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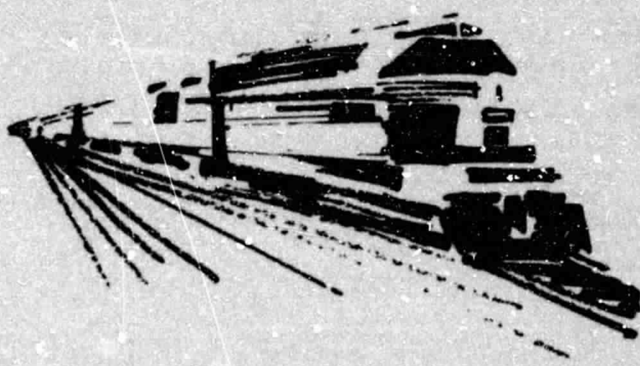
Demonstration of the Coast-Down Technique for Determining Train Resistances

Final Report

Bain Dayman



October 1983

Prepared for
Technology Utilization Office
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
with cooperation from
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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

ABSTRACT

Full-scale measurement or validation of the various factors of train running resistance is an essential step in decreasing train energy consumption. Such a measurement capability would enable railroads to evaluate the cost benefits of operational and train consist configuration changes, and new vehicle and truck designs for decreasing aerodynamic drag and rolling resistance. A decrease in the rolling resistance affects more than just a decrease in energy consumption; it also will result in decreased mechanical wear, hence less wheel and rail maintenance and replacement costs. A demonstration of a simple coast-down technique (based on computer-reduction of distance history) was accomplished using specially configured trains on main line rail provided by the Atchison, Topeka and Santa Fe Railway Co.

This demonstration test shows that this distance-history coast-down technique for trains is easy to execute in the field. The total running resistance history was accurately determined and subsequently separated into rolling resistance (mechanical friction) and aerodynamic drag. In addition, considerable insight was gained on the nature of train running resistance under a wide variety of operating conditions. It is clear that the applicability of the long-standing Davis equation has certain limitations. In many cases the running resistance comparisons of related train consists did not follow normally used predictions. In addition, the effect of moderate side-winds on the aerodynamic drag force was negligible although wind tunnel results had predicted a significant effect.

FOREWORD

This final report is published as two separate volumes. This formal volume summarizes the demonstration test, and an Appendix contains the many details of the test, analysis and results. This two-volume approach is used because it was believed that only a limited number of those interested in the demonstration test would also be interested in all the details. Copies of the Appendix are available through JPL.

ACKNOWLEDGMENT

The author appreciates the assistance of the following people: Don Hoff of the Jet Propulsion Laboratory for developing and operating the coast-down test instrumentation; Geoffrey Dahlman for preparing and making arrangements for the test program and Roy Habegger for operating the test-car instrumentation, both of whom were under the guidance of C.R. Kaelin, Director, Department of Technical Research and Development, Atchison, Topeka and Santa Fe Railway Co. (AT&SF) in Topeka, Kansas. Special thanks are given to the Technology Utilization Office of the National Aeronautics and Space Administracion for their sponsorship under Task RE-170, RTOP No. 141-20-14-01-00 and to AT&SF for their cooperation and support.

CONTENTS

*Appendix is bound as a separate document and is available in microfiche form from the Jet Propulsion Laboratory.

KEY WORDS

Aerodynamic Drag of Freight Trains

Coast-Down Tests

Rolling Resistance of Trains

Train Consists

Train Resistance

Train Running Resistance

Train Energy Requirements

SECTION I

INTRODUCTION

To evaluate this distance-history coast-down technique, the Atcheson, Topeka and Santa Fe Railway Co. (AT&SF) entered into a joint experimental program: National Aeronautics and Space Administration Technology Utilization Office (NASA TU) funded the Jet Propulsion Laboratory's (JPL) effort while the AT&SF provided the track, trains, crews, and railway system measurements. This report presents results of the exploratory test program that was run in May 1983. The purpose of this test program was to demonstrate the application of the coast-down technique to trains.

This report emphasizes those results that are pertinent to evaluating the application of this simple coast-down technique to trains. Also, highlights of interesting features of the running resistances observed during this test are included. These limited results are valid only for the test conditions, particular segment of test track, and the specific rolling stock used. Generalizations from these results may not be appropriate.

A. NEED

1. Santa Fe Railway Co. (excerpted from Reference 1)

The Atchison, Topeka and Santa Fe Railway Co. operates on a 12,500-mile system of track, which extends from Chicago, Illinois, to the Gulf of New Mexico and to the Pacific Coast at Los Angeles, California. The AT&SF owns approximately 75,000 freight cars and 2,000 diesel electric locomotives, and most of their activities involve the movement of freight. A limited amount of passenger train service is operated by the AT&SF for Amtrak.

Diesel fuel costs have gone from 32¢/gallon in 1976 to over $1/gallon in 1983 for an increase of over 300% in seven years. Twenty-five percent of the AT&SF operating costs are due to diesel fuel (over 400 million gallons of fuel per year at a cost of about $400 million). Even small percentage reductions in this amount would result in significant savings. In the last several years, the AT&SF has taken many measures to aid in the conservation of diesel fuel.

Fuel conservation techniques used include reduced train speed, train handling improvements, equipment design, and improved track maintenance standards. The AT&SF has determined that decreasing maximum operating speed from 79 mph (127/km/h) to 70 mph (113 km/h) decreases fuel consumption 12%. Tests also showed that further reduction of speed from 70 mph to 50 mph (80 km/h) resulted in a 22% savings in fuel. AT&SF currently operates many trains at 70 mph. Consequently, the AT&SF is very interested in aerodynamic equipment design, probably more so than a railroad that operates at a 45 mph (72-km/h) top speed.

Because of the need to interchange freight cars among U.S. railroads, individual pioneering in aerodynamic design or other equipment design changes has been limited in the past. Where specialty equipment can be justified, considerable innovation has been made. The AT&SF ten-Pack unit train is a good example of innovative design to reduce equipment weight and thereby reduce fuel consumption.

The AT&SF has sponsored aerodynamic computer modeling of trains as well as small-scale wind tunnel tests; however, both techniques have their limitations and require real-world validation before results can be incorporated into the operation. To date, the validation has been in the form of fuel consumption testing with an accuracy of 2% to 5%, which is not sufficient for validation. There is great interest in this coast-down method because of its accuracy, simplicity, and full-scale capability. This technique offers promise for evaluating a variety of engineering considerations including locomotive, car, and track design, as well as various operating considerations including speed and train consist makeup. In today's changing U.S. railroad climate, the speed at which trains move, as well as the economic analysis of these speeds, is quite vital to the AT&SF.

2. General

The U.S. railroads have an annual operating budget on the order of $25 billion. A significant portion of it is due to items related to the running resistance of trains. For example, the fuel costs are about 16% of the operating budget with the costs (material plus labor) of wheel and rail maintenance and replacement of the same magnitude.

Overcoming running resistance (rolling resistance and aerodynamic drag) requires a significant portion of the diesel fuel that is used. The wear on the wheels and rails is directly related to the rolling resistance (mechanical friction). A decrease in the running resistance will have a significant impact upon fuel costs. A decrease in the rolling resistance will have a significant impact upon wheel and rail maintenance and replacement costs.

The first step in decreasing the running resistance is to quantify it and separate it into its two components, rolling resistance and aerodynamic drag. Then it is necessary to develop an understanding of running resistance before determining approaches to decrease it. Finally, an economic analysis must be carried out to evaluate all of the various costs. This analysis must be based on a realistic assessment of the effect of any change on running resistance, the implementation cost of the change, and its impact on total operating costs. Only then can realistic overall economic and operational assessments be made on the viability of any proposed change.

The capability of quantifying the actual running resistance is required a number of times during this described process for decreasing operational costs to: 1) determine the current impact of running resistance upon costs, 2) relate the rolling resistance to wheel and rail wear, 3) develop the approach(es) to decrease running resistance, and 4) quantify experimentally (full-scale) the resulting change in running resistance for any approach being considered.

A key item in reducing operating costs by decreasing running resistance is the capability of accurately quantifying the running resistance and separating it into its components of rolling resistance and aerodynamic drag. This capability appears to be available. It is the distance-history coast-down technique. The field tests are simple to carry out; they are far easier and more accurate than any of the techniques currently employed.

B. PRESENT KNOWLEDGE

The present knowledge of train running resistance is based upon the work of Davis (Reference 2) published in 1926. It summarized the available information from measurements of running resistance (typified by Reference 3 as well as laboratory tests of train bearing resistance). The measurement techniques were primarily drawbar which has considerable inherent noise due to the unsteady mass effects of a moving train. Consequently, considerable judgment had to be used in order to transform the available information into a useable form to predict running resistance. A quadratic equation of the form $R = A+BV+CV^2$ was selected. It has been updated a number of times, Reference 4 being a major example. Since then no significant improvements in accuracy have been made in the measurement of train running resistance that would permit one to observe the micro-characteristics of this train force composed of both rolling resistance (mechanical friction) and aerodynamic drag.

Improvements have been made in ease of data acquisition* and analysis and modification of the coefficients (A,B,C) of the Davis equation for particular operational approaches and conditions. In spite, or possibly because of, the various individual "improvements" in the coefficients of the Davis equation, the use of the various modified versions of the Davis equation can lead to a rather wide divergence in the prediction of train running resistance (Reference 6).

It is clear that a better understanding of the characteristics of train running resistance is necessary in order to explain the observed phenomena and discrepancies. Substantial improvement over current practices would be required in the measurement of running resistance. With the adoption of aerospace technology (flight vehicle trajectory analysis coupled with the use of the modern large, high-speed computer), it is now practical to determine the micro-characteristics of running resistance and separate it into rolling resistance and aerodynamic drag. Furthermore, it can be done while significantly reducing the complexity of the field testing.

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* For example, a recently developed coast-down technique used by the French railroads (Reference 5) utilizes a gravity-pendulum accelerometer.

SECTION II

DESCRIPTION OF TEST TECHNIQUE

A. BACKGROUND

The coast-down technique for ground vehicles is an outgrowth of ballistic range (Reference 7) and wind tunnel free-flight (Reference 8) tests in which drag, lift, pitching moment, dynamic damping, and motion dynamics of spinning models can be accurately determined from motion history of aerodynamic models. The coast-down technique was originally adapted to automobiles (References 9 and 10) under ideal (non-realistic) conditions (constant rolling resistance, no grade, no wind) measuring speed directly as a function of time. Later, the technique was broadened to include the effects of non-constant grades, and varying rolling resistance and wind with the observed test measurements being distance and time rather than speed and time (Reference 11). It is far easier (and much less costly) to measure distance and time to the required accuracy than a direct measurement of speed. The approach of Reference 11 (described in more detail in Reference 12) forms the basis of the technique applied to trains. It was expanded to include the effects of distributed mass of a train along a surveyed railbed.

This simple coast-down technique used for the studies contained in this report introduces no confusing, accuracy-degrading noise that would be introduced by force measurement devices. Both time and distance (elevation as well as longitudinal) can be easily measured to a degree of accuracy in excess of that necessary. Once that has been accomplished, any variations in the observed data are due to real variations in the running resistance forces themselves and not to superfluous factors such as unwanted inertia effects due to the mass and/or jerking of the trains, or instrumentation noise.

B. GENERAL DESCRIPTION

The distance history of a train coasting on a near-level guideway is obtained. This experimental distance history is converted to an accurate speed history which in turn is "matched" by a computer simulation (integrating the "force equals mass times acceleration" equation) of the coasting vehicle using various values of A, B, and C of the general resistance equation:

$$\text{Running Resistance Force} = A + BV + CV^2 + f(V)$$

where V is the speed of the vehicle. The best matches of the simulated histories to the observed history identify the appropriate values of A, B, and C. The term f(V) may be included in order to account for any non-linearity in the rolling resistance (A+BV) contribution to the running resistance. The characteristic of f(V) can be determined from the observed total running resistance history which is based upon the energy loss as determined from the roadbed elevation and inferred speed history

C. INSTRUMENTATION

The distance history was obtained in a very easy-to-implement manner for this train coast-down demonstration test. Reflective targets were located on the ties (Figure 1) every 1200 ft (336 m) along a 5-mile (8-km) segment of AT&SF main line track. The time of passage of the train over each of the reflective targets was initiated by a special collimated infra-red light transmitter-receiver sensor located on the rear step of the locomotive about 13 in. (33 cm) above the target (Figure 2). The pulse generated by the reflection of the light to the receiver was recorded by a small computer with an internal clock (Figure 3). On occasion similar distance history data were simultaneously obtained using a lap-timer stop-watch. Relative wind was recorded on the test car (see Figure 4 for recorder and inset of Figure 5 for annemometer); absolute wind was recorded beside the track at Pomona, Kansas, near the middle of the test track segment (Figure 5).

D. TEST TRACK

The test segment of track was in the immediate vicinity of Pomona, Kansas (near Topeka where the AT&SF Technical Research and Development facilities are located). This five-mile long segment of tangent (straight) track was nearly level: the greatest grade was less than 0.25%, and the average grade was about 0.05%, resulting in an elevation difference of 14.6 ft (4.5 m). Photographs in Figure 6 are indicative of the track and surroundings along the entire test segment of track. This portion of track was accurately surveyed every 200 ft (61 m) for elevation. This elevation information was converted to a series of 14 constant grade sections (Figure 7) for test planning and some of the analysis. For determination of the running resistance history, the complete survey information was used. Details of the test segment of track are presented in Appendix A.

SECTION III

THE TEST

A. TRAIN CONSISTS

A number of train consists were selected that would yield running resistance information which could be used to evaluate the applications of this simple coast-down technique to trains (Figure 8). The Base train consist was made up of a locomotive, the AT&SF test car, four box cars, four flat cars, and a caboose (Figure 9a). The High-Drag train consist alternated the same box cars and flat cars (Figure 9b). One Heavy train consist was made up of loaded box and flat cars (see inset of Figure 9a) similar to those of the Base train with about 50 tons of load each (45.5 tonnes). A shorter pair of train consists was formed by deleting the flat cars from the Base and Heavy train consists and designated Box and Heavy box, respectively. Finally, the locomotive was run by itself, both forward and backward.

All individual cars of the train consists, as well as the locomotive, were accurately weighed (to within one percent) and their respective rotational inertias were estimated. Estimates were made of the use of consumables by the locomotive to correct for its weight loss on a run-by-run basis. Further information on the train consists (test consists and the two revenue freight trains) tested as well as the individual cars is presented in Appendix B.

B. WEATHER

Ideally, clear and windless conditions were desired for all runs of the test. Fortunately, such conditions were obtained for a number of the runs in which the wind was nearly zero [0 to 3 mph (0 to 5 km/h)]. Moderate winds (mostly crosswinds of 3 to 12 mph) (5 to 20 km/h) existed for many of the runs. Also it rained lightly during several runs and just before (but not during) several other runs. And one run had rain during only the first half. The temperature range was 43 to 82°F (6 to 28°C).

C. RECORDED DATA

The primary data obtained were the times that the train passed over each reflective target (the targets were on 1200-ft spacings). Usually this was done using the sensor. However, on many of the runs the times were also obtained using a lap-timer stop-watch (keying on the numbered posts - see Figure 6) in order to compare the two types of data acquisition. Details of the comparison and consequences appear in Appendix C. On several occasions when the sensor data were not obtained, use was made of the stop-watch data. Also, the stop-watch timing was the only data obtained for the locomotive alone and the two revenue freight train runs.

The weather conditions were recorded (cloud cover, rain, temperature). Wind speed and direction were continuously measured. Comparisons were good of the relative and absolute wind anemometer readings when the train was stopped at Pomona. For the most part, the Pomona data, adjusted for the test car relative wind measurements, were used to quantify the wind.

In all, thirty-two runs were made. They are tabulated in the Run Index (Table 1) along with key conditions. The data for Runs 2, 4 and 28 were not reduced at all. In Runs 2 and 4 there were too few data stations passed at low initial coasting speeds; in Run 28 the data was not felt to be as useful due to the intentional addition of a slight amount of normal train breaking. Runs 15, B and C were reduced only for the running resistance history (see Appendix D); they were not reduced to separate out the rolling resistance and aerodynamic drag; in Run 15 this was due to few data points; in Runs B and C it was due to the complexity caused by the long length of distributed mass.

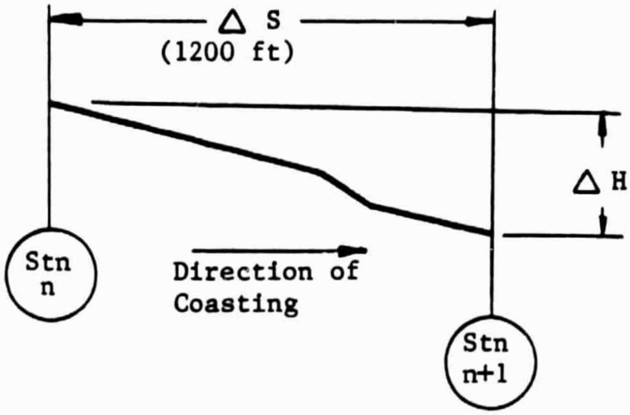
D. DATA REDUCTION

Distance history data (such as shown in Figure 10) were obtained for each run. These data, in turn, were used to infer the speed history (Figure 11) by a technique of corrective curve fitting (described in Reference 12). Two basic force-energy equations were used in the data reduction process. A flow diagram of the complete data reduction procedure is shown in Figure 12.

1. Running Resistance History

The running resistance history was calculated in order to determine the micro-characteristics of the total running resistance and the estimate of the rolling resistance by assuming an appropriate aerodynamic drag coefficient (see Table 2). For the calculation of the total running resistance and an estimation of the rolling resistance, Equation 1 (based upon potential and kinetic energies) was applied to each 1200-ft leg of the five-mile test segment of track. Distributed mass of the train consist along with the surveyed elevations every 200 feet were used.

Useful information as to the total running resistance can be obtained even if the actual surveyed elevations are used with no correction for distributed mass and with the average speeds based directly upon the observed elapsed times rather than the computer-determined accurate speed at each data station. See Appendix C1 for an example. However, this is true only for the short train consists (12 elements or less), as the elevation correction can be several feet even on this near-level test segment of track for a typical revenue freight train, i.e., Runs B and C. Incorporating distributed mass and accurate inferred speeds gives running resistance history data of high quality (accuracy). The primary equation used is:



$$C_{RR} = \underbrace{\frac{\beta}{2g\Delta S}\left(V_n^2 - V_{n+1}^2 + \frac{2g}{\beta}\Delta H\right)}_{C_{Total}} - \underbrace{\frac{\rho A}{4W} C_D \left(V_n^2 + V_{n+1}^2\right)}_{C_{Aero}} \tag{1}$$

C_{Aero} = aerodynamic drag force divided by consist weight

C_{RR} = rolling (mechanical friction) resistance force divided by consist weight (or lbs resistance per lb of consist weight)
= $C_{RO} + C_{RN} V_{mph}$

C_{Total} = total running resistance force divided by consist weight
= $C_{RR} + C_{Aero}$ (Dimensionless coefficients)

g = Gravitational acceleration = 32.16 ft/sec^2

β = $1 + \dfrac{\text{Rotational kinetic energy}}{\text{Translational kinetic energy}}$ = 1.07 to 1.20

ΔS = distance between consecutive data stations

ΔH = change in elevation corrected for effects of distributed mass (sign of ΔH term is negative for rise during coasting)

V_n = train speed (ft/sec) at Stn "n"

A = area (reference)...assumed to be 100 ft^2 (even for locomotive which is 145 ft^2

ρ = air density = 0.002378 slugs/ft^3 (Standard sea level conditions)

W = weight of train consist in lbs

C_D = aero drag coefficient (C_D = 2 to 4 for test consists; around 10 for freights). The value of C_D is estimated, at least for the first iteration of data reduction

2. Rolling Resistance and Aerodynamic Drag

In order to separate the running resistance into its components of rolling resistance (including the level as well as the rate of change) and aerodynamic drag, Equation 2 (based upon Newton's force equals mass times acceleration) was used. Simulations were run to match the experimental speed history data. The simulations providing the best matches identify the appropriate values of the constant term C_{RO} and the linear velocity-term, C_{RN} of the rolling resistance and the aerodynamic drag velocity-squared term, C_D (see Table 3 for an example). Details on the process are in Reference 12. The primary equation used is:

$$-\bar{m}\frac{dV}{dt} = (mg\cos\theta - L)\,C_{RR} + mg\sin\theta + \tfrac{1}{2}\rho(V - U)^2\,C_DA \qquad (2a)$$

The term on the left-hand side of the equation is the mass times the acceleration. The first term on the right-hand side of the equation is the rolling resistance force where the vehicle weight is decreased by the aerodynamic lift; the second term accounts for the effect of a grade; the third term is the aerodynamic drag force in which the wind direction is along the vehicle's direction of travel. For railroad track grade, $\cos\theta = 1$ and $\sin\theta = \theta$. For trains assume $L = 0$. By letting $\beta = 1 + \Delta m/m$, we get:

$$dt = -\frac{m\,\beta}{(mg + \theta)C_{RR} + \tfrac{1}{2}\rho(V - U)^2\,C_DA}\,dV \qquad (2a)$$

The nomenclature used in this program is as follows:

$\overline{m}$	$m + \Delta m$
m	mass of vehicle (slugs)
Δm	effective increase in decelerating mass of vehicle to account for rotational kinetic energy in wheels and drive train
V	velocity of vehicle in mph, except ft/sec for Equations 1 and 2
t	time (sec)
g	gravitational acceleration = 32.16 ft/sec^2
θ	grade (positive indicates uphill); ft rise per ft of horizontal distance
C_{RR}	dimensionless rolling resistance coefficient in lbs/lb of weight of train consist
ρ	air density (0.002378 slugs/ft^2 at standard sea level conditions)
U	wind velocity--either headwind or tailwind (positive indicates tailwind) (mph)
C_D	aerodynamic drag coefficient = $\dfrac{\text{Drag}}{\frac{1}{2}\rho(V - U)^2 A}$ (lbs)
A	reference area of vehicle (100 ft^2 for this report)
S	distance vehicle traveled where $dS = Vdt$ (ft)

For a typical ground vehicle the aerodynamic drag coefficient (C_D) is independent of velocity, especially for speeds above 20 mph. The rolling resistance (C_{RR}) is not constant, and need not be assumed to be so in order to solve for the aerodynamic drag (C_D). For the usual coast-down test the grade should be below ½ %. Since neither the grade nor the wind is likely to be constant, each run should be reduced separately; they should not be combined and averaged prior to data reduction (the averaging process degrades the data quality). Both θ and U can be complicated functions of the speed, time or distance. The effect of a head or tail wind can be accounted for by putting in the proper relation for U. If the effective side wind is significant, C_D can also be made to vary to account for the wind angle. For example,

$$C_D = C_{D_o} \; [1 + fnc(V)].$$

The rolling resistance coefficient is of the form:

$$C_{RR} = C_{RO} + C_{RN} \times fnc \text{ (speed in mph)}$$

For the case when C_{RR} is assumed to be constant, $C_{RN} = 0$. The function of speed can be as complicated as one wants it to be. However, it cannot be simply a V^2 term unless C_{RN} is fixed (known or assumed) because it is in the same form as the aerodynamic drag [fnc (V^2)].

Originally the data of each individual run was reduced in several discrete groups of data stations (see Figure 7) for the RRCDRR program. No definite effects of the position along the track were noticed and, the group containing virtually all of the data stations (Group 2) gave the best consistency. Therefore the final data reduction utilized only a single group containing all stations at which good data appeared to be obtained.

The RRCDRR computer program solutions utilized the 14-segment grade schedule and the point mass assumption for the train consist. However, since a correction was made in the RRDELV ΔV solutions for distributed mass, the resulting RRCDRR solution for C_D, C_{RO} and C_{RN} is effectively for distributed mass train consists. This procedure is necessary in order to reduce computer time by a factor of 3-4. This ΔV correction procedure was not applied to the long revenue freight consists. Therefore Runs B and C were not reduced in the RRCDRR program to determine the best triad values of C_D, C_{RO}, and C_{RN}.

3. Test Accuracy Requirements

Now that the data reduction equations have been described, it would be appropriate to discuss the requirements for test accuracy. Although previous experience with Equation 2 dictates accuracy requirements (and they are quite stringent in order to permit separation of the rolling resistance from the aerodynamic drag), it is easier to describe the accuracy requirements by using Equation 1. Conditions and results of the Base train consist (Run 7-uphill) are used for the following analysis. The basic data are as follows:

Consist weight:	1,020,663 lbs
Beta (rotational energy factor)	1.119
Aerodynamic drag coefficient	$C_D = 2.8$
Data station spacing	1200 ft

Example Station Pairs:	V_n (mph)	V_{n+1} (mph)	h^*_{eff} (ft)
23-22	59.690	57.872	0.423
13-12	40.913	39.103	0.132
2-1	16.628	13.325	0.537

* Actual elevation differences have been corrected for distributed mass of each train consist as per surveyed elevation changes.

QUANTITY	VARIATION	EFFECT ON C_{TOTAL} (%)		
		23-22	13-12 (Station Pairs)	2-1
Weight	1%	0 (0.62)	0 (0.34)	0 (0.04)
Beta-1	10%	1.19 (1.94)	1.15 (1.51)	1.34 (1.39)
Speed*	0.01 mph	1.19 (1.93)	1.16 (1.58)	0.72 (0.81)
Elev. Diff.	0.03 in/100 ft.	0.40 (0.65	0.57 (0.77)	0.96 (1.02)
C_D	5%	0 (3.24)	0 (1.77)	0 (0.32)

( ) are for C_{RR}

The speed accuracy requirements dictate the following requirements on time and distance: A 0.005 mph accuracy in speed infers a timing accuracy of 0.0025 sec (at 40 mph over a 1200 ft timing distance) and a corresponding distance accuracy of 3.6 in. per 1200 ft (0.3 in. per 100 ft of surveyed length). The resulting accuracy requirements are as follows:

Track survey: $\pm$ 0.25 in. longitudinal distance per 100 ft of length

$\pm$ 0.03 in. elevation per 100 ft of length

Reflective target spacing: $\pm$ 3 in (every 1200 ft)

Speed determination: $\pm$ 0.005 mph

Time determination: $\pm$ 0.0025 sec

Consist conditions: $\pm$ 1% in weight

$\pm$ 10% in rotational kinetic energy

All of the above accuracies were met. Consequently, calculated values of the total running resistance (C_{Total}) are valid to within two percent (with faired curves within one percent) with an error in rolling resistance (C_{RR}) of less than five percent.

SECTION IV

RESULTS

A. RUNNING RESISTANCE

The accurate determination of speed along with elevation change makes it practical to calculate the history of the total running resistance, the average resistive forces (mathematically excluding gravity) along each leg (between consecutive stations of the test segment of track). Complete tabulation of all runs are in Appendix E along with plotted results. An example of such a history is shown in Figure 13 for the Base train consist for two speed ranges. This good overlapping of the two speed ranges of data is quite typical. There is virtually no data scatter within an individual run.

This station-by-station analysis is a very important step for understanding the characteristics and nature of the observed data and the solution of the computer simulation match of the entire experimental distance history data for obtaining the rolling resistance and aerodynamic drag coefficients. The variations in the rolling resistance, such as deviations from linear, can be used in the best-fit data reduction to obtain more realistic solutions for the characteristics of aerodynamic drag and rolling resistance.

Additional information on this running resistance history data reduction and analysis is in Appendix C. It can be seen that the approximate data reduction approach (point-mass assumption and average speed between consecutive data stations) can yield information almost as useful as the highly accurate data reduction results of Appendix E. Also, the use of hand timing is shown to give a good general history information but is not adequate to quantify characteristics such as the oscillation. In fact, from the hand timing plots it would appear that there is just considerable data scatter rather than the actual oscillatory characteristic of the total running resistance history (see Appendix C).

B. ROLLING RESISTANCE AND AERODYNAMIC DRAG

The running resistance was separated into its two components, rolling resistance and aerodynamic drag. A summary of the rolling resistance and aerodynamic drag coefficients determined for the various train consists tested is presented in Table 4 and Figure 14. They are based upon reasonable engineering interpretations of the best-fit triads (C_D, C_{RO}, C_{RN} of Appendix E as summarized in Table 5.) Data with high root-mean-square (RMS) values (which indicate a poor fit of simulated histories with the observed histories) were omitted from the averaging process. Also, less credence was given to the drag coefficient for the lower speed range runs.

The effect of the lower quality of hand-timed data upon the separation of running resistance from aerodynamic drag was investigated for Run 22. There was essentially no effect upon the best triads (see Appendix C). Therefore, it was assumed that virtually the same data reduction results (using the RRCDRR computer program) existed for the runs for which only stop-watch times were obtained (Runs 18, 19, 21, 23, 29, 30) as for the sensor-timed runs.

Detailed discussions on the inferred rolling resistance and aerodynamic drag appear in the following subsections on validation and observations. It is believed that the resulting values of C_D and C_{RR} (C_{RO} + C_{RN} V) are good to within 5%; the individual values of C_{RO} and C_{RN} are probably good to about 0.00015 and 0.000005, respectively.

C. TECHNIQUE VALIDATION

Examination of the results shown in Figure 14 indicates many consistencies and several apparent inconsistencies in the resulting aerodynamic drag and the rolling resistance. All of the aerodynamic drag coefficients are of reasonable magnitudes and are consistent with each other. The apparent inconsistencies in the rolling resistances are discussed in the following subsection on observations on running resistance.

The aerodynamic drag coefficients for the two Box-Cars-Only train consists differ less than 4% (they should be the same since the types of box cars were the same) while the rolling resistance coefficients differ. The aerodynamic drag coefficient for the High-Drag train consist is significantly higher than that for the Base consist. The value of aerodynamic drag coefficient for the Box-Cars-Only train consist is appropriately less than for the Base train consist. The aerodynamic drag of the locomotive alone is greater forward than backward (consistent with wind tunnel results of Reference 14), while the rolling resistance is the same in either direction.

Figure 15 shows the relationships of run pairs which ideally should be consistent: repeat runs, up versus down direction of travel and runs with overlapping speed ranges. When consideration is given for the oscillating characteristic of the running resistance, the data of each pair of runs is self-consistent.

The negligible scatter of the total running resistance histories (see typical examples in Figures 13 and 15), the excellent comparison of the run pairs (Figure 15), the consistencies of the aerodynamic results and the locomotive-alone rolling resistance (Table 4), and the accuracy analysis all substantiate the validity of this coast-down technique; it can be used to determine highly accurate values of the total running resistance and then, with reasonable accuracy, separate it into its components of rolling resistance and aerodynamic drag.

D. OBSERVATIONS ON RUNNING RESISTANCE

Although the objective of this demonstration test was to confirm that this coast-down technique was applicable to trains, several interesting aspects of train running resistance were observed. Some of the observations conform to general expectations which this test quantified. However, a number of the observations are in direct opposition to what was expected. The discussion of these observations will be focused on the results. When appropriate, some comment will be included on the rationale. Detailed analyses of these observations were not carried out since it is beyond the present scope of this study.

1. Rain

Some light rain occurred while the tests were being conducted. Rather than temporarily halt the tests until the rain ceased, the test was carried out during the occasional periods of rain and just after the rain stopped. As expected, the rain tended to decrease the running resistance. This is shown quite definitely for the locomotive alone (Figure 16a), but somewhat less definite for the Heavy Box consist (Figure 16b). The effect of rain on the Hi-Drag configuration appears to be unclear (Figure 16c). Although these three comparisons are for the total running resistance, they relate directly to the rolling resistance (mechanical friction) if one assumes that the aerodynamic drag is unaffected by rain. If it is affected, it would probably be increased by the rain, hence result in a definite decrease in the rolling resistance with rain even for the Hi-Drag consist. The wet track (just after the rain stopped) did not appear to decrease the rolling resistance. This may be due to the "wiping action" of the first wheels, hence the track was essentially dry for the rest of the wheels.

2. Truck Hunting

Originally the Base configuration was to include five flat cars and four box cars along with the locomotive, test car, and caboose. But, due to the excessive hunting displayed by the trucks of one of the flat cars, it was deleted from the Base configuration after Run 4. A comparison of the total running resistance with and without the flat car yields information on the increase in rolling resistance due to the excessive truck hunting (Figure 17 and Table 4).

3. Car Arrangement

The original purpose of the Hi Drag configuration (composed of alternating the identical box and flat cars of the Base consist) was to greatly increase the aerodynamic drag without affecting the rolling resistance. However, the total running resistance was about the same for these two consists (Figure 18) in spite of the 32% increase in aerodynamic drag (from C_D = 2.8 to 3.7, ... from Table 4). Therefore, the rolling resistance had to have decreased accordingly, and is shown to have done so in Table 4. A possible explanation is that the box cars had anti-hunting trucks (constant contact resilient side bearings) while those of the flat cars did not. When the flat cars were in a group, the hunting of each car tended to increase that of the adjacent flat car(s). However, when the box and flat cars were alternated, the box cars tended to stabilize the flat cars, hence diminishing the hunting of the flat cars' trucks.

4. Consist Orientation

a. Locomotive

The locomotive-alone was run backward (reverse) as well as forward. The total running resistance was significantly lower for backward than for forward orientation (Figure 19a). The decrease is due entirely to the aerodynamic drag difference as the rolling resistance was the same. The decrease of some

35% in aerodynamic drag (from C_D = 1.4 to 0.9 ... from Table 4) corresponds favorably to expectations based upon wind tunnel tests conducted by EMD (Reference 14) shortly before this demonstration test.

It is interesting to note that the C_{RR} values of the locomotive alone are much higher than those of the Heavy Box consist (see Table 4 or Figure 14). Free-wheeling tests of the locomotive truck performed subsequently indicate that the difference is about the same as gear box and motor windage losses.

b. Base Configuration

The increase in total running resistance with increasing speed for the Base consist is greater for coasting backward than forward (Figure 19b); and the aerodynamic drag, as expected, is slightly less (see Table 4). It is not clear why the rolling resistance slope (which relates quite closely to the total running resistance since the aerodynamic drags are nearly the same) is greater for the consist coasting backward. Perhaps the hunting of the trucks of the flat cars is accentuated by being "pushed" by the other cars than when being "pulled". This "pushed/pulled" assumption is due to the inference that the effective rolling resistance force of the flat cars is greater than that of the rest of the consist.

5. Train Consist Weight

Two basic configurations were run with the flat cars and/or box cars, all empty or all loaded (about 45-50 tons of wheelsets per car). For speeds above 45 mph, the total running resistance of the Box Car consist is about the same whether loaded or empty (Figure 20a). This implies that the rolling resistance force was unaffected since the aerodynamic drag was essentially unchanged. The same is true for the Base consist (having flat cars as well as box cars), and for the entire speed range investigated (Figure 20b). This negligible effect, if any, of axle weight upon rolling resistance is in direct contradiction to normal predictions based upon the Davis equation (Reference 2). The added weight may stabilize truck hunting enough to compensate for the expected effect of increased axle weight.

6. Side Wind

The winds encountered during this test were primarily cross-winds (perpendicular to the track direction) from virtually zero up to about 12 mph. No effects of these winds were noticed on the aerodynamic drag of the Base and the Hi-Drag consists which were run in "the higher" side winds (7-10 mph) as well as during periods of low wind (2 mph). Since the total running resistance data are essentially unaffected by the presence of the side winds (Figure 21), one can infer that the aerodynamic drag is not significantly affected by side winds up to 10 mph; it is unlikely that the rolling resistance would decrease correspondingly with a side force on the train which would tend to force the flanges against the far rail. This observed absence of any effect of the side wind on aerodynamic drag is contrary to the results of wind tunnel tests on small scale and short train consists (Reference 15); the larger side winds encountered should have nearly doubled the aerodynamic drag force at 50 mph train speeds (details in Appendix F). Since the estimated aerodynamic drag force is about one-third of the total observed running resistance (Figure 13), a near-doubling of the aerodynamic drag would have prevented the good comparisons of the results previously discussed.

Another observation of the effects of side winds on the aerodynamic drag was made during the first iteration of data reduction. The wind tunnel aerodynamic drag effect was included. However, this gave very poor matching of the experimental time-distance data; i.e, the RMS was much higher because the force model was incorrect. Ignoring the wind tunnel predicted effect greatly improved the data reduction results. It is interesting to note that engineers driving trains report no effect of cross-winds (up to 15 mph) on the steady-state pull-load of the train (Reference 13).

SECTION V

SUMMARY

A demonstration of this simple coast-down technique was carried out by JPL (sponsored by NASA) in conjunction with AT&SF, which operated specially configured trains on a portion of their main line rail. The technique is based upon accurate time-distance measurements of a coasting train over a surveyed segment of near-level track. The speed history, derived accurately from the distance history, is then matched by a computer simulating each experimental run in order to determine the appropriate coefficients of a quadratic equation (constant term, velocity term, and the velocity-squared term).

For the demonstration carried out, time measurements of the coasting train were made every 1200 ft for a five mile length of straight track having an average grade of about 0.05%. Tests were run in both directions, starting at 45-70 mph. Several carefully weighed train consists were used: a GP-50 locomotive, the AT&SF test car, a caboose, and four box cars followed by four flat cars; the same types of cars, each loaded with 45-50 tons of wheelsets to alter the rolling resistance with a minor effect on the aerodynamic drag; the box cars only, both empty and loaded; and, finally, the locomotive by itself. The locomotive used in the tests was the type previously scale tested in a large wind tunnel by the locomotive manufacturer.

This demonstration test shows that this coast-down technique for trains is easy to prepare for and execute. The total running resistance history was accurately measured and successfully separated into rolling resistance (mechanical friction) and aerodynamic drag. Constants (A, B, and C) in the quadratic train running resistance equation ($A + BV + CV^2$ where V is the train speed) were determined for a number of related train consists. In

addition, the oscillatory term for rolling resistance can also be determined, e.g., it was for the Base Consist of Run 26.

Full-scale measurement and validation of the various factors of train running resistance are essential capabilities in reducing train energy consumption and wheel rail wear. Such capabilities would enable railroads to evaluate the cost benefits of operational and consist configuration changes and new vehicle and truck designs that reduce aerodynamic drag and rolling resistance. The reduction in rolling resistance not only can result in significant decrease in fuel consumption, but also in a substantial decrease in track and wheel wear and subsequent replacement. Up to now it has not been possible for railroads to accurately measure the total running resistance of trains and to quantify separately the rolling resistance and aerodynamic drag. With the development of large, high-speed computers, it is now practical to carry out field tests in a simple manner in order to determine total running resistance and then quantify the aerodynamic drag and rolling resistance.

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NOMENCLATURE

A	Reference area used for reducing aerodynamic drag force to a dimensionless coefficient for aerodynamic drag. $A = 100\ ft^2$ was used throughout even for the locomotive-alone which has a frontal area of $145\ ft^2$
AT&SF	Atchison, Topeka and Santa Fe Railway Co.
C_D	Aerodyamic drag coefficient (dimensionless) $$C_D = \frac{\text{Aerodyamic drag force (lbs)}}{\frac{1}{2}\rho V^2 A}$$
C_{RO}	Mathematical intercept of rolling resistance coefficient C_{RR} at zero speed. It must not be taken to be the physical value at near-zero speeds
C_{RN}	Slope of the rolling resistance coefficient C_{RR}
C_{RR}	Dimensionless rolling resistance coefficient $= C_{RO} + C_{RN} V + f(V)$ for speed ranges above 20 mph (V in mph). For data reduction in this report f(V) set to zero (in lbs/lb).
C_{Total}	Total running resistance coefficient = $$C_{RR} + \frac{\text{Aerodynamic drag force (lbs)}}{W}$$
$C_{(\ )}$	C_{RR} or C_{Total}
f(V)	Oscillatory term in C_{RR} vs. V (assumed to be zero for general data reduction of this report)
H	Time at each data station obtained by handtiming with stop-watch
JPL	Jet Propulsion Laboratory
leg	The distance between successive data stations = 1200 ft.
MP	Milepost - distance markers along rail bed
Rev	Reverse direction (consist coasted backwards)
RMS	Root-mean-square (sec). Measure used to indicate quality of C_D, C_{RO}, C_{RN} of computer reduction of experimental data

NOMENCLATURE (Continued)

RR	Rolling resistance = WC_{RR} (lbs)
S	Time at each data station obtained with sensor system
V	Train speed (mph)
W	Weight of train consist (lbs)
β	$1 + \frac{\text{Rotational kinetic energy}}{\text{Transverse kinetic energy}}$
ρ	Air density (0.002378 slugs/ft^3 for standard conditions)

Relation of Davis Equation to C_{Total} of this Report
(for example, use a locomotive weighing 130 tons)

Davis (Typical for lead locomotive + base drag)

$$R_{D(lb/ton)} = 1.3 + \frac{29}{w} + 0.03V + \frac{0.0024AV^2}{wn} + \frac{0.0001AV^2}{wn}$$

where w = average weight per axle (tons)

n = number of axles

$$R_{D(lb/ton)} = 2.19 + 0.030V_{mph} + 0.00279V^2_{mph}$$

for A = 145 ft^2 and n = 4

JPL (This report - locomotive alone)

$$R_J(lb) = C_{RO}W_{lb} + C_{RN}\, W_{lb}\, V_{mph} + \tfrac{1}{2}\, \rho V_{fps}\, C_D A$$

$$R_J\ (lb/ton) = \frac{C_{RO}W_{lb}}{wn} + \frac{C_{RN}W_{lb}V_{mph}}{wn} + \frac{1.076\ \rho V_{mph}C_D A}{wn}$$

$$R_J(lb/ton) = 3.20 + 0.042V_{mph} + 0.00275V^2_{mph}$$

(for C_{RO} = 0.0016; C_{RN} = 0.000021; $C_D A$ = 1.4 x 100)

Note: A generic form of all above equations is $A+BV+CV^2$

NUMERICAL CONVERSIONS

in	=	2.54 cm
ft	=	0.3048 m
mile	=	1.609 km
mph	=	1.609 km/hr
lb	=	0.454 kg
ton	=	2000 lbs = 907 kg
gallon	=	3.785 liters

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TABLE 1

RUN INDEX

TEST DATE 1983 MAY	RUN	CONFIGURATION	DIRECTIONS	V_O (mph)	V_T (mph)	STNS	DATA	WIND SPEED (mph)	WIND DIRECTION (deg)	WEATHER	TEMP (^oF)	REMARKS
9	1	BASE'	UP	54	10	22-6	S	8½	90	CLEAR	66	PASSING TRAIN
	2	BASE'-Rev	DOWN	15	5	--		12			-	NOT REDUCED
	3	BASE'	UP	55	11	22-6		9½			-	
	4	BASE'-Rev	DOWN	15	5	—		10			-	NOT REDUCED
	5	BASE	UP	39	10	12-1		7			77	
	6	BASE -Rev	DOWN		19	5-16		8			-	PASSING TRAIN
	7	BASE	UP	60	13	23-1		10	120		79	
10	8		DOWN	61	25	1-23		8	60		59	
	9			60	26			10	75		66	
	10			57	24			8			-	
	11	HEAVY		58	38			9			79	
	12			69	48			11	45	SOME CLOUDS	82	
	13							10	75		-	
	14			48	30			8			79	
	15			27	19	14-23		7½			78	
11	16	HEAVY BOX	UP	69	43	23-1	S+H	2	90	HIGH O/C	66	
	17			58	33			4	45	LIGHT RAIN	64	
	18	LOCO		70	31	23-1	H		90		71	
	19			45	10	23-6		5		OVERCAST	71	
	20	BOX	DOWN	59	37	1-23	S+H	4	120		72	
	21			45	24		H	6	135	RAIN 1ST HALF	-	WET TRACK
12	22	HI DRAG		59	28		S+H	4-5	65	HEAVY O/C	69	
	23			50	19		H	7	90	LIGHT RAIN	66	
15	24			59	29		S+H	0-1	45	CLEAR	43	
	25			46	13			2			47	
	26	BASE		59	29			2	30		52	
	27			47	19			2	45		55	
	28			60	5	—			90		56	BRAKES ON
	29	LOCO		69	32	1-23	H		45		-	
	30	LOCO-Rev	UP		33	23-1		3	135		-	
12	B	FREIGHT		52	8	23-2		6	60	OVERCAST	67	WET TRACK
	C		DOWN	62	38	1-23		7½	120	CLEAR	75	

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TABLE 2

EXAMPLE COMPUTER LISTING OF RUNNING RESISTANCE HISTORY

(RUNRES PROGRAM)

TRAIN RUNNING RESISTANCE HISTORY
(AVERAGE BETWEEN SUCCESSIVE PAIRS OF DATA STATIONS)

CASE: TOPEKA RUN 7 BASE UP

WEIGHT LOSS (LBS): 3000.0 CONSIST WEIGHT (LBS): 1020663.0 CONSIST LENGTH (FT): 586.0

CAR WTS:	271663.0	169700.0	77160.0	77300.0	84440.0	84000.0	52300.0	50300.0	49400.0	48800.0	58600.0
CAR LEN:	59.2	77.2	59.8	57.8	60.5	60.5	41.0	43.2	43.3	40.1	43.4

RHO,AREA,BETA: .00237800 100.00 1.11900

STN	DELTIME (SEC)	TIME (SEC)	SPEED (MPH)	STN EL (FT)	EFF EL (FT)	DEL EL (FT)	CTOTAL CD= .00	CROLRES CD= 2.20	CD= 2.40	CD= 2.60	CD= 2.70	CD= 2.80	CD= 2.90	CD= 3.00	AVG SPEED
23	.0000	.000	59.690	23.230	23.182	-.048	.000000	.000000	.000000	.000000	.000000	.000000	.000000	.000000	.000
22	13.9200	13.920	57.872	23.570	23.605	-.065	.006313	.004408	.004235	.004062	.003973	.003889	.003902	.003715	58.777
21	14.3600	28.280	56.049	24.040	23.963	-.077	.006179	.004390	.004228	.004065	.003984	.003902	.003821	.003740	56.9[illegible]
20	14.8410	43.121	54.231	24.320	24.259	-.061	.006005	.004329	.004177	.004024	.003948	.003872	.003796	.003720	55.130
19	15.3470	58.468	52.376	25.210	24.968	-.242	.005577	.004010	.003868	.003726	.003654	.003583	.003512	.003441	53.312
18	15.9200	74.388	50.493	26.160	26.075	-.085	.005119	.003660	.003527	.003395	.003329	.003262	.003196	.003130	51.393
17	16.5150	90.303	48.458	28.190	27.807	-.383	.004836	.003487	.003364	.003241	.003180	.003119	.003057	.002996	49.542
16	17.3050	107.208	46.116	30.370	30.256	-.114	.004867	.003634	.003522	.003410	.003354	.003298	.003242	.003186	47.280
15	19.1050	126.313	44.305	30.340	30.364	.024	.005016	.003889	.003787	.003684	.003633	.003582	.003531	.003480	45.191
14	18.8400	145.153	42.630	30.190	30.224	.034	.004658	.003617	.003522	.003427	.003380	.003333	.003285	.003238	43.428
13	19.5900	164.733	40.913	30.270	30.306	.036	.004405	.003443	.003356	.003268	.003225	.003181	.003137	.003094	41.767
12	20.4350	185.168	39.103	30.470	30.438	-.032	.004406	.003524	.003444	.003364	.003323	.003283	.003243	.003203	40.038
11	21.4250	206.593	37.274	30.640	30.531	-.109	.004279	.003475	.003402	.003329	.003292	.003256	.003219	.003183	39.188
10	22.5700	229.163	35.206	31.390	31.259	-.131	.004068	.003344	.003278	.003213	.003190	.003147	.003114	.003081	35.251
9	23.9950	253.158	33.028	32.250	32.157	-.093	.003986	.003244	.003186	.003128	.003098	.003063	.003040	.003011	34.098
8	25.6400	278.798	30.387	33.170	33.060	-.110	.003516	.002953	.002902	.002850	.002825	.002799	.002774	.002748	31.910
7	27.4100	306.208	28.797	33.960	33.884	-.076	.003203	.002712	.002667	.002623	.002600	.002578	.002556	.002533	29.850
6	29.5250	335.733	26.582	34.900	34.724	-.176	.003126	.002703	.002665	.002626	.002607	.002589	.002569	.002549	27.711
5	32.2100	367.943	24.209	35.710	35.596	-.114	.003032	.002676	.002644	.002612	.002596	.002580	.002563	.002547	25.401
4	35.6500	403.593	21.602	36.690	36.491	-.189	.002979	.002690	.002664	.002637	.002624	.002611	.002598	.002585	22.950
3	40.1650	443.759	19.321	36.620	36.606	-.014	.002815	.002584	.002563	.002542	.002532	.002521	.002511	.002500	20.371
2	45.3700	489.128	16.628	37.460	37.283	-.177	.002455	.002277	.002261	.002245	.002237	.002229	.002220	.002212	18.034
1	54.0900	543.218	13.325	37.670	37.820	-.050	.002638	.002514	.002503	.002492	.002486	.002480	.002475	.002469	15.126

ITERATION NBR: 1 (1)

TOPEKA RUN 7 BASE UP CDEST= 1.0000

AREA,WEIGHT,BETA,RHO 100.000 1072263.0 1.120 .002378

CR1	DCR	NDCR	CRN1	DCRN	NDCRN	CD1	DCD	NDCD	
.0000000	.0002000	13	.0000100	.0000080	9	2.20000	.05000	13	MATRIX = 1521

.0024000 CRMAX .0000740 CRNMAX 3.16000 CDMAX

LOAD1,LOAD2 C0,C1: 1.0000 .0000 UFORDN: .00000 NBR SKIPPED SIN: .00 WIND: .00

VELOCITY INTEGRATION INCREMENT = .08 LIFT-TO-DRAG RATIO = .00

STATION	VEXP (MPH)	TEXP (SEC)	DIF (SEC)	DISTANCE (FT)	DELTADIST (FT)	GRADE	CRREST	CRR(1)	CRR(2)	CRR(3)	WIND (MPH)	ANGLE (DEG)
23	59.691	.0000	.00000	.00	.00	.0003235	.00318	.00383	.00411	.00411	.00	120.00
22	57.878	13.9200	-.26427	1200.00	-22.93	.0003235	.00314	.00377	.00403	.00403	12.00	120.00
21	56.055	28.2800	-.63702	2400.00	-53.65	.0003235	.00310	.00371	.00395	.00395	12.00	120.00
20	54.241	43.1210	-1.12369	3600.00	-93.11	.0000000	.00306	.00364	.00388	.00388	10.00	120.00
19	52.331	58.4680	-.92790	4800.00	-69.99	.0011692	.00302	.00358	.00380	.00380	10.00	120.00
18	50.495	74.3880	-.23809	6000.00	-25.33	.0004819	.00298	.00352	.00372	.00372	7.00	120.00
17	48.361	90.9030	.56565	7200.00	34.40	.0023375	.00293	.00344	.00363	.00363	5.00	120.00
16	46.110	108.2080	.73290	8400.00	48.96	.0005000	.00288	.00337	.00354	.00354	3.00	120.00
15	44.334	126.3130	.04255	9600.00	2.94	-.0000447	.00284	.00331	.00346	.00346	12.00	120.00
14	42.634	145.1530	-.19963	10800.00	-13.92	-.0000447	.00280	.00325	.00339	.00339	10.00	120.00
13	40.958	164.7330	-.10753	12000.00	-8.40	-.0000447	.00276	.00319	.00332	.00332	10.00	120.00
12	39.122	185.1680	-.79498	13200.00	-48.55	.0000000	.00272	.00313	.00324	.00324	10.00	120.00
11	37.270	206.5930	-1.21108	14400.00	-73.22	.0007209	.00268	.00307	.00317	.00317	12.00	120.00
10	35.170	229.1630	-1.94511	15600.00	-105.39	.0007209	.00263	.00300	.00308	.00308	12.00	120.00
9	33.002	253.1590	-2.51995	16800.00	-139.05	.0007209	.00258	.00292	.00299	.00295	12.00	120.00
8	30.874	278.7980	-2.05814	18000.00	-118.20	.0007209	.00253	.00285	.00290	.00290	10.00	120.00
7	28.777	306.2090	-.43112	19200.00	-45.80	.0007209	.00249	.00278	.00281	.00281	10.00	120.00
6	26.561	335.7330	.75962	20400.00	4.63	.0007209	.00244	.00270	.00272	.00272	12.00	120.00
5	24.168	367.9430	1.33675	21600.00	27.81	.0007209	.00236	.00262	.00262	.00262	10.00	120.00
4	21.558	403.5930	.31025	22800.00	-2.01	.0007209	.00233	.00253	.00251	.00251	11.00	120.00
3	19.363	443.7580	.35907	24000.00	-5.50	.0000000	.00228	.00246	.00241	.00241	7.00	120.00
2	16.561	489.1280	1.66891	25200.00	28.61	.0008564	.00221	.00236	.00230	.00230	6.00	120.00

DETERMINATION OF RUNNING RESISTANCES OF "TRAINS FROM VELOCITY VS TIME COAST-DOWN DATA
(CASE: TOPEKA RUN 7 BASE" UP)

MIN RMS	ROLL RES (CR,CRN)		ORDER	AERO DRAG (CD)
.106633+01	.0015000	.0000340	1	2.9200
.119342+01	.0016000	.0000420	2	2.6900
.122901+01	.0016000	.0000420	3	2.6300
.126016+01	.0014000	.0000500	4	2.3500
.179543+01	.0013000	.0000340	5	3.0300
.137574+01	.0014000	.0000500	6	2.4400
.201025+01	.0019000	.0000500	7	2.2300
.205503+01	.0020000	.0000260	8	3.1500

TABLE 3

EXAMPLE COMPUTER LISTING OF ROLLING RESISTANCE AND AERODYNAMIC DRAG SOLUTIONS (RRCDRR PROGRAM)

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OF POOR QUALITY

TABLE 4

AT&SF COAST-DOWN TESTS

SUMMARY OF FINAL RESULTS

CONSIST CONFIG.	SPEED RANGE	WEIGHT (tons)	RMS (sec)	CD	C_{RO} $x10^5$	C_{RN} $x10^7$	C_{RR}* $x10^5$	ROLLING* RESIST. (tons)	NBR OF** RUNS DATA BASED ON
BASE	60-16	507	2.2	2.8	130	480	274-418	1.39-2.12	5 /9
BASE-Rev	39-19	536	1.9	2.6	-37	1210	326-689	1.75-3.69	1 /1
BASE'	52-10	536	2.1	3.0	195	480	339-483	1.82-2.59	2 /2
HI DRAG	59-21	507	3.7	3.7	110	320	206-302	1.04-1.53	3 /4
BOX	60-37	407	1.4	2.3	-6	413	118-242	0.48-0.98	1 /2
HEAVY BOX	69-33	578	0.7	2.2	105	130	144-183	0.83-1.06	2 /2
HEAVY	69-48	906	3.0	2.6	50	350	155-260	1.40-2.36	2 /5
LOCOM.	65-11	130	1.7	1.4	160	210	223-286	0.29-0.37	3 /3
LOCO-Rev	65-33	130	1.0	0.9	160	210	223-286	0.29-0.37	1 /1
RUN 26 (BASE)	59-29	504	3.43	3.12	110	380	$C_{RR}=C_{RO}+C_{RN}V$		
	59-29	504	0.74	2.80	150	360	$C_{RR}=C_{RO}+C_{RN}V+f(V)$		

* Smaller number is at 30 mph; larger is at 60 mph (C_{RR} in lbs/lb)

** Number preceding slash is number of runs data based on; number following slash is total number of runs made of that consist

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TABLE 5

RRCDRR SOLUTIONS

(Average for Orders Considered)

CONFIG	RUN	MATRIX	ORDER	RMS (sec)	C_D	C_{RO} x10^5	C_{RN} x10^7	V RANGE (mph)
BASE	7	1521	1-5	1.31	2.71	164	404	60-16
	7	405	1-5	1.19	2.70	166	400	60-16
	9	1521	1-5	2.76	3.63	47	633	54-26
	9	405	1-6	3.08	3.20	40	692	54-26
	10	1521	1-4	2.68	2.32	95	600	52-24
	10	405	1-2	2.55	2.25	90	625	52-24
	26	1521	1	3.68	2.69	94	477	59-29
	26*	405	1-6	3.42	3.12	110	380	59-29
	26	405	1-2	0.74	2.80	150	360	59-29
	27	1521	1-2	4.66	2.40	120	380	47-19
	27	405	1-4	5.02	2.10	103	488	47-19
	Assumed Values			2.2	2.8	130	480	60-16
BASE'	1	1521	1-7	2.47	2.47	180	580	50-10
	3	1521	1-6	1.98	3.22	200	420	52-17
	3	405	1-6	1.90	3.40	207	433	52-17
	Assumed Values			2.1	3.0	196	478	52-10
BASE-Rev	6	1521	1-10	1.95	2.56	-40	122	39-19
	6	405	1-9	1.95	2.71	-34	119	39-19
	Assumed Values			1.9	1.9	-37	121	39-19

* Includes RR Oscil

TABLE 5 (Continued)

RRCDRR SOLUTIONS

(Average for Orders Considered)

CONFIG	RUN	MATRIX	ORDER	RMS (sec)	C_D	C_{RO} $x10^5$	C_{RN} $x10^7$	V RANGE (mph)
HI DRAG	22	1521	1-5	1.64	3.15	92	468	54-28
	22	405	1-10	1.93	3.77	117	310	54-28
	22 *	1521	1-2	1.51	3.60	100	370	54-28
	23	1521	1-2	5.14	3.52	115	420	44-21
	23	405	1-12	3.74	3.78	78	508	44-21
	24	1521	1-5	2.72	3.72	122	260	58-29
	24	405	1-6	2.74	3.57	120	283	58-29
	25	1521	7	8.30	2.80	180	260	36-13
	25	405	7	7.19	3.20	160	300	36-13
	Assumed Values			3.7	3.7	110	320	59-21
HEAVY	11	1521	1-4	3.86	1.85	40	440	55-38
	11	405	1-4	3.15	1.32	-25	562	55-38
	12	1521	1-5	3.86	2.30	20	436	65-48
	12	1053	1-7	1.55	1.99	-178	804	65-48
	13	1521	1-4	2.71	2.70	55	320	68-49
	13	405	1-4	2.50	2.74	72	288	68-49
	14	1521	1-7	10.92	2.38	277	-208	48-31
	14	405	1-7	11.58	2.47	263	-179	48-31
	Assumed Values			3.0	2.6	50	350	69-48
BOX	20	1053	1-5	1.27	2.21	-19	463	59-37
	20	1521	1-4	1.54	2.46	15	340	59-37
	Assumed Values			1.4	2.3	-6	413	60-37

* Later data reduction performed (9-9-83)

TABLE 5 (Continued)

PRCDRR SOLUTIONS

(Average for Orders Considered)

CONFIG	RUN	MATRIX	ORDER	RMS (sec)	C_D	C_{RO} x10^5	C_{RN} x10^7	V RANGE (mph)
HEAVY BOX	16	1521	1-2	0.42	2.00	105	90	68-43
	16	1521	5	0.80	2.08	120	100	68-43
	16*	1521	5	0.65	2.25	122	68	68-43
	16*	**	-	-	2.25	95	113	68-43
	17	1521	1	0.53	1.60	50	260	57-33
	17	1521	4	0.50	2.08	100	100	57-33
	17*	1521	2-6	1.24	2.19	80	132	57-33
	17	405	1	0.47	2.84	110	0	57-33
	Assumed Values			0.7	2.2	105	130	69-33
LOCO	18	1521	1-7	1.40	1.13	104	314	63-31
	18	225	1-7	1.59	1.23	117	243	63-31
	19	1521	1-7	1.81	1.10	145	240	44-11
	19	225	1-7	2.34	1.52	176	7	44-11
	29	1521	1-7	1.79	1.44	171	160	65-32
	29	225	1-7	1.84	1.40	160	200	65-32
	Assumed Values			1.7	1.4	160	210	65-11
LOCO-Rev	30	1521	1-7	0.92	0.96	151	194	65-33
	30	225	1-7	1.14	0.83	134	293	65-33
	Assumed Values			1.0	0.9	160	210	65-33

* Later data reduction performed (9-9-83)

** From C_{Total} vs. V analysis

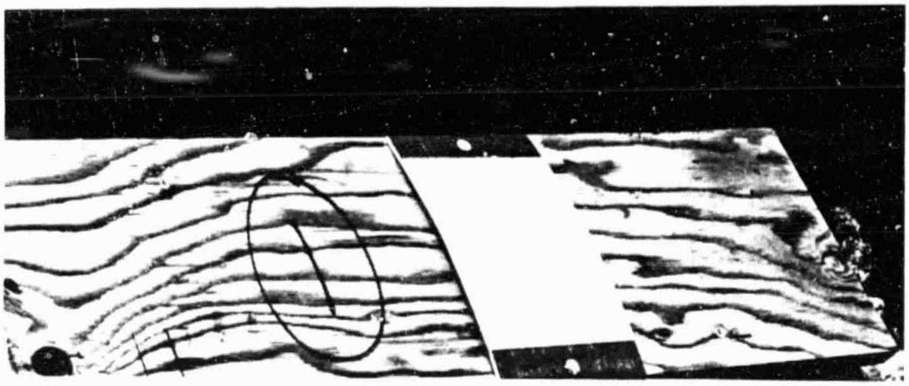
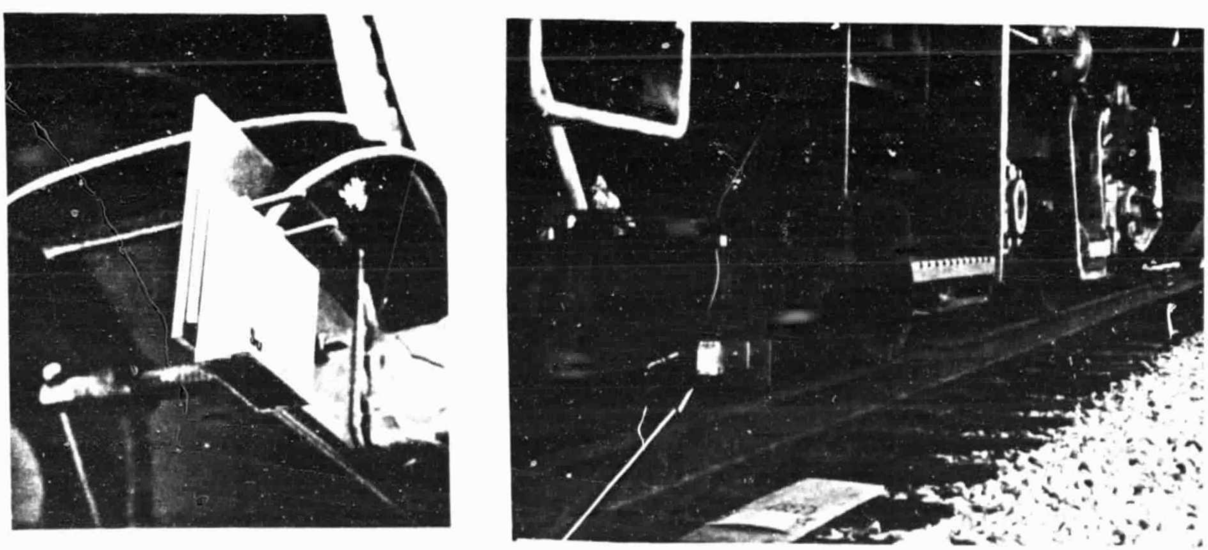


Fig. 1 Reflective Target
Mounted on Ties



a. Close-up of Sensor

b. Location of Sensor Near Rear Step of Locomotive

Fig. 2 Light Transmitter-Receiver Sensor

Fig. 3 Computer with Internal
Electronic Clock

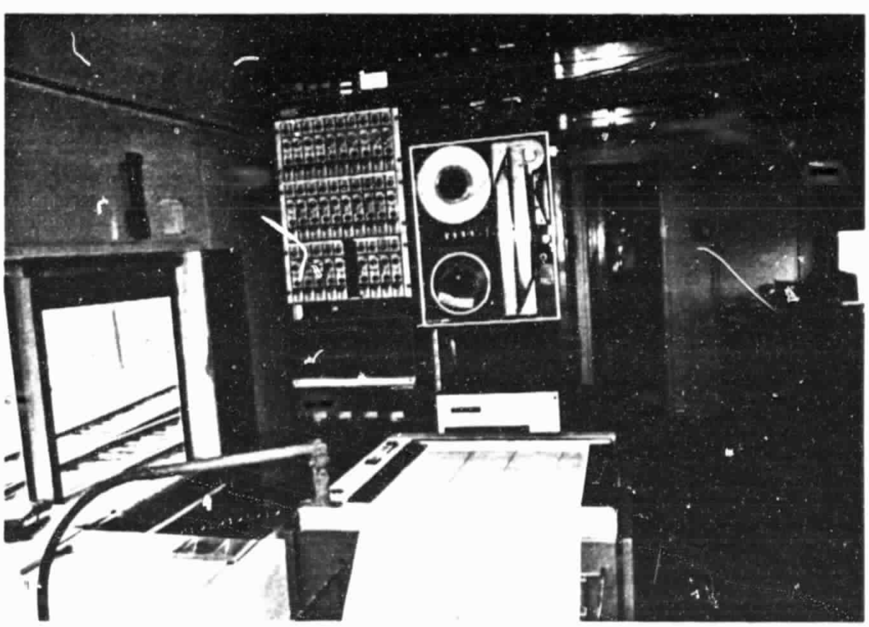


Fig. 4 Consoles Inside Test Car

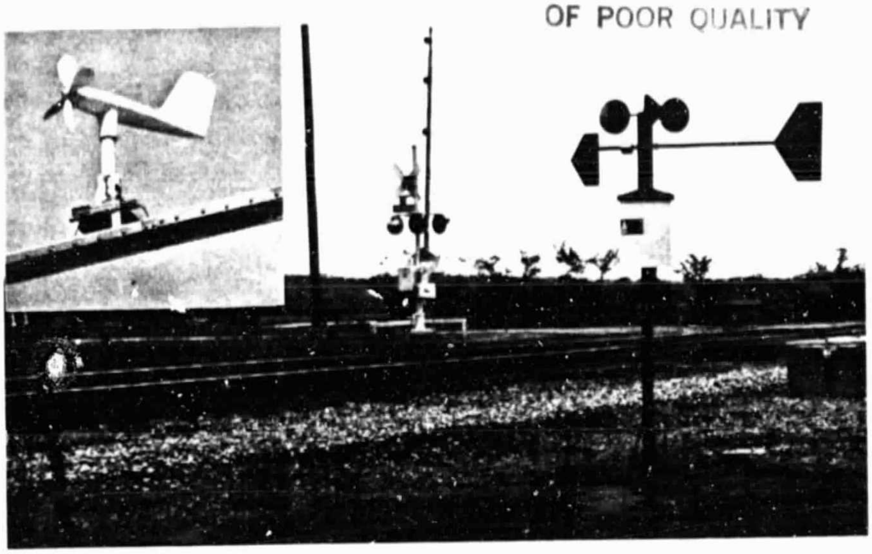


Fig. 5 Wind Annemometers:
At Wayside and on Test Car (inset)

a. Looking West from Data Station 18

b. Looking East from Data Station 18

Fig. 6 Typical Views Along Test Segment of Track

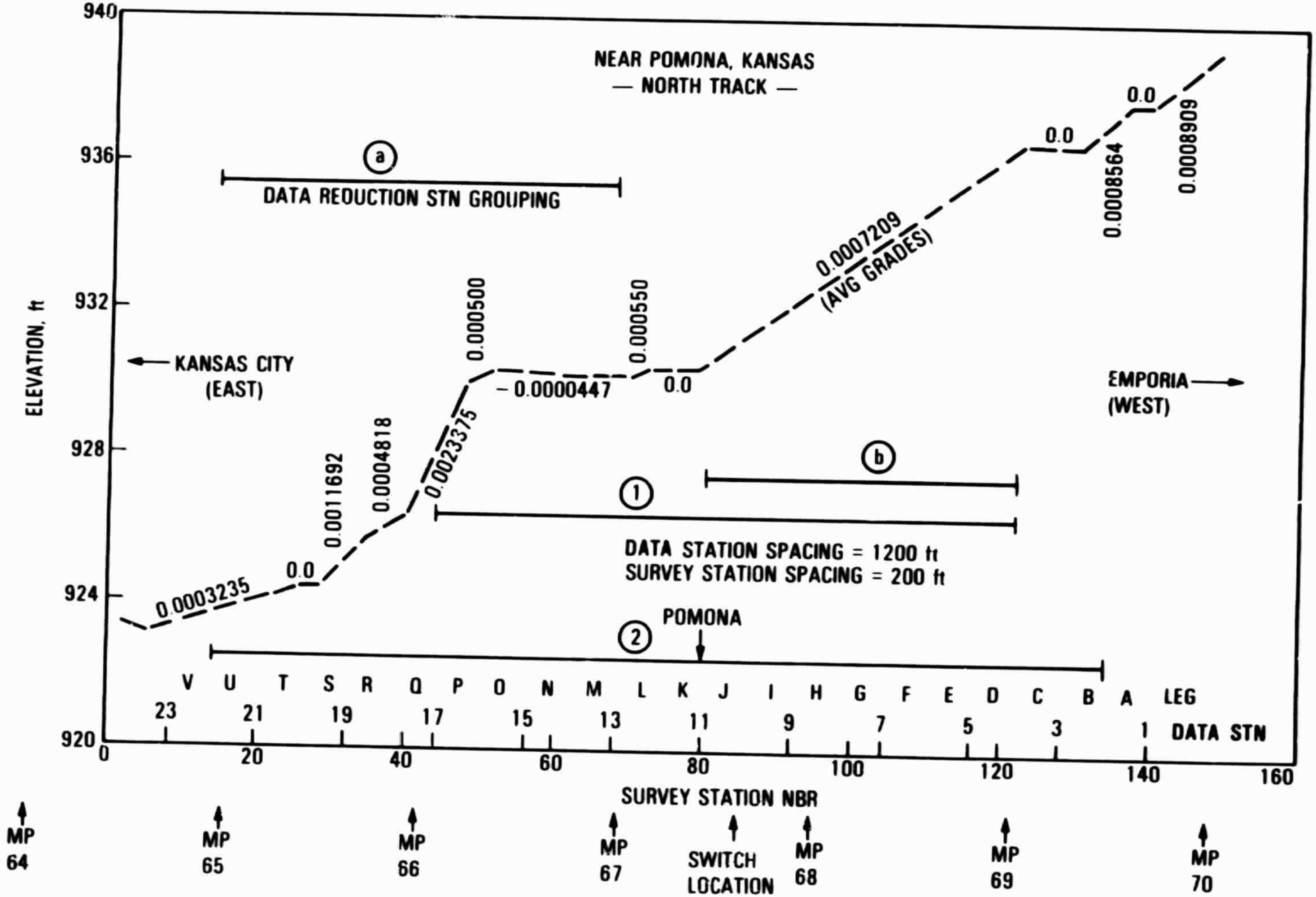


Fig. 7 Survey Results of Track Elevation and Grade

CONSIST MAKE-UP

CONSIST I.D.	CONSIST MAKE-UP	NO. OF ELEMENTS	LENGTH (ft)	WEIGHT (tons)	TONS AXLE (avg)
LOCO	L	1	59	130	32.5
BASE'	L+T+B+B+B+B+F+F+F+F+F+C	12	626	537	11.2
BASE	L+T+B+B+B+B+F+F+F+F+C	11	586	507	11.5
HEAVY	L+T+$\bar{B}$+$\bar{B}$+$\bar{B}$+$\bar{B}$+$\bar{F}$+$\bar{F}$+$\bar{F}$+$\bar{F}$+C	11	574	906	20.6
HI DRAG	L+T+F+B+F+B+F+B+F+B+C	11	586	507	11.2
BOX	L+T+B+B+B+B+C	7	415	407	14.5
HVY BOX	L+T+$\bar{B}$+$\bar{B}$+$\bar{B}$+$\bar{B}$+C	7	401	578	20.6
FREIGHT-B	3$\bar{L}$+40TOFC+C	46	4100	3574	19.4
FREIGHT-C	3$\bar{L}$+46TOFC+C	50	4284	3725	18.6

		APPROXIMATE WEIGHT (tons)	APPROXIMATE LENGTH (ft)
L	4-AXLE LOCOMOTIVE #3838	130	59
$\bar{L}$	6-AXLE LOCOMOTIVE	189	68
T	AT&SF TEST CAR #83	85	77
B	EMPTY BOX CAR	41	59
$\bar{B}$	LOADED BOX CAR	83	55
F	EMPTY FLAT CAR	25	42
$\bar{F}$	LOADED FLAT CAR	82	43
C	CABOOSE	29	43
TOFC	TRAILERS ON FLAT CARS	47-75	89

Fig. 8 Description of Train Consists Tested

a. Base (Loaded flat cars in inset)

b. Hi Drag

Fig. 9 Typical Test Train Consists

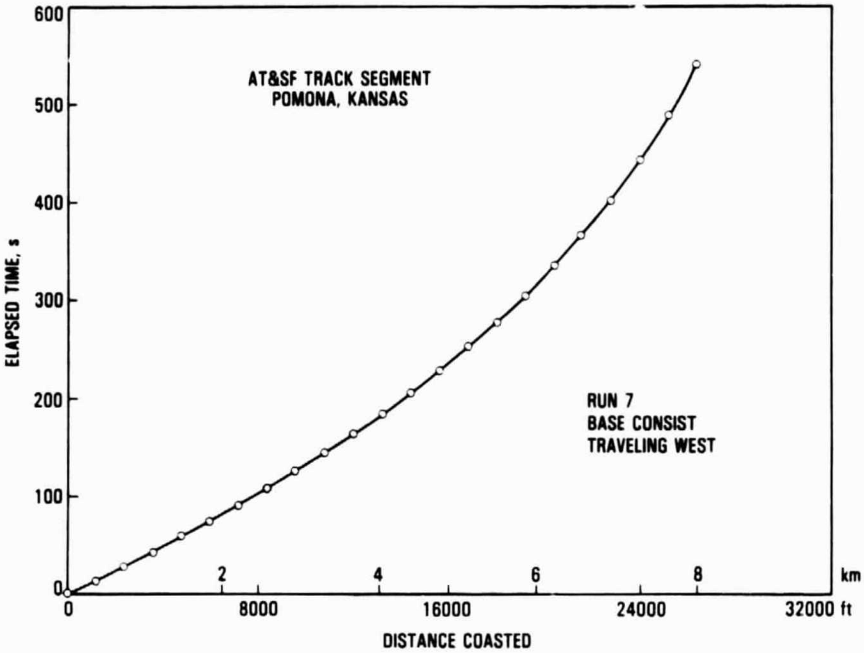


Fig. 10 Time versus Distance of Coasting Train

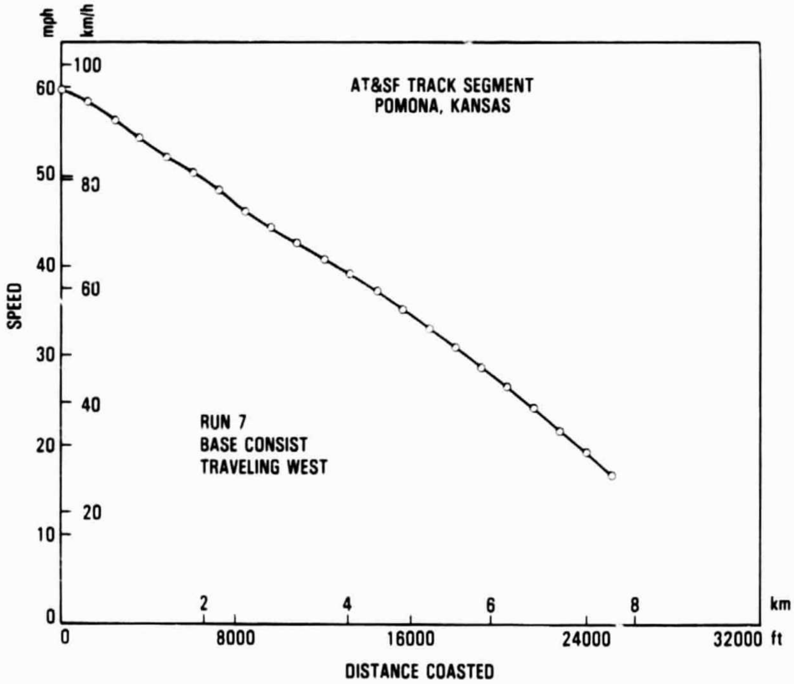
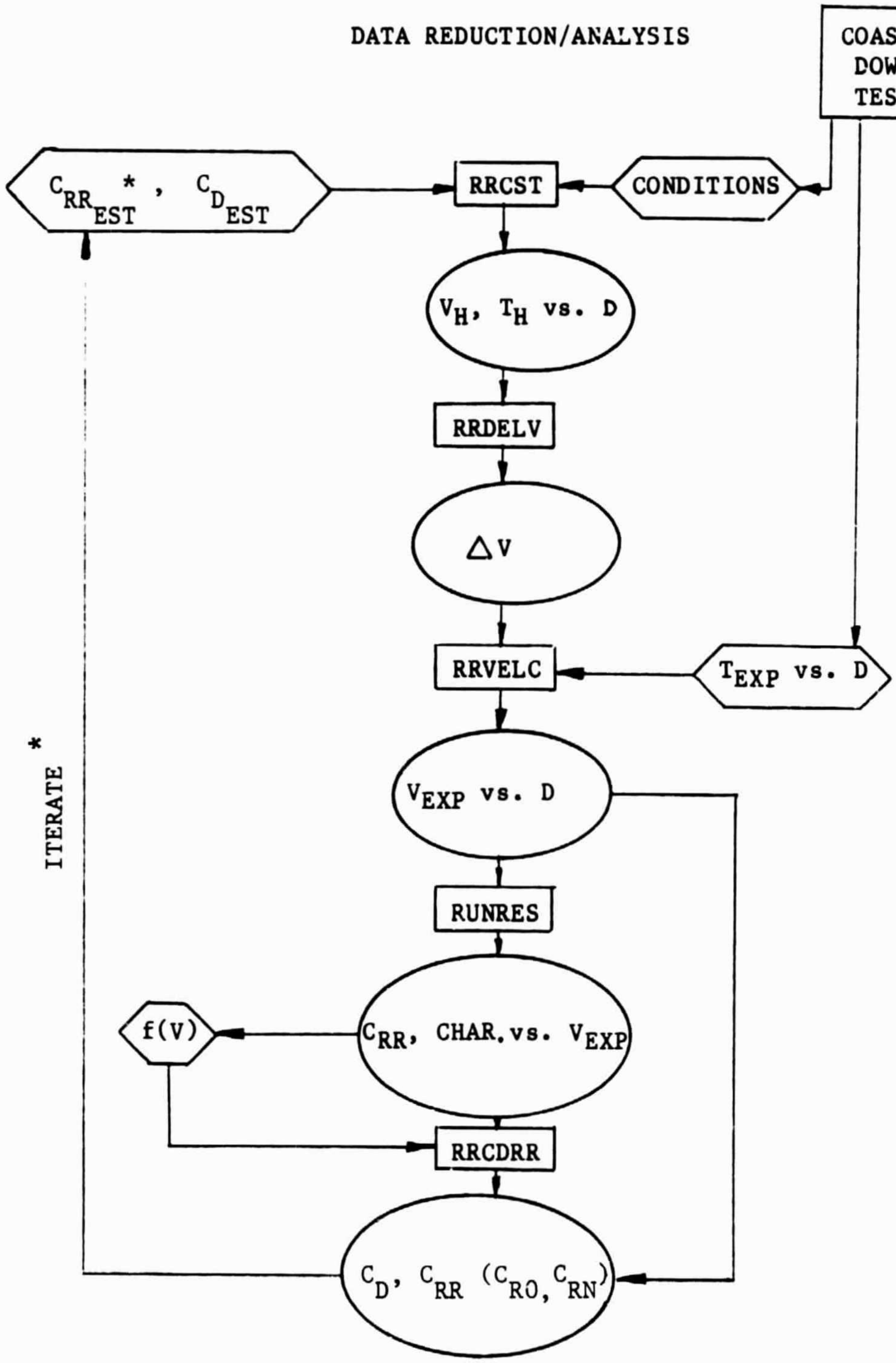


Fig. 11 Speed versus Distance of Coasting Train

a. FLOW DIAGRAM FOR

DATA REDUCTION/ANALYSIS



*ITERATE TO GET SPEEDS CLOSE TO EXPERIMENTAL VALUES

Fig. 12 Computer Programs

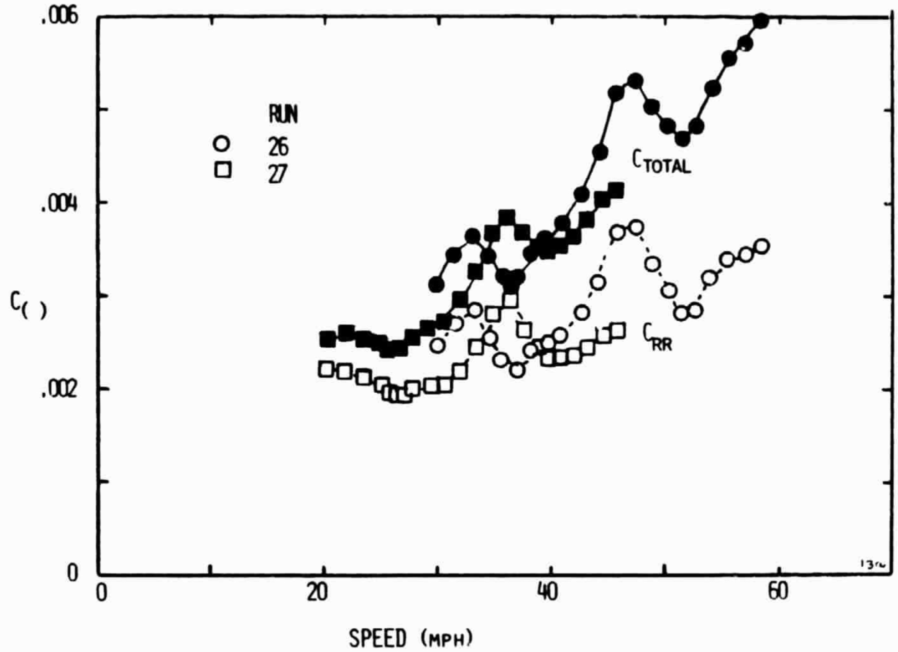
b. EXPLANATION OF COMPUTER PROGRAMS

I.D.	PURPOSE
RRCST	Calculates hypothetical coast-down histories including force and power of mechanical and aerodynamic resistances.
RRDELV	Calculates correction velocity increments to time-distance slope values of velocity (ΔV). Includes corrections for point and distributed mass assumptions as well as any difference in corresponding grade schedules.
RRVELC	Calculates (infers) experimental velocity at each data station from measured time-distance data using correction velocity increments.
RUNRES	Determines total running resistance history on a station-by-station basis. Also, estimates rolling (mechanical) resistance as a function of aerodynamic drag coefficient.
RRCDRR	Determines best triad sets of values for total running resistance coefficients: C_{RO}, C_{RN}, C_D, (A, B, C of generic Equation)*

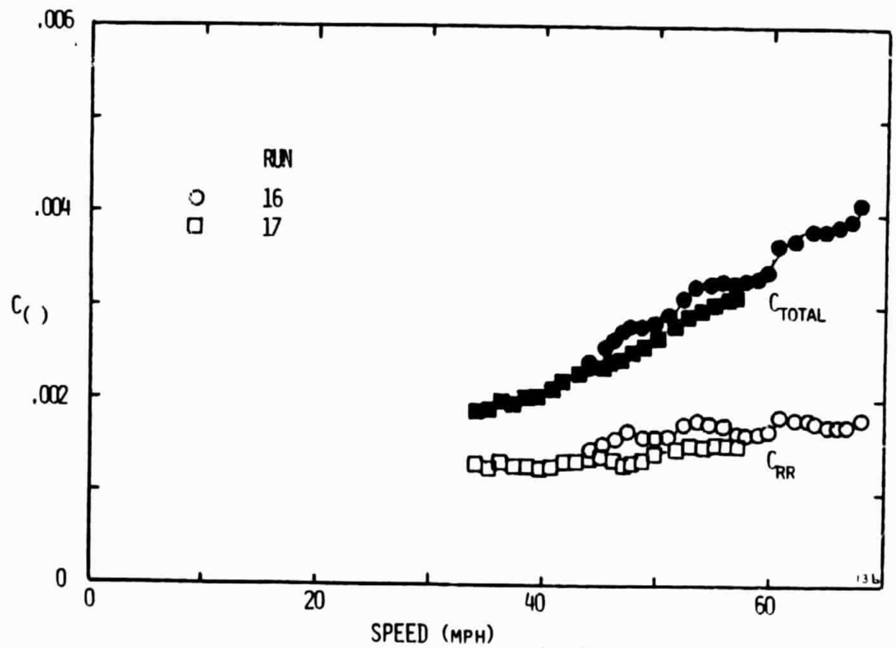
* Running Resistance = Weight x (C_{RO} + C_{RN} x Vel) + $\frac{1}{2} \rho V^2 C_D A$ (JPL Equation)

Running Resistance = A + BV + CV^2 (Generic Equation)

Fig. 12 [Cont.]

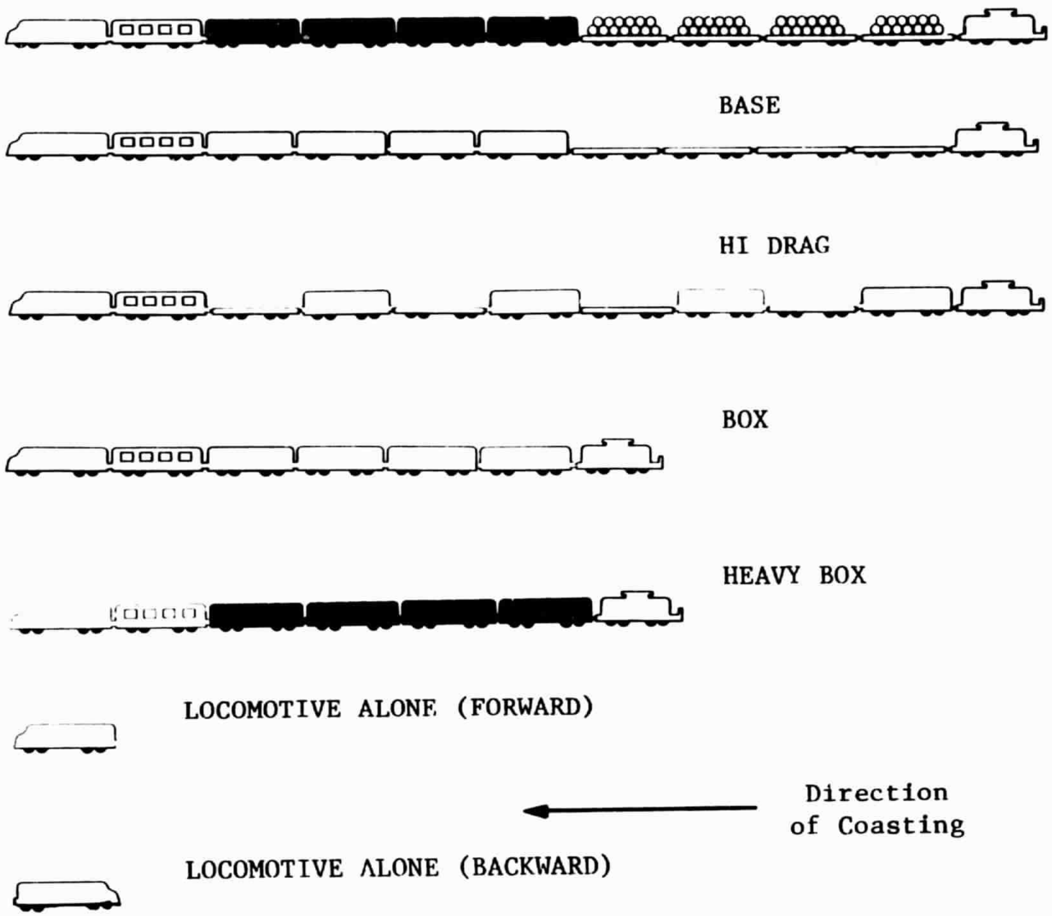


a. Base Train Consist



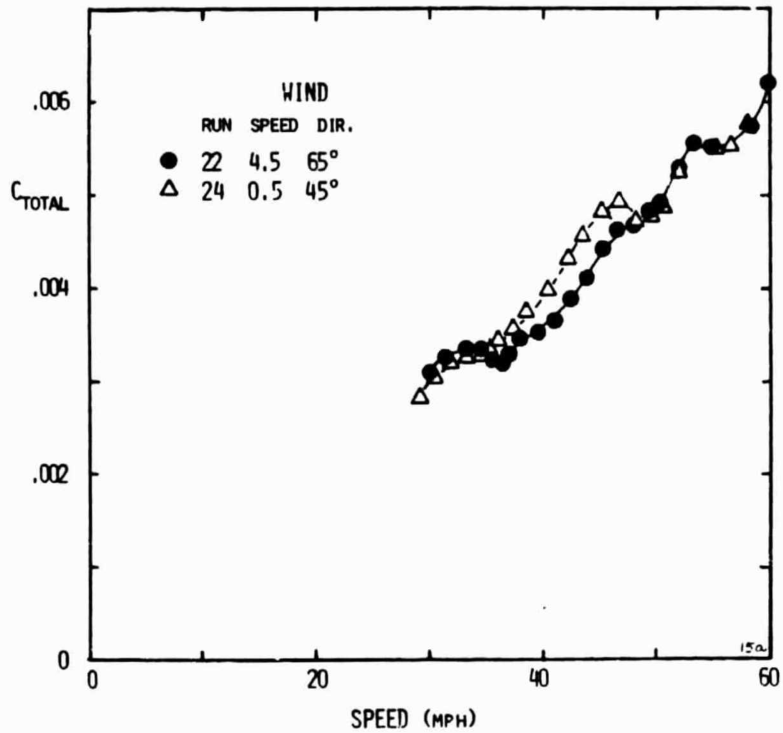
b. Heavy Box Train Consist

Fig. 13 Typical Running Resistance Histories

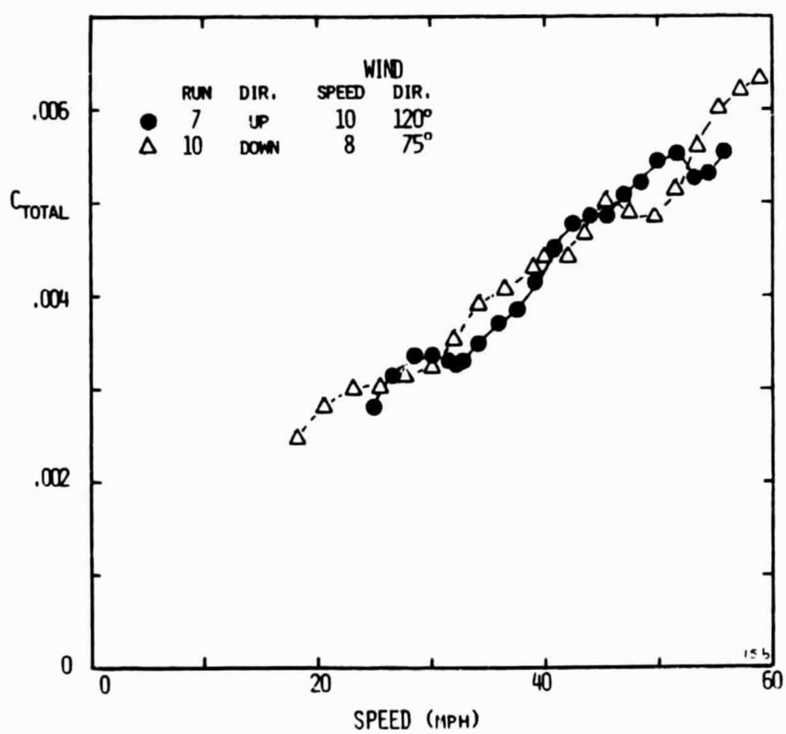


CONFIGURATION	TRAIN CONSIST WEIGHT (tons)	C_D ($A=100\ ft^2$)	$C_{RR} \times 10^5$ 30 mph	$C_{RR} \times 10^5$ 60 mph
HEAVY	906	2.6	155	260
BASE	507	2.8	274	418
HI DRAG	507	3.7	206	302
BOX	407	2.3	118	242
HEAVY BOX	578	2.2	144	183
LOCOMOTIVE ALONE (FORWARD)	130	1.4	223	286
LOCOMOTIVE ALONE (BACKWARD)	130	0.9	223	286

Fig. 14 Summary of Results

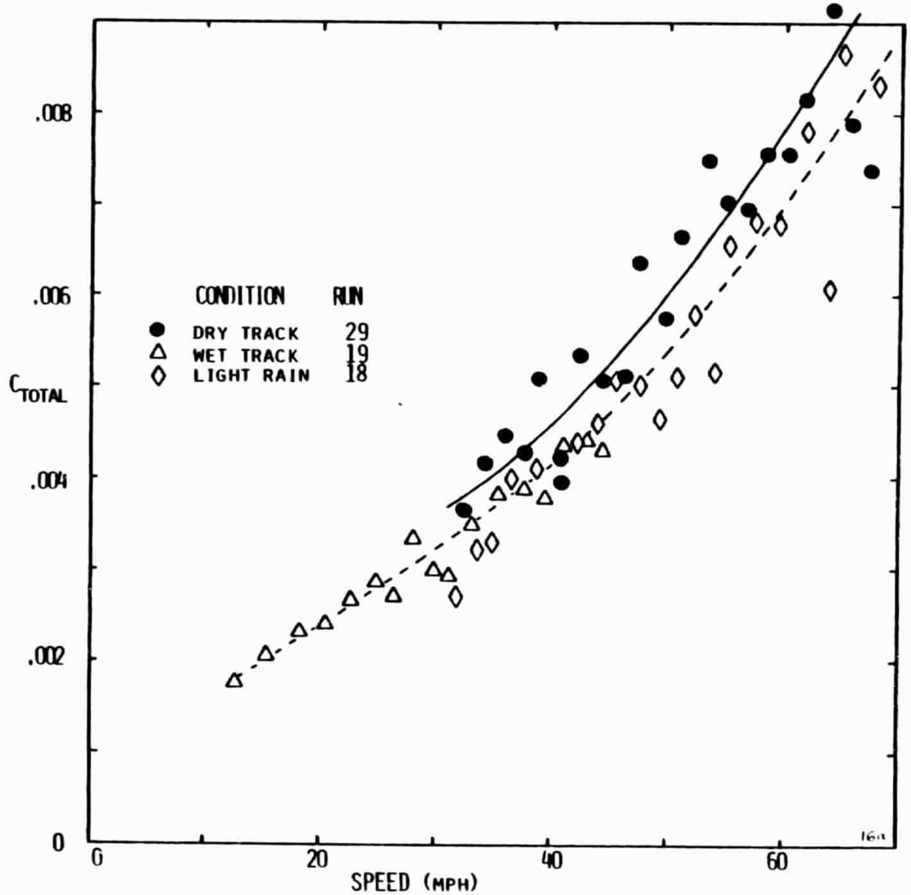


a. Repeat Runs

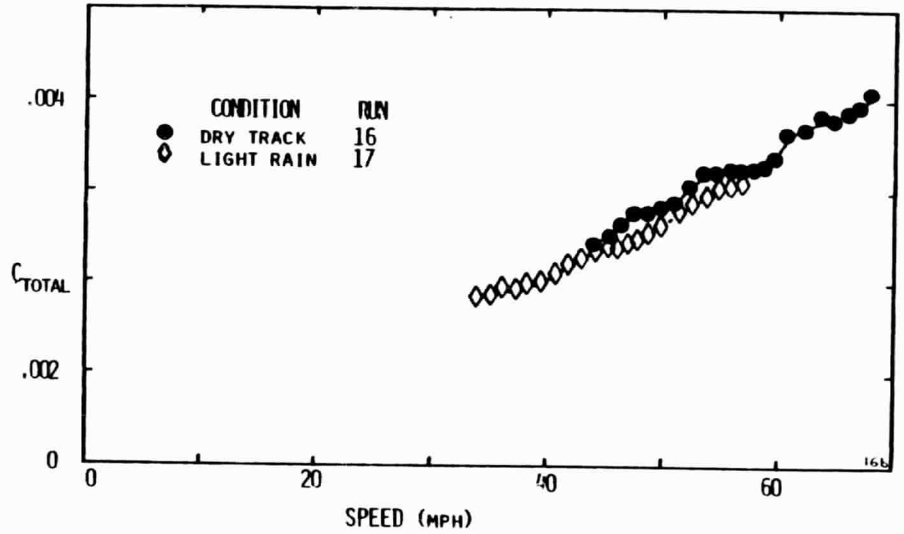


b. Uphill vs. Downhill

Fig. 15 Examples of Consistency of Runs



a. Locomotive



b. Heavy Box Train Consist

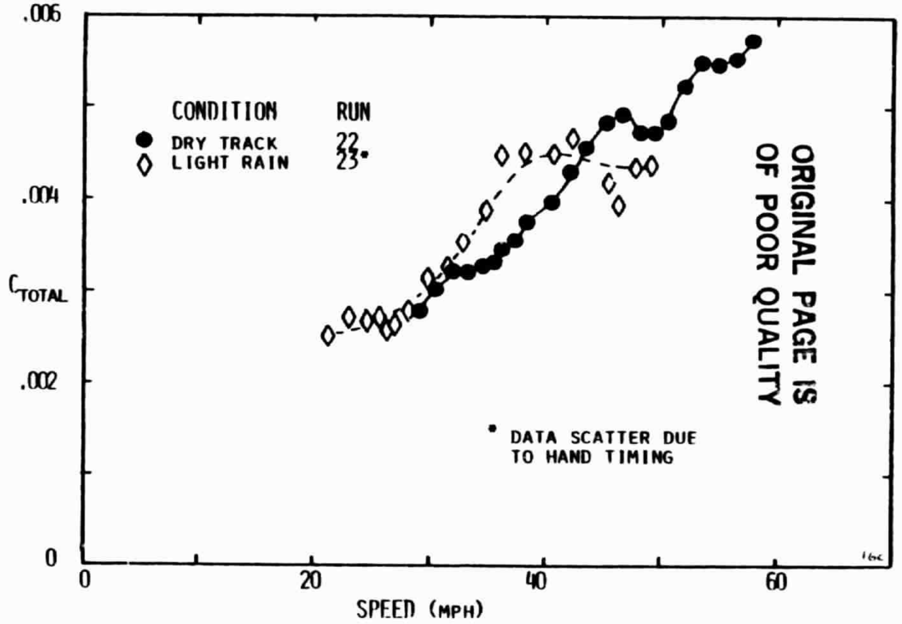


Fig. 16 Effect of Rain on Total Running Resistance

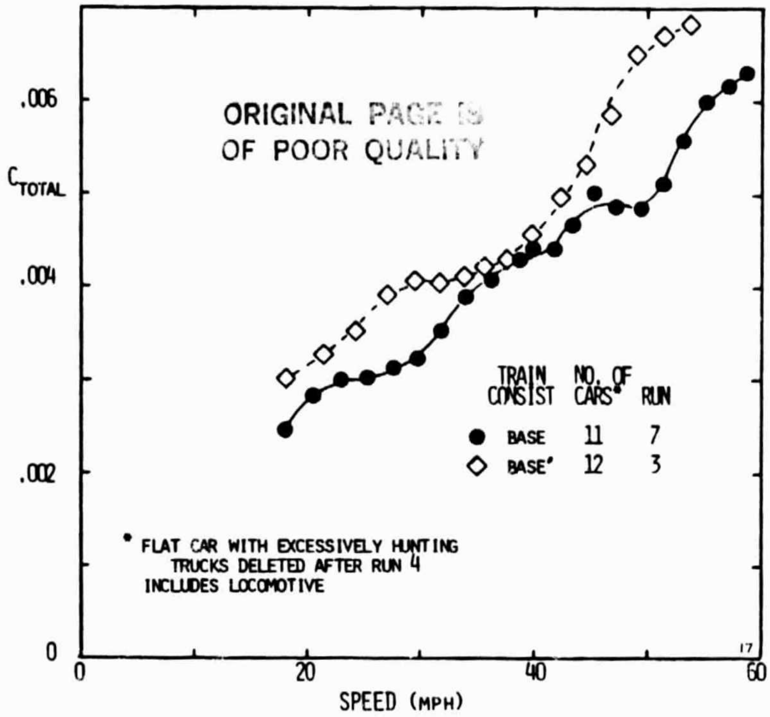


Fig. 17 Effect of Excessive Truck Hunting on Total Running Resistance

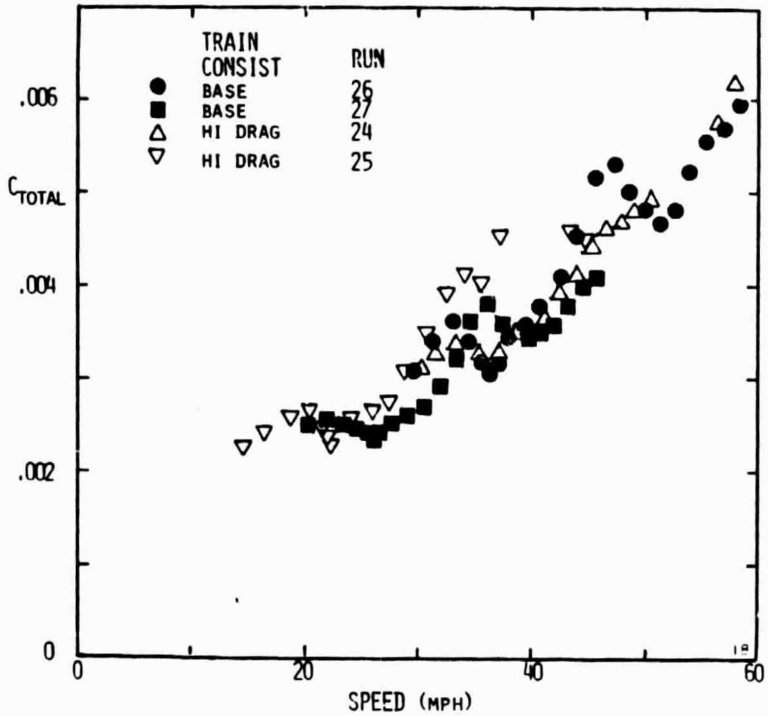
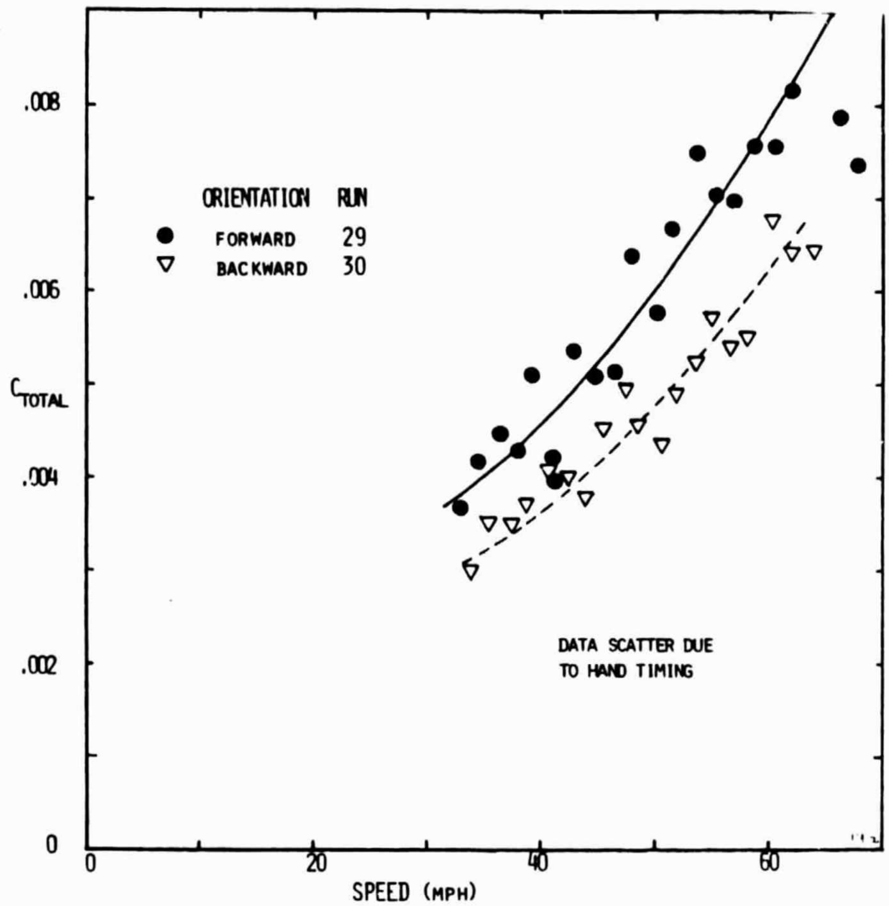
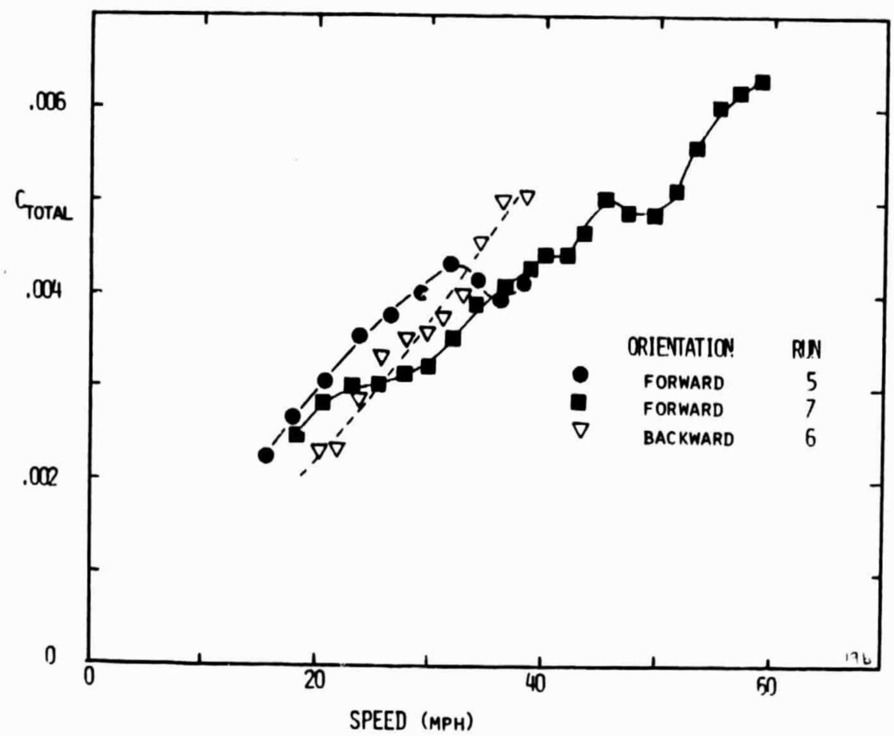


Fig. 18 Effect of Car Grouping on Total Running Resistance

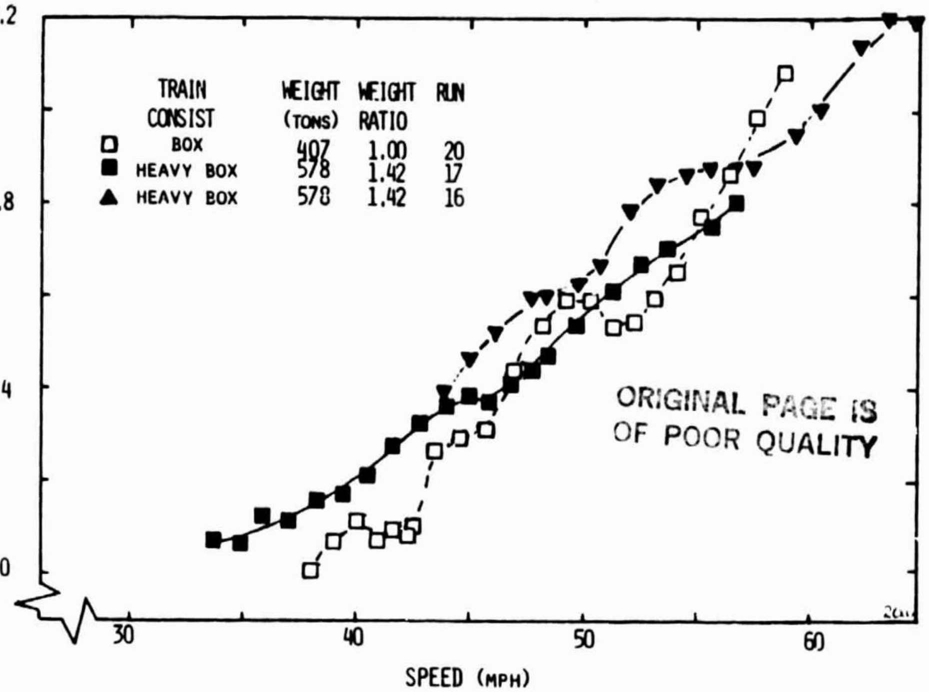


a. Locomotive Alone

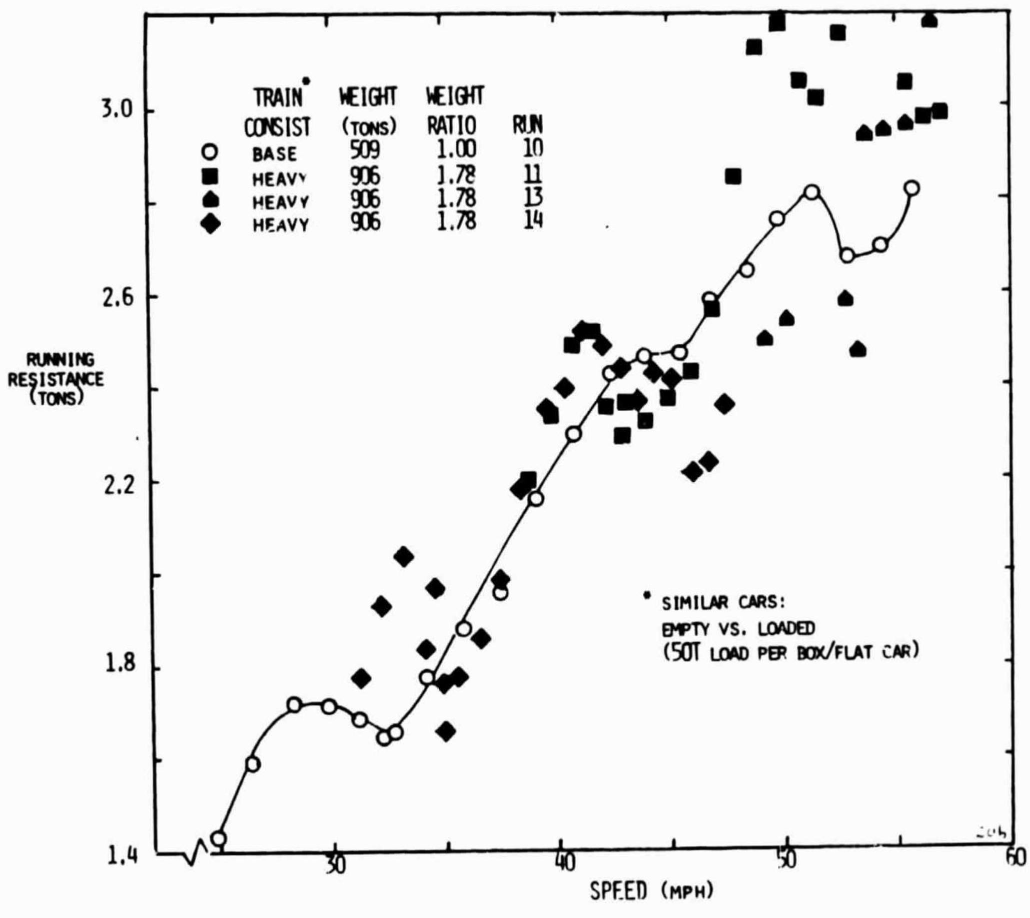


b. Base Configuration

Figure 19. Effect of Train Consist Orientation on Total Running Resistance

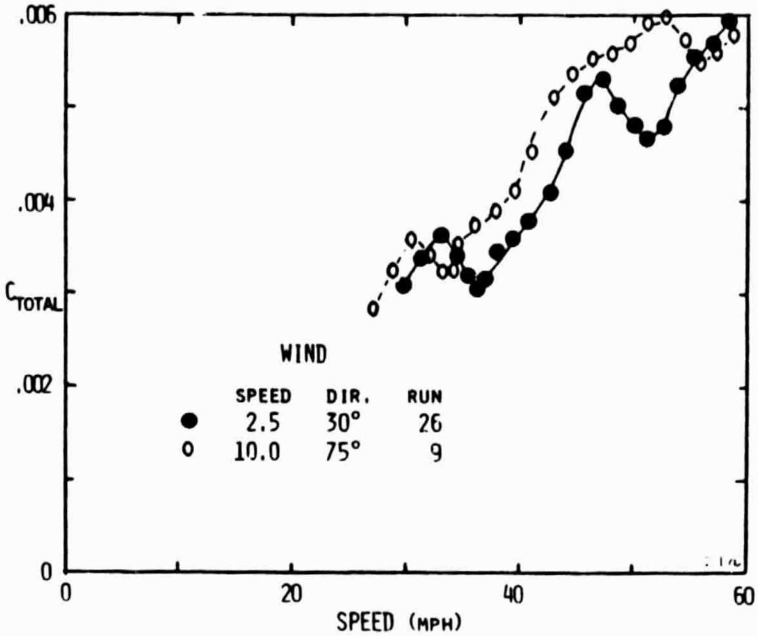


a. Box Cars

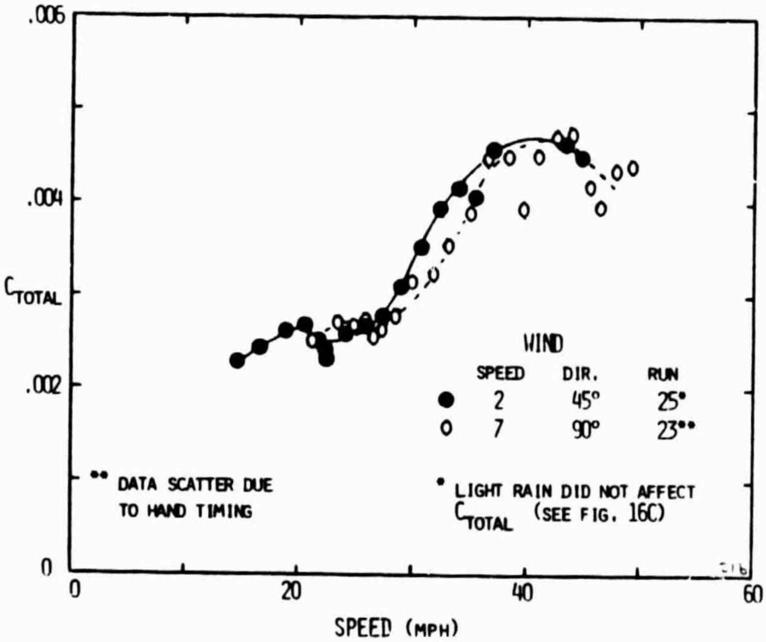


b. Box and Flat Cars

Fig. 20 Effect of Loaded Cars on Total Running Resistance



a. Base Train Consist



b. Hi-Drag Train Consist

Fig. 21 Effect of Side Wind on Total Running Resistance