TO (970,971,972,973,974,975,976,977),UU
970 TEH = NL*65062.0/(VP+.1)
TEL = NL*(-197.0*VP+7294.0)
GO TO 999
971 TEH = NL*176287.0/(VP+.1)
TEL = NL*(-534.0*VP+19765.0)
GO TO 999
972 TEH = NL*289387.0/(VP+.1)
TEL = NL*(-878.0*VP+32445.0)
GO TO 999
973 TEH = NL*418125.0/(VP+.1)
TEL = NL*(-1267.0*VP+46880.0)
GO TO 999
974 TEH = NL*582375.0/(VP+.1)
TEL = NL*(-1765.0*VP+65296.0)
GO TO 999
```

FIGURE 12
SUBROUTINE FOR LOCOMOTIVE CHARACTERISTICS

```

975  TEH = NL*797625.0/(VP+.1)
      TEL = NL*(-2417.0*VP+89430.0)
      GO TO 999
976  TEH = NL*1016625.0/(VP+.1)
      TEL = NL*(-1714.0*VP+90500.0)
      GO TO 999
977  TEH = NL*1179375.0/(VP+.1)
      TEL = NL*(-1314.0*VP+90500.0)
      GO TO 999
980  GO TO (990,991,992,993,994,995,996,997),UU
990  TEH = NL*40000.0/(VP+3.0)
      TEL = NL*(-236.7*VP+5444.0)
      GO TO 999
991  TEH = NL*120000.0/(VP+7.0)
      TEL = NL*(-415.2*VP+11210.0)
      GO TO 999
992  TEH = NL*187000.0/(VP+6.0)
      TEL = NL*(-730.5*VP+18992.0)
      GO TO 999
993  TEH = NL*270454.5/(VP+5.82)
      TEL = NL*(-1080.6*VP+27903.0)
      GO TO 999
994  TEH = NL*391000.0/(VP+6.5)
      TEL = NL*(-1436.2*VP+38059.0)
      GO TO 999
995  TEH = NL*531666.6/(VP+7.08)
      TEL = NL*(-1822.5*VP+49347.0)
      GO TO 999
996  TEH = NL*657105.2/(VP+6.95)
      TEL = NL*(-2287.2*VP+61645.0)
      GO TO 999
997  TEH = NL*749152.4/(VP+3.81)
      TEL = NL*(-3928.1*VP+93514.0)
      GO TO 999
999  RETURN
      END

```

FIGURE 12 (Concluded)
SUBROUTINE FOR LOCOMOTIVE CHARACTERISTICS

the early version of this report, the reader is referred to Volume III of the series (Reference 3). As an example of computation speed, CPU time for a simulated operation of a 103 vehicle train over a track characterized by 664 track records (89.75 miles) was 55 seconds.

The output of the program is numerical, although a routine for plotting the velocity and the instantaneous rate of fuel consumption (variables the value of which for a particular iteration of the loop is known) was desired and utilized during the investigation phases of the development of the calculation. The program requires only 80 characters per line for printing the output in order to be compatible with printers with limited column capacity.

The initial portion of the program calculates the resistance of the train as a function of velocity, as determined by the particular consist. The subsequent portion of 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.

3.3 Symbols and Definitions

This section defines the alphanumeric symbols used in the program, in order of their appearance in the program.

NUM (1), N1, N2	Integer random numbers
LOCO1	A data file of locomotive parameters
TRACK	A track data file
ARRAY	An integerized "DATA" File
DATA	The "TRAIN" data file listing original order of consist and vehicle type
COEFF	A data file of vehicle parameters
ORDER	A data file listing a rearranged order of the consist
CUTOFF	A parameter used to control random stops, value between or including 1 to 1,000
OPTN1	An option selected by operator regarding printing of output
P, PP, PPP	Indicators for directing program logic
Q	A loop index
U	A throttle or braking position indicator
TIME	A time in seconds, a logic parameter
SIGMA	Standard deviation of a Gaussian distribution
AM	Mean value of a Gaussian distribution
WT	Gross train weight
SUM1L	Gross weight of locomotives
SUM1C	Gross weight of cars
SUM1-SUM6	Various sums internal to program
J	An integer parameter indicating track record corresponding with train location
V1	Train velocity in previous time step
VDD	Train acceleration
IX	A nine digit random integer associated with the random stop routine
NL	Number of locomotives in train
NV	Number of vehicles in train
NTR	Number of track records in track file
INDEX	Loop iteration number at which printing of data is to start
HW	Headwind, mph
GROSS	Gross vehicle or train weight, tons
GF	Forward gap factor
GA	Aft gap factor
CFE	Coupling factor, forward
CFA	Coupling factor, aft
AFF	Area factor, forward
AFA	Area factor, aft
FF	Coefficient for forward aerodynamic drag
FA	Coefficient for aft aerodynamic drag
D	Aerodynamic drag constant, forward end of vehicle
E	Aerodynamic drag constant, surface area of vehicle

F	Aerodynamic drag constant, aft end of vehicle
UC	Aerodynamic drag constant, bottom of vehicle and trucks
G	Vehicle aerodynamic drag constant (compare value to modified Davis formula value of .07)
WL	Weight of locomotives
DTO	An initialization of DT
L	A program parameter related to "U"
K	An indicator
TE	Tractive effort
DV	Differential velocity
V	Train velocity, present time step
DS	Differential distance
S	Cumulative distance
RFC	Rate of fuel consumption
DIF	Difference between train velocity and desired velocity
BETA	A parameter for braking effort curves
FRF	Braking friction factor
BFC	Braking force, cars
UU	A throttle notch position indicator
X, Y	Loop indices
Z	Loop index
Z, ZX, ZSL	Indicators for directing program logic
MV	Mean velocity
MF	Multiplication factor
LIMIT	Tractive effort limitation
N3, N4	Real random numbers
MDFC	Minimum differential fuel consumption
KD, KE, KF	Dimensional constants
MN	Mean value of a Gaussian distribution
NET	Net vehicle or train load, tons
OSL	Operational speed limit
MPH	Transition point on approximations to locomotive tractive effort curves
CDT	Cumulative differential time
CFC	Cumulative fuel consumption
CRFC	Cumulative rate of fuel consumption
CIT	Cumulative idle time (at stop)
CF, CF2	Dimensional constants
DT	Differential time
NI	Number of intervals (in main loop)
TOL	Semi-width of tolerated velocity band, mph
NC	Notch change, a logic parameter
BFL	Braking force, locomotives
FB	Force of brakes

LT	Locomotive type
VP	Velocity, previous time step
TEH	Tractive effort as determined by hyperbolic curve approximation (higher velocities)
TEL	Tractive effort as determined by straight line approximation (lower velocities)
R	Train resistance exclusive of grades and curves
TR	Train resistance including resistance of grades and curves
VDDI	Acceleration in previous time step
DST	Distance to end of track record
DSC	Discriminant
RR	Train resistance, including resistance of grades and curves, plus acceleration forces
MDFC	Minimum differential fuel consumption
V2	Velocity two time steps previous
TE1	Tractive effort in previous time step
S1	Cumulative distance in previous time step

3.4 Mathematical Rationale

3.4.1 Resistance Calculation

The equation for the resistance of the train is calculated by determining the individual resistance of each car and locomotive and summing the results. It has been assumed that the resistance of each car or locomotive is governed by the modified Davis formula, which for the absolute resistance in pounds has the form:

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

in which "a" and "b" are functions of weight. The numerical values for "a" and "b" correspond to the values normally associated with the formula, which for this version in pounds become

$$a = .6W_o + 20.0 n$$

$$b = .01W_o$$

in which W_o is the vehicle weight in tons and n is the number of axles on the vehicle.

Rather than using a particular value for the parameter "c" (.07 is the usually accepted value for average consists), the program calculates a coefficient for each car based upon cross-sectional areas at the front and rear of the car, surface area, undercarriage drag, and the shielding effects of the car immediately preceding and following the car. The user is referred to Reference 1 for the rationale behind the aerodynamic drag calculation. Thus the ordering of the consist is significant, and such information must be entered into the program before the operation can be successfully simulated. The value of the parameter "c" which the program effectively uses can be determined if the option to print all results of the program is selected, and is the coefficient of the velocity-squared term in the resistance equation given.

3.4.2 Velocity Determination

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

$$TE \cdot v = \text{Constant} = K_1 \quad (2)$$

Hence
$$TE = K_1/v \quad (3)$$

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

$$TE - R = m \frac{dv}{dt} \quad (4)$$

Combination of the above expressions results in:

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

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, together with the velocity, determines the constant power to be applied during the next time interval. 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 power 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 Reference 2) 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 preceding 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.

3.5 Acceleration and Braking Considerations

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

3.5.1 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 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 between desired velocity and actual velocity 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 . Ten seconds has been 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 two steps. 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 I th iteration of the loop. It is first determined whether the previous velocity $V(I-1)$ is within the permissible band or not. The tolerance band has been set at ± 2.5 miles per hour at the beginning of the program. The following paragraphs discuss the subsequent decision process.

3.5.1.1 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 ($MF \cdot DT$), 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 a value of 2 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.

3.5.1.2 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 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 "TIME" set at ten seconds at the beginning of the program. 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.

3.5.2 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 percent 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 (Reference 6). Thus, a minimum braking effort of about 6 psi would be required, or about 25 percent 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 fractions of full braking.

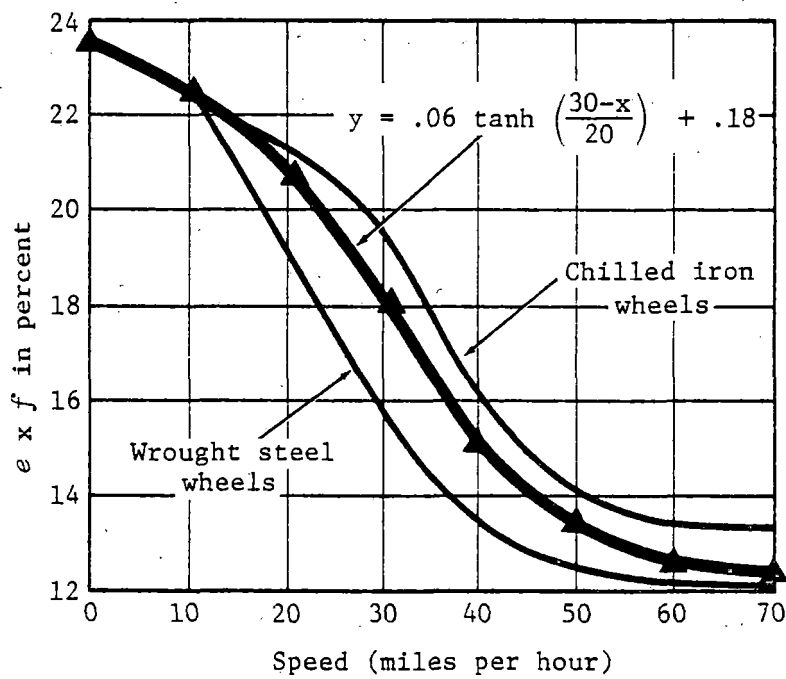
While it is recognized that this does not precisely duplicate actual braking operation, the difference in fuel consumption attributable to the small difference in simulation during the short periods when brakes will be applied is believed to be of second order magnitude.

A further consideration with regard to braking is the approximation of braking friction as a function of speed. Following the discussion in Hay (Reference 7) the cars have been braked at 60 percent of light weight (66,000 pounds) and locomotives at 90 percent. 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 13.

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.

3.6 Random Stop Algorithm

The random stop algorithm has been eliminated from functioning by specification as part of the program of the value of the parameter "CUTOFF" at 1000. This ensures that the probability of a random stop is zero, and the program will only permit the train to stop along the way at points where a zero speed limit has been introduced into the track records.



Values of $e \times f$ at various speeds for chilled iron and wrought steel wheels.

(Original curves from Hay (7))

FIGURE 13
BRAKING CURVE APPROXIMATION

The functioning of the algorithm can be easily restored however, by making the value of "CUTOFF" an operator input to the program and specifying at the initiation of the program a value other than 1000. The algorithm logic is still retained in the program and will perform as expected with an input different from 1000.

In normal operation of the algorithm, the probability of making a stop at any given iteration of the "DO" loop is specified by this "CUTOFF" parameter, and is equal to $(1000 - \text{inserted value}) / 1000^*$. Specifying 1000 ensures that no random stops (intended to simulate unforeseen stops of any nature) will be incurred at all.

The value of the standard deviation parameter "SIGMA" is also related to the stopping algorithm. 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.

* A typographical error in Reference 2 had the denominator equal to 2000.

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.

3.7 Program

This section provides commentary which may help explain portions of the program more adequately than the comments interspersed throughout the program by means of which the sections below are identified. Titles below identifying lines refer to all lines between the indicated comment line and the following point.

Initial Lines Prior to First Comment

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

Lines Subsequent to Comment 1

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

Lines Subsequent to Comment 2

These lines read the data from the data files describing the characteristics of railroad rolling stock, request the inputs to the program, and direct the information to the appropriate places.

Lines Subsequent to Comment 3

These lines merely compute the train weights of interest for later printing.

Lines Subsequent to Comment 4

These lines essentially repeat a program previously developed for computing train resistance. The reader is referred to Reference 1 for an explanation of that program and the rationale

behind it. Reference 2 also contains some commentary on two comparatively minor changes made in the computation of the coupling and area factors.

Lines Subsequent to Comments 5 and 6

As noted, these lines examine the track file and speed limit restrictions.

Lines Subsequent to Comment 7

These lines merely initialize certain constants and start the main "DO" loop.

Lines Subsequent to Comment 8

These lines constitute the initial step 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. 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. The subroutine TRCKRD is called to extract the speed limit, grade, and curvature for the initial 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 latter 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 Subsequent to Comment 9 But Before Statement 300

These lines begin the normal calculation of velocity and fuel consumption after the initial calculation. The subroutine TRCKRD establishes a value for J, which is used as a parameter locating the train so that subsequent calculations may extract pertinent track data. Track records are updated to the current train position. 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. The statement directly following the "CALL" statement for TRCKRD ensures 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 Between Statements 300 and 310

The next 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 the calculation is directed to statement 300, and 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 calculation is directed to statement 400 and 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 Between Statements 310 and 313

These lines merely define certain braking constants used subsequently.

Lines Between Statements 313 and 224.

These lines determine the initial choice of tractive or braking effort. If the parameter "U" is nine or less, braking equations which are part of the main program are utilized to calculate the retarding force. Otherwise, the program is directed to subroutine LOCO2, which calculates the tractive effort from equations which approximate the tractive effort curves for certain locomotives. At the present time, the subroutine incorporates characteristics of only three locomotives. The equations calculating braking effort reflect certain assumptions and theoretical considerations derived from Hay (Reference 7) and other sources. The tractive effort curves above a certain velocity represent approximately constant power curves; the braking effort equations represent a fraction of the available braking force. For further discussion see the earlier section entitled "Acceleration and Braking Considerations".

Lines Between Statements 224 and 225

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 Between Statements 225 and 730

These lines calculate the resistance of the locomotives and the trailing cars based upon variables calculated earlier and compute the acceleration of the train from the tractive effort selected and the resistance computed above. A check of the time required to return the velocity to within the permissible band is made; 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. The comparison of VDD with $1.0E-2$ was inserted later in the development of the program to avoid a digital problem associated with the acceleration nearing zero as the train approaches its limiting velocity at full-throttle.

Lines Between Statements 730 and 354

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 value of the parameter "TIME" 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 traveled over that time interval.

Lines Between Statements 354 and 750

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 Between Statements 750 and 800

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 Between Statements 800 and Final Comment

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 Between Final Comment and End of Program

The remaining lines merely calculate the values of certain additional variables of interest and direct the printing of the program variables. The subroutine for generating random numbers between 0 and 1 with a uniform probability density function is also included.

LIST OF REFERENCES

1. Muhlenberg, J.D., "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-87/04.I. April, 1978.
2. Muhlenberg, J.D., "Resistance of a Freight Train to Forward Motion, Volume II: Implementation and Assessment," U.S. Department of Transportation, Federal Railroad Administration Report No. FRA/ORD-78/04.II.
3. Muhlenberg, J.D., "Resistance of a Freight Train to Forward Motion, Volume III: Correlation and Economics," U.S. Department of Transportation, Federal Railroad Administration, Report No. FRA/ORD-78/04.III. to be published, summer, 1980.
4. Car and Locomotive Cyclopedia, 1970 Edition, Simmons Boardman Publishing Company, New York, N.Y.
5. Cetinich, J.N., "Fuel Efficiency Improvement in Rail Freight Transportation," U.S. Department of Transportation, Federal Railroad Administration OR&D Report No. FRA/ORD 76-136, December, 1975.
6. Management of Train Operation and Train Handling, Air Brake Association, Chicago, Illinois, July, 1977 edition.
7. Hay, W.W., Railroad Engineering, John Wiley and Sons, New York, N.Y., 1953.

**PROPERTY OF FRA
RESEARCH & DEVELOPMENT
LIBRARY**

Resistance of a Freight Train to Forward Motion,
Volume IV: User's Manual for Freight Train Fuel
Consumption Program (Final Report), US DOT,
FRA, 1981 -21-Freight Operations

SNEAD CO VPS85A