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# Railroad Classification Yard Technology Manual

## Volume III: Freight Car Rollability

FRA/ORD-81/20.III

Final Report

August 1982

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16. Abstract

This volume (Volume III) of the Railroad Classification Yard Technology Manual documents the results of analyzing data on freight car rolling resistance (rollability) obtained from the existing process control computer systems at five railroad yards. The report presents a survey of rolling resistance research, histograms of rolling resistance from five yards, a statistical regression analysis of causal factors affecting rolling resistance, procedures for constructing a rolling resistance histogram at a new yard, and an analysis of errors in the measurement of rolling resistance.

Volume I presents methods and procedures for the physical design of a railroad classification yard. Volume II concerns the design and specification of the yard inventory and process control computer systems. Volume I and II may be referenced as Report #FRA/ORD-81/20.I & II, respectively.

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# PREFACE

This work was performed by members of the Transportation Operations and Information Systems Center of SRI International for the Department of Transportation's Transportation System Center (TSC), Cambridge, Massachusetts. Dr. John Hopkins of the TSC was technical monitor of the project (under Contract DOT-TSC-1762). The effort was sponsored by the Office of Freight and Passenger Systems, Federal Railroad Administration (FRA), as part of a program managed by Mr. William F. Cracker, Jr.

The research was performed under the technical leadership of Dr. Peter J. Wong, Director, Transportation Operations Research Department. Dr. William A. Stock performed the analytical investigations into the causal factors of rolling resistance, developed procedures for deriving histograms for new yards, and analyzed the measurement errors inherent in measuring rolling resistance. Ms. Mary Ann Hackworth was responsible for the collection, analysis, and presentation of the histogram data from the five cooperating railroad yards. The survey and assessment of rolling resistance research was conducted by Messrs. Stephen Petracek and Neal P. Savage.

Appreciation is expressed to the following for their cooperation in providing data for the project: Mr. B. Gallacher (retired, Southern Pacific), Messrs. M. J. Anderson, J. Conway, and S. Shelton (Union Pacific); Messrs. J. Wetzel, T. O'Dwyer, and C. Williams (Conrail); Mr. W. Butler (Burlington Northern); Mr. J. A. Rice (Southern Railway); Mr. W. L. Henry (ATSF); and Mr. B. B. Laves (GRS).



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# EXECUTIVE SUMMARY

## A. INTRODUCTION AND BACKGROUND

An understanding of car rolling resistance (rollability) is critical in the design and operation of railroad hump yards. Because cars are accelerated by gravity, design engineers must have a knowledge of rolling resistance to design the hump height and classification track grades and to determine the placement and length of retarders so as to ensure proper switching between successive cars on the hump and to control coupling speeds on the classification tracks.

Despite this need, however, rolling resistance has not been well understood, and an industry-wide data base has not been developed. Recognizing the importance of information on rolling resistance, the American Railway Engineering Association (AREA) Committee on Yards and Terminals recommended that this study of rolling resistance be conducted.

This study was specifically limited to the collection and analysis of existing data on car rollability and to data that can be obtained using existing yard sensing devices (e.g., velocity, position, time, distance-to-couple) and yard computers. No special instrumentation of yards, tracks, or freight cars was installed. The objectives of the study were to:

- Characterize freight car rolling resistance distributions in sufficient detail for use in the design of yard grades, the placement of switches, and the placement and size of retarders.
- Determine the influence of a variety of causal (physical and environmental) factors on freight car rollability.
- Examine rollability measurement schemes.

## B. MAJOR RESULTS

### B.1 Yard Design

The following railroads agreed to provide SRI with the desired rolling resistance information:

- Hinkle yard (Union Pacific)
  - GRS yard
  - Located in eastern Oregon (near Pendleton).
- Northtown Yard (Burlington Northern)
  - GRS yard
  - Located in Minneapolis.
- DeWitt Yard (CONRAIL)
  - GRS yard
  - Located in Syracuse, New York.
- Linwood Yard (Southern)
  - GRS yard
  - Located in North Carolina (near Charlotte).
- Argentine Yard (Santa Fe)
  - WABCO yard
  - Located in Kansas City.

Chapter 4 presents detailed information on each yard, including track layout, measurement locations, weather conditions, and car population. Chapter 4 also provides detailed rolling resistance histograms for the two measurement periods (summer and winter) and the four measurement locations where applicable (master retarder, group retarder, tangent point, and classification tracks).

The yards were selected to represent a variety of yard characteristics and climatic conditions so that designers of new or rehabilitated yards can use them as references. Referring to the histograms corresponding to the various measurement sections, designers should establish their own hard and easy rollers, and determine to what extent they will design for summer or winter conditions. (The establishment of the hard and easy roller on the histogram is a subjective process and reflects the design "safety" margin.) To aid designers in this process, Table ES-1 lists the 2.5 percentile (easy roller) and 97.5 percentile (hard roller) rolling resistances in pounds per ton for each of the five yards; 95% of the cars fell within each of these bounds. The values shown are the average energy losses per foot of travel over the measurement section and include the effects of track switches and curvature, car speed and weight, temperature, wind velocity, and the like. Consequently, the yard designer need not add in these rolling resistance factors because they are implicitly included in the measurements.

### B.2 Understanding Causal Factors

Traditionally, rolling resistance has been believed to be influenced by such factors as:

- Car speed
- Car weight
- Car type
- Bearing type
- Truck center length
- Wind

Table ES-1

ROLLING RESISTANCE SUMMARY FOR DESIGN
(Pounds per Ton)

| Yard | Master Retarder Winter | Master Retarder Summer | Group Retarder Winter | Group Retarder Summer | Tangent Point Winter | Tangent Point Summer | Classification Tracks Winter | Classification Tracks Summer |
|---|---|---|---|---|---|---|---|---|
| Hinkle | | | | | | | | |
| Easy roller | 3.95 | 2.37 | 3.72 | 2.50 | 4.22 | 3.50 | 1.53 | 0.0* |
| Hard roller | 13.97 | 9.79 | 21.70 | 16.00 | 14.25 | 9.31 | 10.58 | 7.35 |
| DeWitt | | | | | | | | |
| Easy roller | 2.63 | 2.63 | 4.77 | 3.73 | 4.00 | 2.99 | 2.52 | 1.61 |
| Hard roller | 16.69 | 10.58 | 20.09 | 14.40 | 15.35 | 12.39 | 15.39 | 11.17 |
| Northtown** | | | | | | | | |
| Easy roller | 13.16 | 10.55 | 10.71 | 6.45 | N/A | N/A | N/A | N/A |
| Hard roller | 32.50 | 19.38 | 33.79 | 21.64 | N/A | N/A | N/A | N/A |
| Argentine | | | | | | | | |
| Easy roller | N/A | N/A | 3.73 | 3.31 | 3.10 | 2.72 | N/A | N/A |
| Hard roller | N/A | N/A | 15.50 | 13.97 | 10.80 | 9.45 | N/A | N/A |
| Linwood | Nov. | Feb. | Nov. | Feb. | | | | |
| Easy roller | 5.76 | 4.97 | 3.52 | 3.42 | N/A | N/A | N/A | N/A |
| Hard roller | 16.33 | 20.41 | 18.20 | 20.57 | N/A | N/A | N/A | N/A |

Notes: Easy roller denotes the 2.5 percentile of rolling resistance. Hard roller denotes the 97.5 percentile of rolling resistance.

N/A signifies "not applicable"; that is, the computer system did not provide data.

*This value was caused by a small number of negative rolling resistances in the classification tracks.

**Just before printing of this report, Dr. Dennis C. Henry of Gustavus Adolphus College, a consultant to Burlington Northern, indicated to SRI that the rolling resistance values at Northtown Yard were treated as a "tuning parameter" and arbitrarily adjusted to improve yard operations. Thus, the Northtown Yard data are unreliable.

- Temperature
- Moisture
- Switches and curves
- Distance from crest
- Type of rail.

SRI analyzed the effects of these factors by linear regression. This technique reveals how the mean rolling resistance varies as a function of a set of independent variables (basically the above factors). Because of the nature of the data available, however, the effects of certain factors could not be reliably isolated. The inability of the statistical regression analysis to reveal causal relationships between specific factors does not reflect negatively on the quality of the data analyzed.

Isolating the influence of any single factor on rolling resistance is difficult because all factors influence rolling resistance simultaneously. Where relationships were quantified, an artifice called "nominal car and nominal conditions" was used. In this way, nominal values could be chosen for all factors except the one being studied, which was allowed to vary.

Some of the major results of the regression analysis were as follows.

Car Weight--The relationship between rolling resistance and car weight is inverse: As cars become lighter, they roll harder. Results indicate that a nominal 30-ton boxcar has a rolling resistance of approximately 8.3 lb/ton, whereas that for a nominal 80-ton boxcar is approximately 5.4 lb/ton.

Car Type--Relative to the nominal car (a boxcar), "on the average":

- Gondola cars roll about 1.2 lb/ton harder.

- Flatcars roll about 0.55 lb/ton harder.

- Tank cars roll about 0.66 lb/ton harder.

The other car types considered--hoppers, refrigerator, and vehicular cars--were not significantly different from the reference boxcar.

Bearing Type--Cars with roller bearings traditionally have been assumed to roll easier than cars with journal bearings. This study, however, revealed no statistically significant difference in the rollability of the two types of cars. Cars with journal bearings constituted about 17% of the regression sample--more than sufficient to have revealed any statistically significant difference.

Truck Center Length--No statistically significant effect of truck center length on rolling resistance was found. This applied even on curves, contrasting with the conventional notion that cars with long wheelbases roll harder because of a binding effect.

Car Speed--Rolling resistance increases with car speed. Although a $V^2$ (velocity squared) dependence was found, the actual curvilinearity appeared to be small both under zero ambient wind conditions and with a 10-ft/sec headwind. Thus, for most yard applications a linear relationship with velocity can be used when headwinds are small.

Wind--A headwind against the motion of a car can contribute significantly to the rolling resistance of a nominal car.* Results indicate that each foot/second of headwind contributes approximately 0.2 lb/ton to rolling resistance, for the nominal conditions.

Temperature--Cars roll easier with increasing temperature. The available data sample did not have extreme cold temperatures. A very slight, but nonetheless statistically significant, variation with $T^2$ (temperature squared) was noted. In the temperature ranges investigated, "on the average" a car rolls 0.39 lb/ton heavier for every drop of 10 °F in temperature.

Moisture--The traditional assumption has been that cars roll easier in the rain but that deep snow, particularly when it covers the rail, impedes a car's rolling. Although the data from the process control computers indicated whether moisture was present, no differentiation was made between rain and snow. Moreover, only on a few days was moisture present (about 3.4% of the data). There could also have been a discrepancy between what was automatically recorded in the cut statistics and the moisture conditions on the ground. No significant effect of moisture was found, but the extent to which the above difficulties are responsible for the lack of effect cannot be determined.

Switches and Curves--The effect on rollability of switches and curves appears to be significant, but a reliable quantification of the individual effects was not possible based on the data available. The measurement sections from which the switch and curve data were recorded were the same in most cases, so that the effect of each variable could not be reliably isolated. Moreover, these measurement sections were located just beyond the oilers, further complicating the analysis.

Distance from Crest--A statistically significant increase in rolling resistance farther from the crest was found--a counterintuitive finding. The effect was slight, but it was evident in all the analyses performed. The effect may be related to the statistical difficulties encountered with switches and curves.

### B.3 Measurement of Rolling Resistance

The procedures currently available for calculating rolling resistance tended to amplify and compound small measurement errors in time, velocity, or distance, so that the error in calculated rolling resistance was greatly magnified. This problem could be overcome by taking numerous redundant measurements and using a least squares estimation technique.

## C. CONCLUSIONS AND RECOMMENDATIONS

The results of this study have greatly augmented knowlege about rolling resistance, but much more research remains to be conducted. In this study, the experimental setup could not be controlled, and the researchers had to rely on existing process control sensors and their location and accuracy. Thus restricted in the types of data that could be obtained, SRI was restricted in the results that could be obtained. Consequently, the next logical step in furthering knowledge about rolling resistance is to conduct carefully controlled field experiments.

*This term is proportional to the square of the headwind, times the cross-sectional area of the car, divided by the weight of the car.

# CHAPTER 1: INTRODUCTION

## 1.1 BACKGROUND

An estimated 300 million freight cars are classified (i.e., sorted into different tracks) in railroad yards every year (Petracek et al., 1976). About 80% of these cars are classified in flat yards and the remainder are classified in hump yards.* In hump yards, classification is performed by pushing a large group of freight cars up a slight hill, or hump, uncoupling them at the crest of the hump, and then switching them into the appropriate classification tracks as they roll freely down the other side of the hump. The free-rolling cars are controlled in one to four short track sections, where mechanical retarders decelerate the cars.

For proper switching in a hump yard, sufficient headway between successive cars must be created and maintained. At the hump crest, the speed of the cars is determined by their centers of gravity, and this creates an initial time separation between the cars. As the cars accelerate in rolling down the hump grade, the initial time separation is translated into a coupler-to-coupler distance separation and time headway. The retarders maintain sufficient headway (1 to 2 seconds minimum) between freight cars to allow yard personnel to throw the switches safely. The retarders are also used to control the coupling or impact speeds of cars on the classification tracks within specified speed limits (1 to 6 mph).

The design of the hump profiles and the control of headway and coupling speeds in hump yards are difficult because freight cars have different characteristics and rolling resistances. Faster rolling cars tend to overtake slower rolling cars, and the imprecision in predicting the rollability of individual cars on the classification tracks makes achievement of a desirable coupling speed more difficult.

The design of a hump grade is usually based on an assumed hardest (slowest) and easiest (fastest) rolling car. Hump grades are usually designed to deliver the hardest rolling car to the clear point at a specified speed or to a specified distance into the classification track. The size and placement of retarder sections are usually determined by examining a worst-case sequence of a hardest rolling car followed by an easiest rolling car traveling to the last switch on the farthest outside track.* The retarders are placed where the separation between the two worst-case cars becomes less than a specified value. When that occurs, the retarder slows the trailing car to reestablish proper headway. The length (power) of the retarder is based on the amount of energy that must be removed from the trailing car in a worst-case situation. Knowledge of the rolling resistances of cars in the yard is critical in the hump profile design and speed control strategy. Unfortunately, such information on rolling resistances is scarce, and yard designers therefore must use engineering judgment based on their experience in previous yard design projects. Key design variables may differ from yard to yard, however, and a new yard may not function as intended. In particular, poor estimates of car rollability can result in:

- Cars stopping in the switching area, necessitating temporary shutdown of the hump.
- Cars being misswitched, causing more yard engine work.
- Cars stopping short of coupling on the classification tracks, causing extra work in train makeup.
- Cars coupling on the classification tracks with too high a velocity, causing damage to cars and lading.
- Excessive hump height and grades and more retarders than needed, adding to the capital costs of the yard.

Because of the need for and importance of information on rolling resistance, the American Railway Engineering Association (AREA) Committee on Yards and Terminals and other groups and individuals in the railroad industry recommended that a study of rolling resistance be conducted.

## 1.2 OBJECTIVES AND SCOPE

The objective of this study was to improve understanding of freight car rolling resistance at the low speeds typical of railroad freight car classification yards. This characterization of freight car rollability is intended to be of practical value in both the design and operation of classification yards.

*For a brief description of operations in hump yards and flat yards, refer to Petracek et al. (1976), Troup (1975), and Beckmann et al. (1955).

*In a complete study, the dynamics of a hardest rolling car, followed by an easiest rolling car, followed by a hardest rolling car would be examined.

This was an exploratory study, specifically limited to the collection and analysis of existing data on car rollability and to data that could be obtained using existing yard sensing devices (e.g., velocity, position, time, distance-to-couple) and yard computers. No substantial special instrumentation of yards, tracks, or freight cars was installed.

The study focused on identifying the following elements:

- The influence of a variety of physical and environmental factors on freight car rollability.
- The characterization of freight car rolling resistance distributions in sufficient detail for use in the design of yard grades, the placement of switches, and the placement and size determination of retarders.
- The examination of rollability measurement and prediction schemes.

## 1.3 ORGANIZATION OF THE REPORT

Chapter 2 discusses the basic concepts of car rollability. Car rollability is defined mathematically in terms of the physics of car motion down an incline, and the procedure to measure car rollability in yards is detailed.

Chapter 3 is a review of previous related international and U.S. research. The information available on the components and factors of rolling resistance is also presented. In addition, Chapter 3 contains previously unpublished rolling resistance data obtained by individual railroads over the years (e.g., CONRAIL's Elkhart Yard, Southern Pacific's Englewood Yard, and Santa Fe's Argentine Yard). Appendix A is a statistical analysis of the Englewood Yard data. The rolling resistance data collected in this project and the collection methods are described in Chapter 4. Histograms for the data collection periods and environmental data are presented for the following five yards: Hinkle Yard (Union Pacific), DeWitt Yard (CONRAIL), Northtown Yard (Burlington Northern), Argentine Yard (Santa Fe), and Linwood Yard (Southern).

The process control computers at Hinkle Yard and DeWitt Yard provided an extensive amount of data in computer-readable form. SRI subjected the data from these two yards to a statistical regression analysis to discover and quantify underlying causal factors relating to car rollability. The causal factors were: car speed, car weight, car type, wind, temperature, switches and curves, moisture, bearing type, and truck center length. Chapter 5 presents the results of the statistical analysis. Appendix B provides a comprehensive description of the statistical regression analysis technique, and Appendix C documents the derivation of the measurement error analysis, Appendix D describes the software interface and processing procedures used.

Chapter 6 presents a methodology to assist in the construction of rolling resistance histograms for a new yard. The methodology is based on manipulating the data collected at Hinkle Yard, which were the most complete and extensive data obtained in the project. The methodology requires that the user specify temperature range and car weight distributions for the new yard.

# CHAPTER 2: BASIC CONCEPTS ABOUT CAR ROLLABILITY

## 2.1 DISCUSSION AND DEFINITION OF CAR ROLLABILITY

The motion of a freight car rolling down a grade can be analyzed and described by the concepts of classical mechanics. Of particular importance are Newton's first two laws of motion:

(1) Every body persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it.

(2) The change of motion is proportional to the resultant force impressed and is made in the direction of the straight line in which that force is impressed. (This law is the basis of the equation, Force = mass x acceleration, or F = ma).

As Figure 2-1 indicates, a freight car rolling down a grade is subject to two opposing forces acting along its path of travel. One force is the along-track component of the gravitational force, or gradient force, resulting from the mass of the vehicle and the acceleration of gravity. This force is related to the weight of the vehicle and the angle between the track and the horizontal plane by the following equation:

$$F_g = mg \sin \theta \quad , \qquad (2.1)$$

where

$F_g$ = gradient force

$mg$ = weight of freight car

$m$ = mass of freight car

$g$ = gravitational acceleration (32.2 ft/sec$^2$)

$\theta$ = angle between track and horizontal.

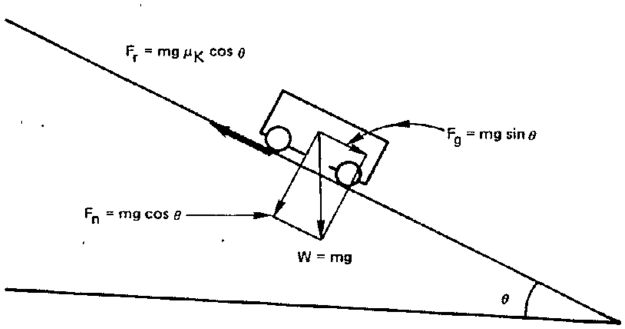



FIGURE 2-1 FORCES WORKING ON A RAILCAR

The other force acting on the freight car along its path of travel is a resistive force. For convenience, Figure 2-1 shows this force as a single force acting at the vehicle's center of gravity. However, this resistive force has many components, such as wind resistance, wheel-rail friction resistance, and others, that can act at many points of the car. It is this cumulative force, resisting car movement down the grade, that is the subject of this study. The force acting on the freight car along its path of travel, $F_r$, is proportional to the force, $F_n$, that this car exerts normal to the track surface over which it moves.

$$F_r = R \cdot F_n = R \cdot mg \cos \theta \quad , \qquad (2.2)$$

where

R = frictional coefficient or rolling resistance of the car

$\theta$ = angle between the track surface and the horizontal plane.

If the acceleration of the car is denoted by a, the resultant force of $F_g$ and $F_r$, F, is expressed as*

$$\begin{aligned} ma &= F \\ &= F_g - F_r \\ &= mg \sin \theta - R\, mg \cos \theta \quad . \qquad (2.3) \end{aligned}$$

Solving equation 2.3 for R yields

$$\begin{aligned} R &= \frac{mg \sin}{mg \cos} - \frac{ma}{mg \cos \theta} \\ &= \tan \theta - \frac{a}{g \cos \theta} \quad . \qquad (2.4) \end{aligned}$$

If the approximation** that $\cos \theta \cong 1$ is made, and if the $\tan \theta$ term is simply the grade, G,

$$R = G - \frac{a}{g} \quad . \qquad (2.5)$$

Equation 2.5 is the basic relationship used for computing a car's resistance.

---

*For simplicity and clarity, this derivation assumes a constant acceleration.

**This approximation is equivalent to ignoring the difference between distances measured over the actual sloping grade and those measured along the horizontal projection of the grade.

The car will accelerate if $a > 0$; it will travel with a constant speed if $a = 0$; and it will decelerate if $a < 0$. From equation 2.5, if $a = 0$, then

$$R = \tan\theta \quad . \qquad (2.6)$$

In equation 2.6, the rolling resistance or rollability* of a car is expressed as the tangent of the angle of the grade (i.e., the slope of the grade) on which the car is moving with a constant speed. The slope of a 100% gradient is equivalent to $\tan\Theta = 1$, 2,000 lb = 1 ton, and R is defined as the ratio of two forces. Thus, using these facts produces the relationship that

$$\begin{aligned} 100\%\text{ grade} &<=> 1\text{ ton/ton} \quad , \\ &<=> 2000\text{ lb/ton} \quad ; \end{aligned} \qquad (2.7)$$

therefore,

$$1\%\text{ grade} <=> 20\text{ lb/ton} \quad . \qquad (2.8)$$

## 2.2 MEASUREMENT OF CAR ROLLABILITY IN YARDS

Defining freight car rollability in terms of the accelerations of a car down a specific grade provides the basis for measuring car rollability in hump yards. That is, the rollability of a car moving down a grade is calculated from measured or previously calculated values of car acceleration and track grade. Therefore, the precise determination of a railcar's rollability to four significant digits requires the measurements of car acceleration and track grade to the same level of precision.

By using modern surveying techniques and equipment, engineers can measure track grades with a very high degree of accuracy. However, as Alexander (1965) recognized, even with the best maintenance a track grade can change significantly over time because of such factors as soil compaction or subsidence and frost heave. Therefore, regular surveying checks of the grade must be made at every rollability measurement section in a yard.

Measuring the acceleration of a car in the rollability measurement section can pose some problems. Basically, acceleration is determined either (1) by measuring the velocity of a car at two or more points within the rollability measurement section or (2) by measuring the time required by the car to traverse a track section with at least three position and time measurement points.

The first approach is based on recognizing that acceleration is the first derivative of velocity relative to time (i.e., $a = dv/dt$ or approximately $a = \Delta v/\Delta t$). From this relationship, the following equation for the average car acceleration over a fixed-distance measurement section can be derived:

$$a = \frac{V_j^2 - V_i^2}{2L_{ij}} \quad , \qquad (2.9)$$

where

- $a$ = average acceleration over the test section
- $V_i$ = velocity measured at position i
- $V_j$ = velocity measured at position j
- $L_{ij}$ = length between points i and j.

Analogous relationships using more than two velocity measurements can be developed easily. Freight car velocity in yards can be measured almost instantaneously with radar speedometers. A major supplier of speed control equipment uses radar measurements of car velocity in the test section for determining the values of car rollability to use in the yard's car speed control system. In addition, portable radar devices can be used for field measurements of freight car velocities and accelerations.

A drawback that must be considered in using this approach to measure car acceleration and rollability is the error propagation caused with formulas based on derivatives. Generally, the original measurement error doubles after taking the first derivative. Thus, the original measurements of car velocity must be as precise as possible. Experience with portable radar speed measurement devices, however, indicates that the car rollability data collected with these instruments are not as precise as desired and therefore must be considered with caution in calculating rolling resistance.

The second method of measuring acceleration is based on the fact that acceleration is the second derivative of distance, or car position, relative to time. For a measurement section where the time of car travel among three or more points can be accurately measured, car acceleration can be determined. For a test section with three points, it can be shown that:

$$a = 2(d_{13}t_{12} - d_{12}t_{13})/(t_{13}t_{12})(t_{13} - t_{12}) \qquad (2.10)$$

where

- $a$ = car acceleration (assumed constant over entire test section)
- $d_{ij}$ = distance between points i and j
- $t_{ij}$ = time required for car to travel between points i and j.

*Rolling resistance and rollability are reciprocal definitions of the same concept and are described by the measure defined above. A freight car that exhibits low rolling resistance is said to have good (or high) rollability and vice versa.

One of the major vendors of speed control equipment uses an acceleration measuring system based on this concept of multiple measurements of car travel time and position. Similar approaches have been used for manual measurements of car rollability.

This approach for measuring car rollability also has the potential for significant propagation of the original measurement error. A simple test of the sensitivity of the acceleration formula shows that even small errors in the measurement of car travel time between points (assuming a 100-foot test section) can result in unacceptably large errors in the car acceleration calculated by this technique. Nevertheless, permanently installed test sections in yards appear to give acceptably precise measurements of car acceleration and rollability. Conversely, using manually actuated stopwatches (with digital display precision of 1/100 of a second) for measurement of car rollability results in very little accurate or useful data on car rollability.

# CHAPTER 3: REVIEW OF RELATED WORK

Even though the industrywide consensus is that a better characterization of freight car rolling resistance would be beneficial for the design and operation of freight car classification yards, the amount of published research on this subject is very limited. Undoubtedly, the major signal companies have the most complete and up-to-date data, but because these data have competitive value, the companies are understandably reluctant to divulge them. Many railroads have collected and analyzed car rollability data, but for the most part these results have not been widely disseminated. In fact, the historical rolling resistance data from CONRAIL and Southern Pacific, presented in Section 3.3, are being published for the first time.

This chapter provides an overview of the published research available on freight car rollability. Included are an historical perspective on major research on freight car rollability and a discussion of the physical factors that have been hypothesized to influence car rollability.

## 3.1 HISTORICAL BACKGROUND

Experimental work on train and rail car resistance was performed throughout most of the Nineteenth Century. Most of this research was oriented toward the characterization of train resistance rather than the rollability of individual freight cars, but many of the relationships developed for train resistance have been used to describe car rolling resistance. Unless otherwise stated, the variables for formulas in this section are stated in terms of: rollability in pounds per short ton (R), weight in short tons (W), and velocity in miles per hour (V).

### 3.1.1 International Research on Rolling Resistance

Research on the rolling resistance of railroad stock began in the mid-1800s. Although the coefficients of relationships developed abroad may differ significantly from those developed here in the United States because of differences in car design, track weight, and track gauge, the underlying theories are important and the structures of the relationships themselves are quite similar. As early as 1855, Daniel Clark developed the following formula that related train resistance to the square of the velocity of the train (Muhlenberg, 1978):

$$R = 6 + \frac{1}{240} V^2 \quad . \qquad (3.1)$$

This formula was used throughout Europe for nearly half a century. In 1885, research by the Eastern Railway of France also suggested that train resistance increased as train velocity increased (Muhlenberg, 1978). The truth of this hypothesis has been demonstrated in numerous experiments since then and is one of the most widely accepted concepts relating to both train and car resistance.

In 1913, Strahl, of Germany, developed the following formula, which Muhlenberg (1978) cites: $R = 4.0 + 0.001657V^2$. In 1932, this was recalibrated to $R = 4.0 + 0.001294V^2$. Early in this century, Strahl, Aspinall, and other Europeans began suggesting the use of three-term formulas of the form $R = A + BV + CV^2$, where A, B, and C are constants depending on the configuration and consist of the trains.

In 1927, Mucklachen, of the USSR, used the formula: $R = 2.4W + .319nV + .1709 (1.0 + .04n)V^2$, where n is the number of vehicles (Muhlenberg, 1978). A 1968 version of the formula for a 75-ton car was: $R = 1.752 + .0189V + .00076V^2$ (Muhlenberg, 1978). Of recent note have been the test results from the USSR on rolling resistance in two hump yards (Railroad Transport Editorial Board, 1967). In this test, the effects of weather on car rollability were found to be small enough to be eliminated in the development of car rollability distribution curves.

Japanese research on rollability before World War II has not been documented in English, but it is known that until recently several formulas were used. The general formula now in use was developed in 1967 by Harada (1967) for freight cars. Harada expresses rolling resistance as:

$$R = A + BV + CV^2 \quad ,$$

where for standard four-axle freight cars,

$$A = (0.7K + 0.275)\ e^{-t/30}$$

$$B = 0.133$$

$$C = 0.00106S_1/(1.0 + S_2S_3) \quad .$$

This formula is unique because the constants K, $S_1$, $S_2$, and $S_3$ take into account car type and wheel and track conditions, and t is the temperature in °C. (The units in this formula are metric.) In recent work, Bernard in France, Hara in Japan, and Gluck in Germany, have divided the $V^2$ term into two parts, one for drag and the other for skin friction (Muhlenberg, 1978).

Muhlenberg (1978) models the individual air resistances of cars. He also breaks air resistance into skin friction and air drag to weight the shielding effects of surrounding cars on air drag.

In an article entitled "Tractive Resistance of Rolling Stock," Koffman (1964) presents a detailed analysis of many of the factors that affect the coefficients of rolling resistance equations. Included are analyses and formulas based on the physics of bearing friction, wheel and rail deformation, rail joint resistance, parasitic motion, sinusoidal motion, one- and two-point contact running, parallel axles, and suspension oscillation resistance. This article identifies important physical properties that have led to a better understanding of rolling resistance, but the values are too small for each of these factors to be recorded in an experimental situation.

### 3.1.2 U.S. Research on Rolling Resistance

The wind tunnel tests on scale models of trains and freight cars at Purdue University in the late 1890s apparently represent the first work in the United States on car or train rolling resistance (Muhlenberg, 1978). In 1906, an attempt was made in a full-scale experiment to measure the air resistance of a street railway car.

In 1910, Professor Schmidt of the University of Illinois published rolling resistance formulas based on his tests of full-size freight cars weighing 10 to 75 tons and traveling at various speeds up to 40 mph (Muhlenberg, 1978). In 1912, Schmidt reported on the relationship of rolling resistance to car weight and temperature. In 1937, Tuthill, also of the University of Illinois, extended the upper velocity range of Schmidt's formulas to 75 mph (Muhlenberg, 1978). Tuthill's experiments showed that air resistance caused car rolling resistance to increase disproportionately more at this higher speed.

In 1926, Davis published the first comprehensive analysis and report on train rolling resistances. That report, entitled "Tractive Resistance of Electric Locomotives and Cars," gives a resistance formula for a single "average" rail car that demonstrates a relationship between air resistance and the factors of car weight, number of axles, cross-sectional area, and velocity. Since its introduction, the Davis formula has been the one most often used in the U.S. railroad industry. Innovations in train operations--such as higher speed trains, a greater percentage of cars with roller bearings, and newer freight car designs--have prompted others to determine new values for the coefficient in the Davis formula. However, the basic formula and theory have remained essentially the same.

The most widely accepted recalibrations of the Davis formula were based on dynamometer tests run by the Canadian National Railway (CNR) using modern railroad rolling stock. These experiments led to the development of new coefficients for the formula, referred to as the modified Davis formula or the CNR formula. The use of this formula results in lower values of car rolling resistance for all velocities, reflecting the relative efficiencies of cars with roller bearings and modern car designs.

In 1965, the Erie-Lackawanna Railroad tested the resistance of piggyback and auto-rack cars using the results of dynamometer tests to solve the modified Davis formula for a new $V^2$ coefficient (Muhlenberg, 1978). The new coefficient was three times the previous value, reflecting the increased air resistance of auto-rack and piggyback cars.

Five formulas, as quoted by Muhlenberg (1978), for calculating car rollabilities for 75-ton boxcars are listed below. (The Erie-Lackawanna formula is not listed because it has been specifically calibrated for auto-rack and piggyback cars.) R represents rolling resistance in pounds per short ton.

$$R = 2.87 + 0.019 + 0.00113V^2 \text{ (Schmidt)} \quad (3.3)$$

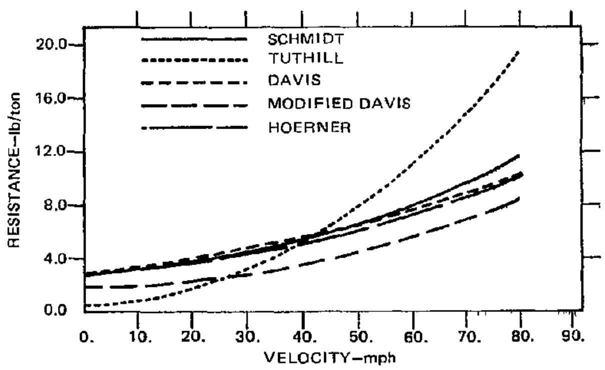
$$R = 0.53 + 0.002V + 0.00290V^2 \text{ (Tuthill)} \quad (3.4)$$

$$R = 2.85 + 0.045V + 0.00060V^2 \text{ (Davis)} \quad (3.5)$$

$$R = 1.67 + 0.010V + 0.00093V^2 \text{ (modified Davis, (CNR)} \quad (3.6)$$

$$R = 2.89 + 0.020V + 0.00089V^2 \text{ (Hoerner).} \quad (3.7)$$

Examination of the differences in the coefficients of these formulas, as well as of the curves in Figure 3-1, indicates that while the Tuthill formula yields results that diverge significantly from the other formulas, the results of the Schmidt, Davis, and Hoerner equations are nearly the same and the results of the modified Davis formula are consistently lower, as would be expected.




Source: Muhlenberg (1978)

FIGURE 3-1 COMPARISON OF ROLLING RESISTANCES OF A 75-TON CAR CALCULATED BY FIVE DIFFERENT FORMULAS

Other research on various aspects of car rolling resistance has been performed by railroad equipment suppliers, individual railroads, universities, and other research organizations. In most cases, this research was not directed toward characterizing the rollability of individual cars or small cuts of cars in classification yard operations, but rather toward analyzing rolling resistance in line-haul operations. Moreover, the few documented efforts to collect data on car rollability in yards have been oriented toward describing car rollability in a particular yard and not toward collecting related ancillary data that could be used to characterize freight car rollability more generally. In addition, most of the data reported have described car rollability strictly as a static term, although it is recognized that rollability changes as the car rolls from the crest to its coupling point on the appropriate classification track.

## 3.2 COMPONENTS OF CAR ROLLING RESISTANCE

The equations that have been developed to analytically determine the rolling resistance of rail cars and trains almost invariably have been of the form $R = A + BV + CV^2$. This formulation has been used frequently because it is mathematically convenient and tractable. However, an engineering examination of the physical mechanisms that influence car rollability reveals an almost natural breakdown of factors into those that are independent of car or train velocity, those that are linearly related to car or train velocity, and those that are nearly related to the square of car or train velocity. Examination of the modified Davis formula reveals that the non-velocity-related factors are dominant in determining car rollability at the car speeds typically observed in yard (i.e., under 20 mph). An analysis of the Tuthill formula, however, does not indicate this dominance as clearly.

The following section is a brief description of the three categories of physical factors that influence car rollability. In many cases, the actual physical mechanisms underlying the influence of various factors are not completely understood, and some disagreement exists about the category to which various factors belong.

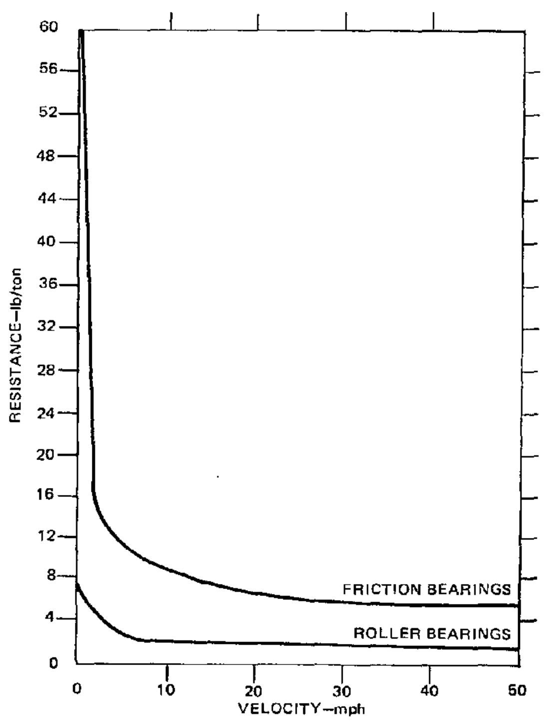
### 3.2.1 Factors Independent of Car Velocity

The first term in all major rolling resistance formulas is one describing the various mechanical resistances that are considered to be independent of velocity. Velocity-independent mechanical resistance is considered to be the dominant component of total car rolling resistance at the 15- to 20-mph speeds typical in yard switching operations. At yard switching speeds, mechanical resistance can account for more than 60% of the total rolling resistance (based on calculations using the modified Davis or CNR formula). Above 30 mph, however, velocity-related terms quickly become the dominant factors.

Mechanical resistance is primarily caused by bearing friction resistance, track resistance, rolling friction resistance, and wheel inertial resistance. There is some disagreement in the literature about whether a portion of track-related resistance and rolling friction resistance are the only factors independent of velocity and whether track resistance caused by track deformation is strictly velocity dependent (Tope, 1971).

#### 3.2.1.1 Bearing Friction Resistance.

As shown in Figure 3-2, the resistance caused by friction within the freight car's wheel bearings can be extremely high when starting and at low speeds. Tests have shown that this resistance can be as high as 54 lb/ton for a plain or journal bearing. However, bearing resistance appears to decrease rapidly until it is almost constant at speeds greater than 10 mph. (Researchers have yet to determine whether this dramatic decrease is due solely to increased speed or perhaps to other unmeasured factors, such as increased bearing temperature and reduced lubricant viscosity.) For most purposes, bearing resistance is assumed to be constant for all speeds apart from the initial starting resistance. Bearing resistance depends on the type and condition of the car's bearings, ambient and journal temperature, the temperature properties of the bearing lubricant, and the weight of the car. Bearing resistance is generally assumed to follow the form used in the Davis equation. That is, $R_b = A + Bn/W$, where W is the weight of the car (tons), n is the number of axles, and A and B are constants that depend on the bearing design and condition. Koffman (1964) has developed a theoretical formula for bearing resistance that includes the effects of the coefficient of bearing friction, u, the diameter of the bearing, d, and the wheel, D, as well as the unsprung axle load,




Source: Tope (1971)

FIGURE 3-2 ROLLING RESISTANCE OF FRICTION BEARINGS COMPARED WITH ROLLER BEARINGS (GERMAN FEDERAL RAILWAYS)

$W_u$, and the total axle load, $W_t$. A modified form of this formula is:

$$R_b = 2000\ u\left(1 - \frac{W_u}{W_t}\right)\left(\frac{d}{D}\right) \quad . \qquad (3.8)$$

This formula does not appear to have been widely used by U.S. railroads.

Two major types of bearings are used on U.S. freight cars, friction or plain bearings and roller bearings. With a friction bearing, the end of the axle (journal) turns on a brass fitting covered with an oil film to reduce friction between the bearing surfaces; the lubrication comes from an unsealed well below. Roller bearings are a sealed set of lubricated cylinders, similar to ball bearings, that rotate around the axle. Many variations of both of these bearing types exist.

Tests have consistently shown that roller bearing-equipped cars, on the average, exhibit less resistance than friction bearing-equipped cars. Tests by the Pennsylvania Railroad at Altoona in 1931 showed that empty cars with friction bearings had ten times more starting resistance than cars with roller bearings (Tope, 1971). Comparative tests of car resistance at various speeds have demonstrated that roller bearing-equipped cars have consistently lower rolling resistance than cars with friction bearings. This difference does not appear to be proportionately as great at running speeds as low as those in classification yards. Koffman (1964) uses constant coefficients of bearing friction of 0.008 for friction bearings and 0.003 for roller bearings. This implies nearly a 3 to 1 advantage for roller bearing-equipped cars in terms of bearing resistance alone. However, to our knowledge these coefficients have never been precisely determined for the bearings found on U.S. railcars.

Theoretically, the oil film of the friction bearing should produce less bearing resistance than a roller bearing and in fact has done so in laboratory tests and rigidly controlled field tests (DeIvernois et al., 1966). However, this capability appears to be significantly related to the condition of the bearing and only occurs under ideal conditions. Perhaps because of inconsistencies in the maintenance and lubrication of friction bearings, cars with friction bearings exhibit a much wider variation around the mean rolling resistance than cars with roller bearings.

Bearing friction can vary greatly as temperatures change. These changes in friction are most directly linked to changes in the temperature of the bearing and the lubricant. Relating them to ambient temperatures is more convenient, although this does not take into account the difference between the ambient temperature and the temperature of the friction surface. However, at low speeds very little difference exists between ambient and lubricant temperatures when the ambient temperature is higher than −30 °F (Crisp & Ellis, 1963).

An hypothesis is that friction bearings are more significantly affected by temperature changes than roller bearings. No relevant test data on friction bearings were found in this literature review, but tests by the Timken Company indicated that roller bearing resistance can increase dramatically (depending on the bearing lubricant) when the ambient temperature drops to between 20 °F and −40 °F (Crisp & Ellis, 1963). Published results of experiments in the USSR and Japan also demonstrate a significant increase in car resistance as the temperature decreases (Railroad Transport Editorial Board, 1967; Harada, 1967).

3.2.1.2 Track Resistance. Track resistance, another mechanical resistance considered to be independent of velocity, is caused by the deformation and deflection of the rail from the car's weight at the wheel-rail junction. Such resistance is obviously related to the weight of the car and the rigidity of the track (based on the type of steel and the tracks' section modulus). Track resistance is caused by two physical mechanisms: (1) the loss of the energy required to depress and deform the wheel or rail and (2) the extra energy required for the wheel to run "uphill" out of the depression in the track.

The resistance due to wheel and rail deformation may be expressed in terms of the wheel radius, $R_D = b/8r$ (pounds per ton), where $R_D$ is the resistance due to wheel and track deformation, b is the length of the deformation contact area, and r is the wheel radius.

3.2.1.3 Rolling Friction Resistance. Friction between the wheel and the rail constitutes a third factor of velocity-independent mechanical resistance. This rolling resistance is a function of the coefficient of friction and the weight of the car. The coefficient of friction varies with the type of metal, maintenance conditions, and weather. Oil, water, or frost may decrease the rolling resistance, but a track in poor condition may increase the friction-related resistance.

3.2.1.4 Wheel Inertial Resistance. Another factor in car rolling resistance, which can be considered in the area of mechanical resistance, is the rotational acceleration of the car's wheels. As a freight car accelerates down a grade, its wheels must experience a corresponding angular acceleration. This angular or rotational acceleration of the mass of the car's wheels requires the application of some force that, in effect, reduces the magnitude of the force causing the translational acceleration of the car down the grade. The converse is true when the car decelerates and the inertial energy stored in the wheel is dissipated. (At a constant speed, this factor should not affect rollability.)

The AREA Manual for Railway Engineering (AREA, 1976) recommends that this energy storage be taken into account by reducing the energy head ($h_e = V^2/2g$) by using the reducing factor:

$$h = \frac{1}{1 + \frac{4wr^2}{D^2}\frac{1}{W}} h_e = kh_e \qquad (3.9)$$

or

$$h_e + \frac{h}{k} \quad , \qquad (3.10)$$

where

- $h$ = velocity head (translational head) (ft)
- $w$ = weight of the wheels and axles (lb) of the car
- $r$ = radius of gyration of the wheels and axles of the car relative to their axis of rotation (inches)
- $D$ = car wheel diameter at tread (inches)
- $W$ = gross weight of car (lb).

The variable k is also expressed with E as the equivalent additional weight for the energy stored as:

$$k = \frac{W}{W + E} = \frac{W}{W + \frac{4wr^2}{D^2}} \quad . \qquad (3.11)$$

Some prefer to express the rotational energy storages as an effective g, $g_e$, where

$$g_e = kg \quad . \qquad (3.12)$$

This influence on car acceleration naturally affects measurements of freight car rollability. Typically, this effect is accounted for by using a correction factor of about 10%, but this simplistic approach may actually exaggerate any errors because the effect of the wheel inertial factors will change depending on the magnitude of the acceleration or deceleration of the car. In addition, the weight and size of the wheels, relative to the car's total weight, is an important factor. For lightweight empty cars, the wheel inertial correction factor may be more than 10% while for heavily loaded cars it may be less than 5%.

### 3.2.2 Factors Linearly Related to Car Velocity

As mentioned, universal agreement does not exist on which factors influencing car rolling resistance are related to car velocity and which are not. For example, many people believe the effect of track deformation is independent of car velocity, whereas others firmly state that it is predominantly a velocity-related factor.

3.2.2.1 Flange Resistance. Flange resistance, caused by the friction between rail and flange, provides a major portion of velocity-related resistance. Flange resistance is affected by many conditions other than velocity. A bad flange angle (attitude of flange to rail) may increase friction, and a large flange-to-wheel clearance will increase nosing action and lateral oscillations. The flange-to-wheel clearance is a function of gauge, wheel base, and equipment upkeep. Occurrences of nosing action and lateral oscillation increase flange resistance.

The condition of the car and track can increase friction by causing an uneven ride or increased swaying. Unfortunately, quantitatively measuring these factors is difficult.

3.2.2.2 Truck Skewing. Many cars that are measured as easy rollers or medium rollers at the master retarder rollability measurement section become relatively hard rollers at the classification tracks. One hypothesis is that the trucks of these cars may be skewed as they travel around a curve just before the tangent point, thereby increasing the flange resistance of the car. This phenomenon is also referred to as curve memory, and some experienced railroaders believe that it is the reason a large percentage of cars are labeled as hard rollers.

Suggested remedies for this situation include the use of guardrails or retarders at the tangent point to straighten car trucks. Tests by SRI have indicated that the use of tangent point retarders can reduce the mean and variance of freight car rolling resistance on the classification tracks, primarily by reducing the number of hard rollers. These results, however, were based on a small sample taken at one yard and may not be universally applicable.

3.2.2.3 Energy Loss from Vibration. The energy dissipated by vibration, swaying, and concussions has also been identified as proportionate to velocity. The amount of such disturbances is greatly influenced by the design and subsequent upkeep of individual cars. Poor maintenance of cars and road beds and irregularities in wheels and tracks increases oscillations and vibration.

Heavier, more rigid track and good road bed conditions may decrease the loss of this energy. Muhlenberg (1978) restates resistance reduction results from Keller's work. In a test comparing 110-pound and 130-pound rails, the heavier rail showed reduction of resistance of 1 lb/ton. This reduction may also be attributed to the reduction in sinusoidal motion and rail deflection.

3.2.2.4 Sinusoidal Motion. The sinusoidal motion of conical wheels results in the two wheels running on different radii, thus leading to slippage and possibly creating additional oscillations and flange friction (Troup, 1975).

3.2.2.5 Internal Truck Resistance. The fifth velocity-related resistance factor is internal truck resistance. No researchers have reported a relationship between velocity or velocity squared and truck resistance, but internal truck resistance is similar to velocity-related resistance. Internal truck resistance depends on the condition of the center plate, the condition of the bolster and side-frame wear surfaces, the clearance and condition of the side bearings, the condition of the brakes, and the energy absorption of the springs (Tope, 1971).

### 3.2.3 Factors Linearly Related to the Square of Car Velocity

3.2.3.1 Curve Resistance. Flanged-wheel vehicles such as rail cars encounter additional resistance when traveling around curves because of the action of the railroad flange on the curve. The extra resistance from a curve is believed to be a function of curve radius, gauge, wheel base, flange-to-rail clearance, and flange angle. The centrifugal acceleration caused by a freight car traveling around a curve causes an additional frictional force to act between the wheel flange and the rail head. Theoretically, this force should increase in proportion to a decrease in the radius of the curve and be directly related to the square of the freight car's velocity around the curve. That is, a two-fold increase in the car's velocity will increase curve resistance by a factor of 4.

The mechanism of curve resistance is not completely understood, however, because of the many factors that can influence it. Measured values of curve resistance have varied from 0.4 to 0.8 pound of resistance per ton of car weight per degree of curvature. The AREA (1976) has recommended the use of 0.8 pound for most railroad engineering applications. Use of this figure results in:

$$R_c = 0.8\ DW \quad , \qquad (3.13)$$

where

$R_c$ = additional resistance due to curve (lb/ton)

D = degree of curvature

W = weight of rail car (tons).

Koenig's paper on freight car rolling behavior in classification yards (1966) suggests that the rolling resistance on a curved track is approximately 0.3% higher than for a tangent track.

Curve resistance can be a critical element in the design of yard track layouts. In large hump yards, the classification tracks in the outside groups can be particularly affected by the curve resistance encountered by cars in the switching area. To reduce the effect of curve resistance in this part of the yard, for many years yard designers have been using various types of track oilers to reduce friction between the rail and the wheel flange. Although we could find no evaluation of the effect of such devices in U.S. yards, Koenig (1966) of the Swiss Federal Railways found that rail lubrication achieved about a 33% reduction of curve resistance.

3.2.3.2 Rail Joint Resistance. The resistance caused by rail joints is due to the kinetic energy lost by the car in jumping the rail joint. The following formula is a modification of one developed by Koffman (1964) of British Railways to describe rail joint resistance. $R_j$ represents rail joint resistance in terms of pounds per short ton.

$$R_j = \frac{2000\ j^2 v^2}{r^2 g^2} \quad , \qquad (3.14)$$

where

j = rail joint gap (ft)

r = wheel radius (ft)

v = car velocity (ft/sec)

g = acceleration of gravity (32.2 ft/sec$^2$).

If the joint gap is excessively large and the car velocity is high, this factor can significantly influence total car rollability. The increasing use of continuous welded rail (CWR) in the construction of new hump yards should alleviate the influence of this factor.

3.2.3.3 Switch and Frog Resistance. As a freight car rolls through a turnout, it is usually raised slightly above the overall track grade when it rolls over the frog. It is reasonable to expect that an increase in elevation causes a loss in the car's kinetic energy similar to the mechanism causing rail joint resistance. Significant lateral forces can also be placed on the wheel flange by the abrupt change in the car's direction within the switch mechanism (forces similar to those experienced by cars traveling around curves). Therefore, switch and frog resistance would be expected to be related to the square of the car's velocity. However, no technical discussions on this postulated relationship were found. In practice, railroad design engineers considering switch and frog resistance use a constant value of energy loss, regardless of car velocity.

3.2.3.4 Aerodynamic Drag. The aerodynamic drag of railroad freight cars can be divided into five principal components: (1) front pressure resistance, (2) skin friction, (3) airflow separation drag at the rear of the vehicle (rear pressure drag), (4) car underbody drag, and (5) truck aerodynamic drag. These five components are usually considered to increase railcar or train rolling resistance in direct proportion to the square of the headwind velocity relative to the vehicle. Thus, resistance increases in direct proportion to the square of car velocity only when winds are calm. However, even with a headwind, the aerodynamic drag may still be expressed in terms of $A + BV + CV^2$. Aerodynamic drag is expressed as $C(v_c + V_w)^2$, where $V_c$ is the velocity of the car and $V_w$ is the headwind velocity. Thus,

$$R = A + BV_c + C(V_c + V_w)^2$$

$$= A + BV_c + C(V_c^2 + 2V_cV_w + V_w^2)$$

$$= (A + CV^2) + (B + 2CV_w)V_c + CV^2. \qquad (3.15)$$

This concept of velocity relative to the air mass (or wind) is important for classification yard operation. Although free-rolling freight cars in yards rarely exceed or even approach velocities (relative to the ground or track) where air resistance is an important factor, their velocity relative to the air can be high enough that aerodynamic drag becomes a major component of the car's total rolling resistance. In many yards with severe winds, free-rolling freight cars have actually rolled up grades that they would normally accelerate down in calm wind conditions.

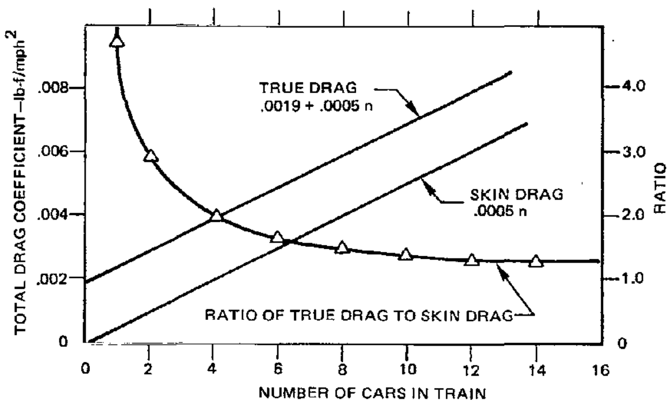
The front and rear pressure resistance is related to the size of the front and rear surfaces as well as their shapes. In cuts of two cars or more, the shape and the distance to surrounding cars also affect these two resistances (Muhlenberg, 1978).

Skin friction is theoretically related to $V^{1.85}$, but for simplicity most authors discuss skin friction as if it were relative to $V^2$ (Davis, 1926). This resistance is related to the airflow of both sides of the railcar and its roof, as well as the streamlining and surface roughness. Skin friction increases with airflow disturbances, such as an open door (Koffman, 1964).

In formulas similar to that developed by Davis, skin friction has been identified as the dominant factor in producing air drag. $V^2$ terms represent an average car in a large train consist of cars with nearly identical drag characteristics.

In Davis's formula, the air drag resistances of the lead and end cars are averaged among all cars. This is not to say that Davis did not recognize the effects of front and rear drag. He reports that the average drag of the trailing cars is 13.8 to 16.8% of that of the lead car. This implies that front and rear drag are the dominant air resistance factors in consists or cuts of fewer than six to eight cars. Figure 3-3 shows the relationship between true drag and skin friction for various sizes of trains. A subsequent generation of drag resistance formulas contains separate terms for front and rear drag.

These types of resistance models do not take into account any of the added front and rear pressure resistances or turbulence caused by consists of aerodynamically inconsistent cars. Muhlenberg (1978) attempts to remedy this problem by treating each car separately according to its type and the type of cars surrounding it. The individual resistance of each car is then summed for a train total. This may serve as an example for the structure of a model of a single running car.




Source: Muhlenberg (1968)

FIGURE 3-3 RELATIONSHIP BETWEEN TRUE DRAG AND SKIN DRAG

If the skin friction coefficient used is an average between the Davis and the modified Davis formulas, the value given for a skin friction estimate for a single car is: $1/2\,\gamma_1 V^2(.0085)S$, where S is the area for the two sides and the top of the car.

To approximate front and rear drag for cars in the middle of a consist or cut, Muhlenberg (1978) describes a method that weights the air drag formula according to a comparison of the end cross-sections and the gap between cars. The formula is: $R_d = F(1/2\,\gamma_2 V^2 C_d A)$, where F is between 0 and 1 and is a weight of the equation for the air deflection of surrounding cars; $C_dA$ is the area of the front and rear drag areas.

Approximations of the total air resistance for a single rail car with no shielding effects would be weighted as 1. This gives a formula of: $R_a = 1/2\,\gamma_2 V^2\ C_dA + 1/2\,\gamma_1 V^2(.0085)S$. In this case, front and rear drag and truck drag have been eliminated. Muhlenberg uses the rough approximation one-half the skin coefficient and 0.272 (based on a Davis approximation) for underside drag and truck drag, respectively.

Sidewind is an unknown factor in air resistance. It may disturb airflow around and between cars, thereby increasing air resistance. Cars in classification yards are more likely to be affected by sidewinds because of increased flange resistance. Use of this assumption gives a sidewind resistance relative to the velocity of the sidewind squared and the coefficient of flange resistance:

$$R_{sw} = K\alpha_F V_{sw}^2.$$

Muhlenberg (1978) cites an AREA report that gives the increase in magnitude of air resistance for a locomotive in a sidewind as 2.8 lb/ton.

Air resistance is only a dominant factor in rolling resistance for large trains at high speeds.

At lower speeds (less than 35 mph) and with small trains (one to five cars), as in hump yards, air resistance becomes a less important factor. Using a modified Davis formula for a 75-ton car, the air resistance at 15 mph is 10% of the total rolling resistance. With a 10-mph headwind, it increases to 23% of the total, and at 20 mph, it increases to 36% of the total rolling resistance.

### 3.3 PREVIOUSLY UNPUBLISHED ROLLABILITY DATA

The historical rolling resistance data presented here were collected by various railroads. In all cases except one, the data were provided in summary, graphical form.

#### 3.3.1 Robert R. Young (Elkhart) Yard

Rolling resistance data were collected in December 1957 and September 1958 by personnel of what was then New York Central Railroad at Robert R. Young Yard in Elkhart, Indiana. As Figures 3-4 and 3-5 indicate, the two data sets are distinctly different: The mean resistance and variance of resistances are noticeably higher in the December set.* These trends may be due to the difference in the weather in September and December; September may have been relatively warm and summery, whereas December would have been colder, perhaps with snow.

As part of the Freight Car Speed Control Study (Kiang et al., 1980), SRI experimented with fitting various statistical distribution functions to the cumulative distribution derived by integrating the histogram of the December data set. Among them were a log-normal distribution, with offset parameter,** an algebraic distribution, and an algebraic distribution with offset. Figures 3-6 through 3-9 present the results of these statistical analyses. The algebraic distribution without offset was used for the analyses in that study. Table 3-1 gives a numerical tabulation of the fitted distribution shown in Figure 3-8.

#### 3.3.2 Pine Bluff Yard

In March and April 1960, rolling resistance data were recorded at Southern Pacific's (Cotton Belt) Pine Bluff yard in Arkansas. These data are presented in the form of a histogram in Figure 3-10 and are correlated with car speeds in Figure 3-11. The data in Figure 3-11 appear to be a subset of the data in Figure 3-10, and a fairly strong correlation with speed is apparent.

#### 3.3.3 Englewood Yard

In fall 1969, SRI had obtained rollability data at Englewood Hump Yard in Houston, Texas, as part of a study (Gardiner et al., 1970) to assist Southern Pacific in designing the hump for the then-planned West Colton Yard. To collect the data, SRI attached electronic switches to the rail on a single hump-to-classification track, which indicated the route, passage times for the first axle of selected cars. By combining these passage times with the known locations of the electronic switches, SRI computed velocities and hence accelerations and resistances.

Figures 3-12 through 3-17 are histograms of these data, stratified by track location. Noticeable in these histograms is the drop in resistance (and variance of resistance) between section A (between the master retarder and group retarder) and B (immediately after the group retarder) and the more gradual further decline in resistance values between sections immediately before the tangent point (Section C), immediately after the tangent point (Section D), approximately 600 feet down the classification track (Section E), and approximately 1,000 feet down the classification track (Section F). These data have also been plotted as a function of car speed in Figure 3-18. Some dependence of resistance on speed is evident.

Because these data were available in their original numerical distance-time form, SRI could perform some further analysis on a subset of the data (certain cars in the classification track area). In this analysis, a velocity-dependent resistance relationship was assumed, and an individual relationship was fitted to each car. This approach contrasts with that used in most other investigations, in which researchers used the static (velocity-independent) resistance computation formulas to compute a resistance and then attempted to correlate these resistances with velocity for a combined agglomeration of many cars (as would be the case if some relationship were fitted to the data shown in Figures 3-11 and 3-18). The results of this analysis are presented in Figure 3-19, which shows resistance-velocity curves for individual cars in the data base. (Appendix A contains more detailed discussions of how the Englewood data were collected and of SRI's new analysis of these data.)

#### 3.3.4 Morrisville Yard

These data were collected at Morrisville Yard, Pennsylvania, sometime during the existence of Penn-Central, so they probably date from the late 1960s or early 1970s. Figure 3-20 is a histogram of these data.

#### 3.3.5 City of Industry Yard

These data were obtained from June 8 through 10, 1970, at Southern Pacific's City of Industry Yard in California. Figure 3-21 is a histogram of these resistance data, and Figure 3-22 correlates these resistance data with car speed. Very little speed dependence is evident in Figure 3-22.

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*In the December set, however, are one or two outliers at a lower resistance level than in the September set.

**An offset parameter allows the distribution to begin accumulating at some rolling resistance value other than zero.

### 3.3.6 West Colton Yard

Resistance data were collected sometime during the 1970s at Southern Pacific's West Colton Yard. Figure 3-23 is a histogram of these data.

### 3.3.7 Conclusions

Examination of the data presented in this chapter reveals that little agreement exists among the empirically observed rolling resistance distributions at the various yards. For example, the empirical distributions presented in Figures 3-4 and 3-17 were based on measurements taken on the classification tracks of Robert R. Young and Englewood yards, yet their variances differ by a factor in excess of 4. This difference might be due partly to additional variable factors such as wind, although it is doubtful that such factors could account for the widely differing results. A more plausible explanation is that the differing results arise from measurement error—an explanation especially likely for such wide variance distributions as in Figure 3-4. The data presented in Figures 3-4 and 3-5 may have been taken manually with a stopwatch, which would tend to increase errors greatly, thus increasing the variance of the observed distribution. Chapter 5 and Appendix B present an assessment of the effects of a number of variables, such as wind and car speed; Appendix C presents an error analysis of the measurement of rollability.

Table 3-1

TABULATION OF FITTED ALGEBRAIC DISTRIBUTION

| Zone Rolling Resistance (lb/ton) From | To | Probability Function* | Cumulative Distribution Function** | Zone Rolling Resistance (lb/ton) From | To | Probability Function* | Cumulative Distribution Function** |
|---|---|---|---|---|---|---|---|
| 0.000 | 0.500 | 0.002 | 0.002 | 15.000 | 15.500 | 0.307 | 97.937 |
| 0.500 | 1.000 | 0.032 | 0.034 | 15.500 | 16.000 | 0.260 | 98.197 |
| 1.000 | 1.500 | 0.162 | 0.196 | 16.000 | 16.500 | 0.221 | 98.418 |
| 1.500 | 2.000 | 0.480 | 0.676 | 16.500 | 17.000 | 0.189 | 98.607 |
| 2.000 | 2.500 | 1.078 | 1.753 | 17.000 | 17.500 | 0.162 | 98.769 |
| 2.500 | 3.000 | 2.023 | 3.776 | 17.500 | 18.000 | 0.140 | 98.909 |
| 3.000 | 3.500 | 3.322 | 7.098 | 18.000 | 18.500 | 0.121 | 99.029 |
| 3.500 | 4.000 | 4.880 | 11.978 | 18.500 | 19.000 | 0.105 | 99.134 |
| 4.000 | 4.500 | 6.483 | 18.461 | 19.000 | 19.500 | 0.091 | 99.225 |
| 4.500 | 5.000 | 7.847 | 26.309 | 19.500 | 20.000 | 0.080 | 99.305 |
| 5.000 | 5.500 | 8.715 | 35.023 | 20.000 | 20.500 | 0.070 | 99.375 |
| 5.500 | 6.000 | 8.958 | 43.981 | 20.500 | 21.000 | 0.061 | 99.436 |
| 6.000 | 6.500 | 8.618 | 52.599 | 21.000 | 21.500 | 0.054 | 99.491 |
| 6.500 | 7.000 | 7.854 | 60.453 | 21.500 | 22.000 | 0.048 | 99.539 |
| 7.000 | 7.500 | 6.865 | 67.318 | 22.000 | 22.500 | 0.043 | 99.581 |
| 7.500 | 8.000 | 5.819 | 73.137 | 22.500 | 23.000 | 0.038 | 99.619 |
| 8.000 | 8.500 | 4.828 | 77.965 | 23.000 | 23.500 | 0.034 | 99.653 |
| 8.500 | 9.000 | 3.951 | 81.916 | 23.500 | 24.000 | 0.030 | 99.683 |
| 9.000 | 9.500 | 3.208 | 85.124 | 24.000 | 24.500 | 0.027 | 99.710 |
| 9.500 | 10.000 | 2.595 | 87.719 | 24.500 | 25.000 | 0.024 | 99.734 |
| 10.000 | 10.500 | 2.097 | 89.816 | 25.000 | 25.500 | 0.022 | 99.756 |
| 10.500 | 11.000 | 1.698 | 91.514 | 25.500 | 26.000 | 0.020 | 99.775 |
| 11.000 | 11.500 | 1.378 | 92.892 | 26.000 | 26.500 | 0.018 | 99.793 |
| 11.500 | 12.000 | 1.123 | 94.015 | 26.500 | 27.000 | 0.016 | 99.809 |
| 12.000 | 12.500 | 0.919 | 94.934 | 27.000 | 27.500 | 0.015 | 99.824 |
| 12.500 | 13.000 | 0.756 | 95.690 | 27.500 | 28.000 | 0.013 | 99.837 |
| 13.000 | 13.500 | 0.625 | 96.315 | 28.000 | INFIN | 0.163 | 100.000 |
| 13.500 | 14.000 | 0.519 | 96.834 | | | | |
| 14.000 | 14.500 | 0.433 | 97.267 | | | 100.000 | |
| 14.500 | 15.000 | 0.364 | 97.631 | | | | |

Equation for cumulative distribution F(R):

$$F(R) = 1 - \frac{1}{1 + a\left(\frac{R}{10}\right)^b} \qquad a = 7.14 \quad b = 4.32$$

*Percentage of cars.
**Cumulative percentage to upper zone boundary.

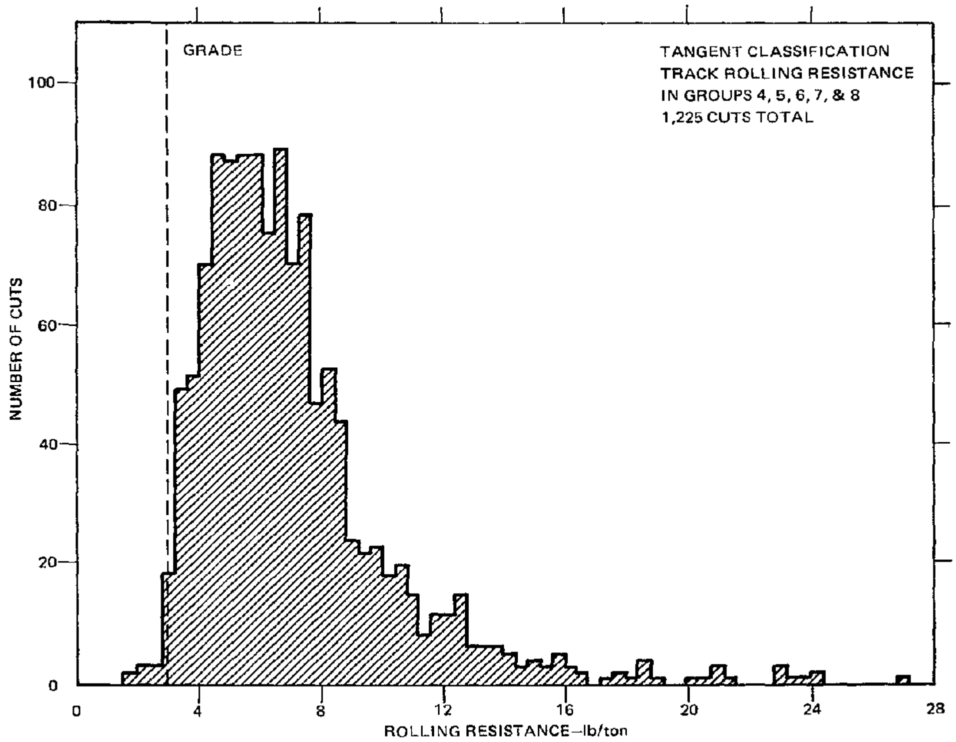



FIGURE 3-4 ROLLING RESISTANCE HISTOGRAM FROM ROBERT R. YOUNG YARD, DECEMBER 1957

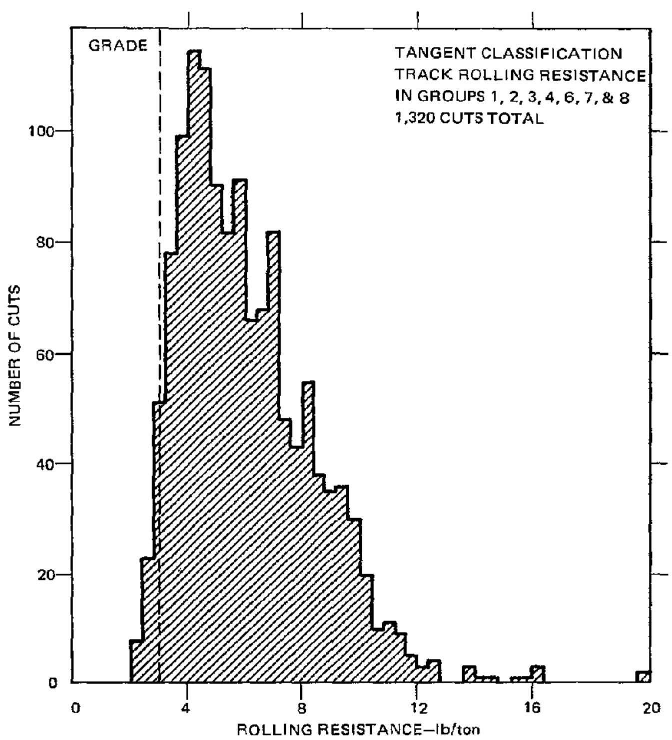
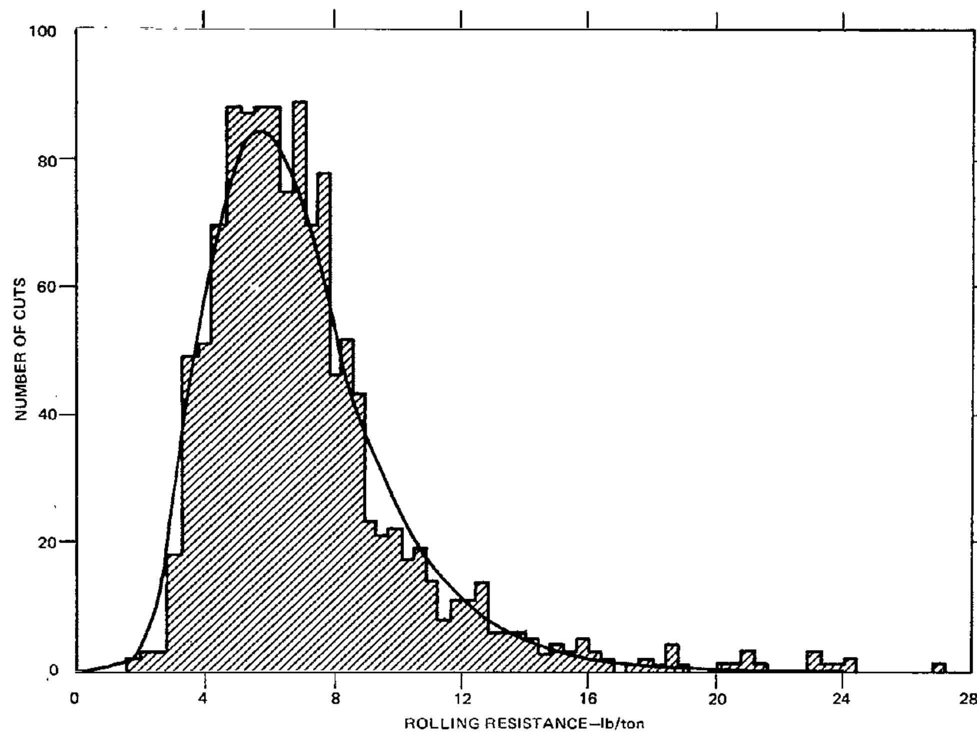



FIGURE 3-5 ROLLING RESISTANCE HISTOGRAM FROM ROBERT R. YOUNG YARD, SEPTEMBER 1958




STATISTICAL FIT OF LOG-NORMAL DISTRIBUTION:
$\mu = 1.85$
$\sigma = 0.394$ } PARAMETERS OF THE NORMAL DISTRIBUTION IN THE LOGARITHMS

FIGURE 3-6 LOG NORMAL DISTRIBUTION FITTED TO ROBERT YOUNG YARD DECEMBER 1957 HISTOGRAM

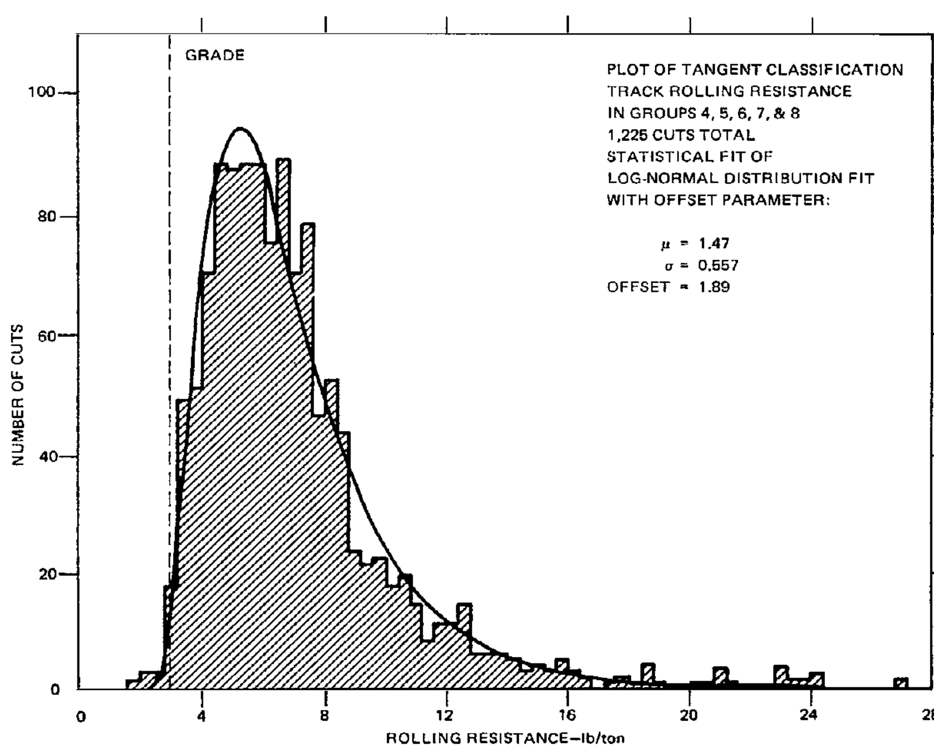



FIGURE 3-7 LOG NORMAL DISTRIBUTION WITH OFFSET FITTED TO ROBERT YOUNG YARD DECEMBER 1957 HISTOGRAM

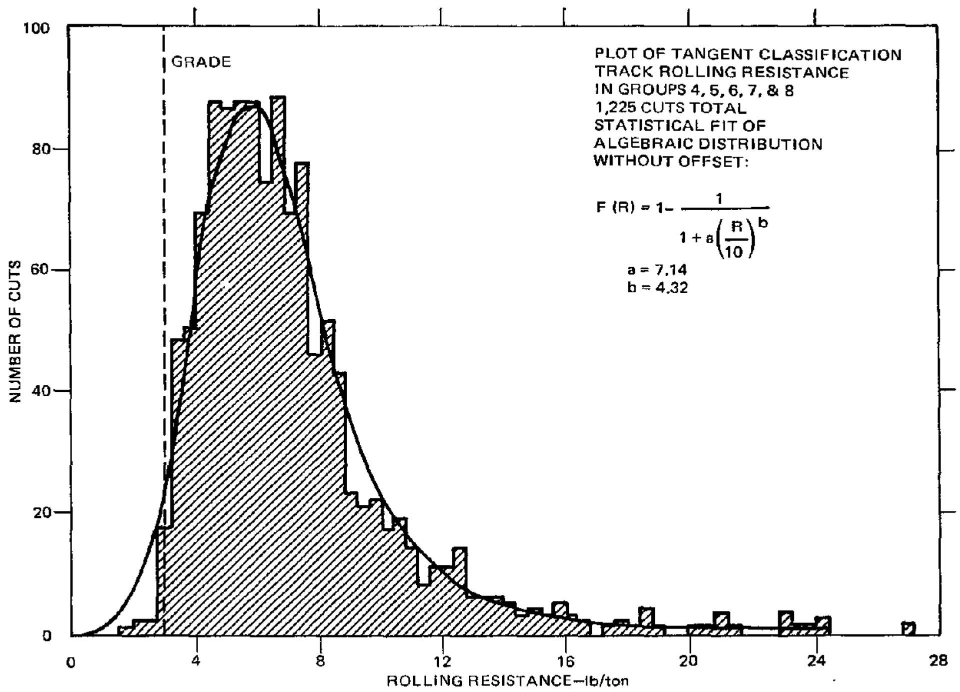



FIGURE 3-8 ALGEBRAIC DISTRIBUTION FITTED TO ROBERT YOUNG YARD DECEMBER 1957 HISTOGRAM

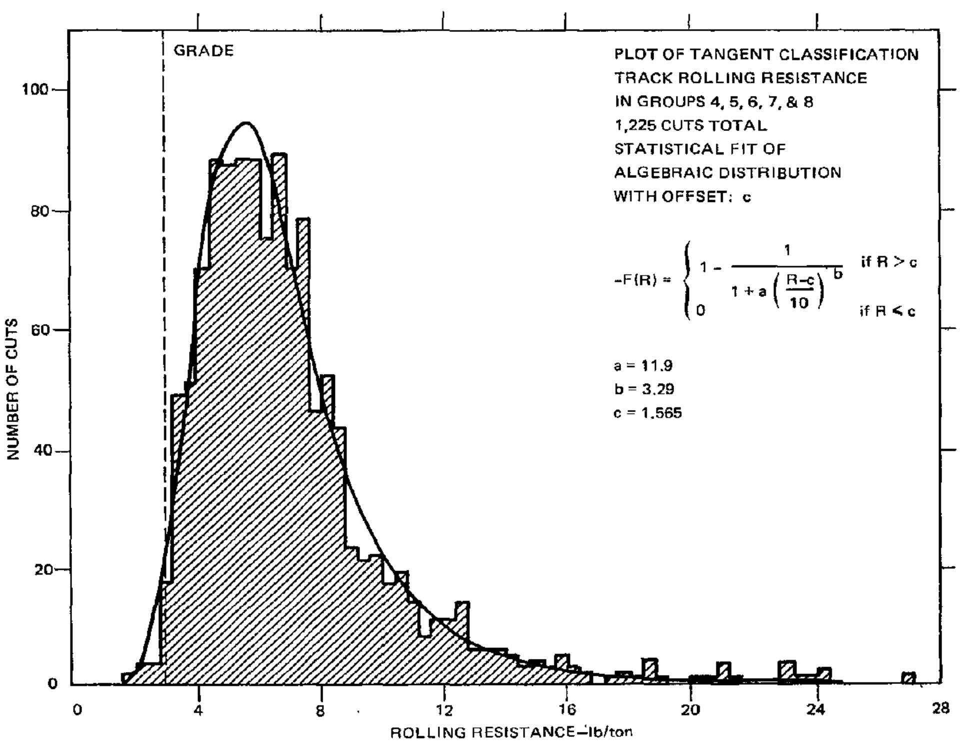



FIGURE 3-9 ALGEBRAIC DISTRIBUTION WITH OFFSET FITTED TO ROBERT YOUNG YARD DECEMBER 1957 HISTOGRAM

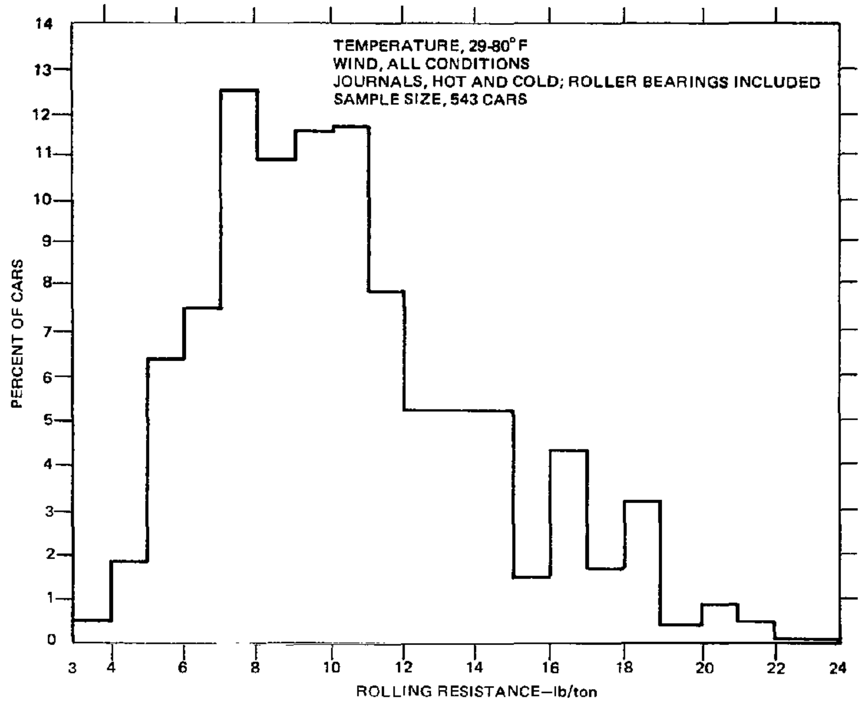



FIGURE 3-10 ROLLING RESISTANCE HISTOGRAM FROM PINE BLUFF YARD, MARCH-APRIL 1960

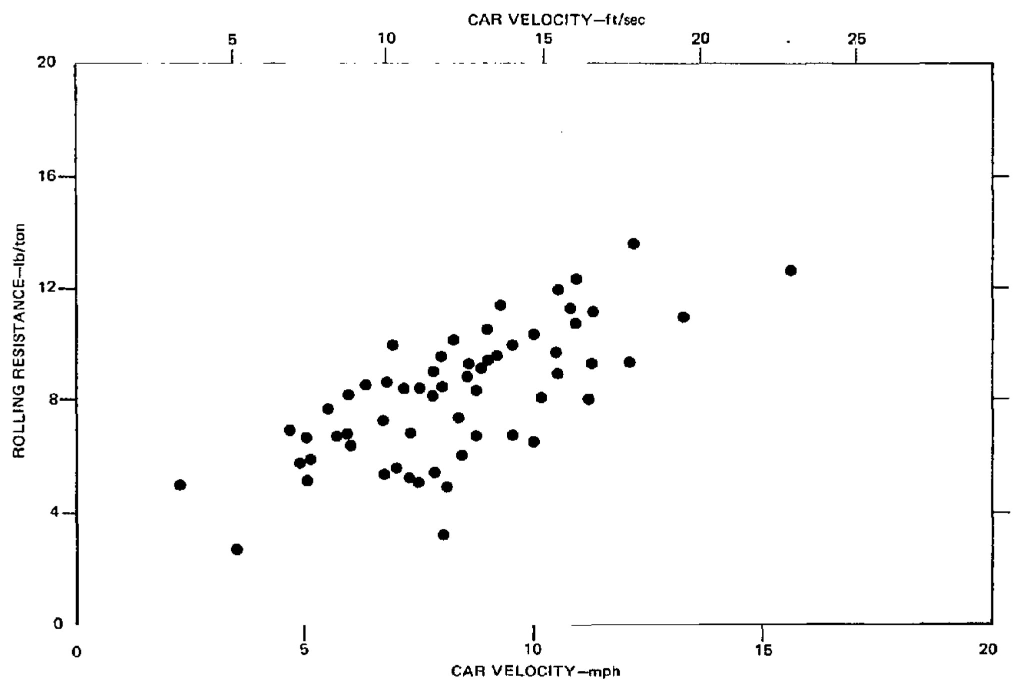



FIGURE 3-11 RESISTANCE AS A FUNCTION OF CAR SPEED FOR PINE BLUFF YARD DATA

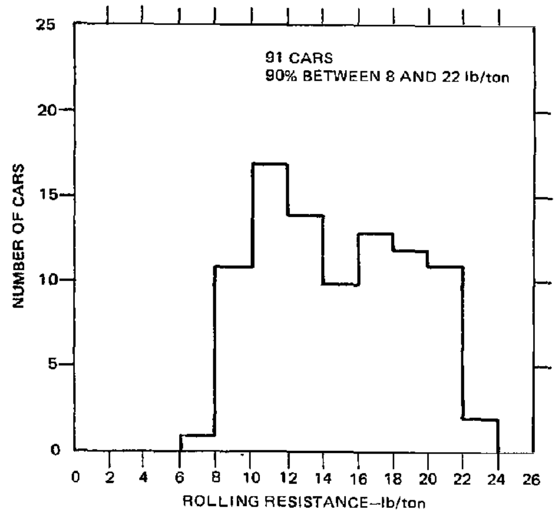
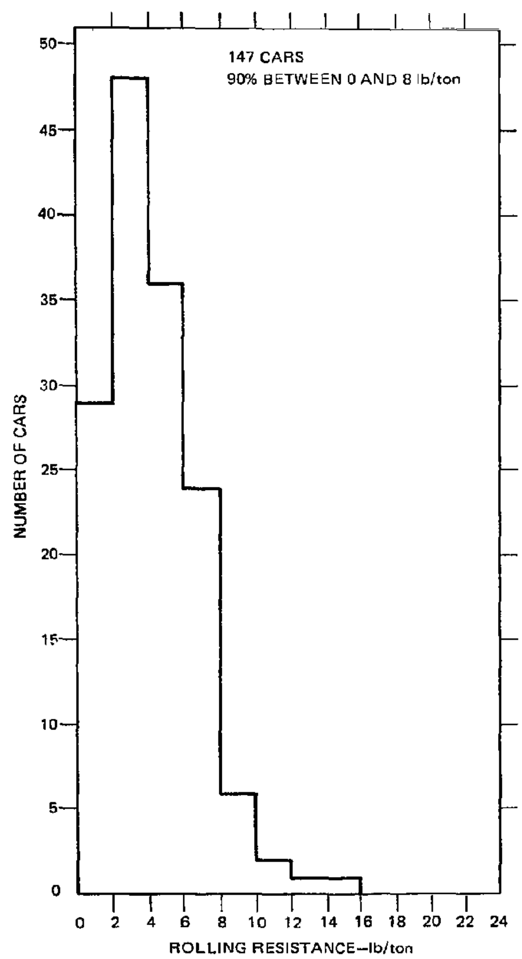



FIGURE 3-12 HISTOGRAM OF ROLLING RESISTANCE FROM ENGLEWOOD YARD DATA, SECTION A (BETWEEN MASTER AND GROUP RETARDERS)




NOTE: OIL ON TRACK

FIGURE 3-13 HISTOGRAM OF ROLLING RESISTANCE FROM ENGLEWOOD YARD DATA, SECTION B (IMMEDIATELY AFTER GROUP RETARDER)

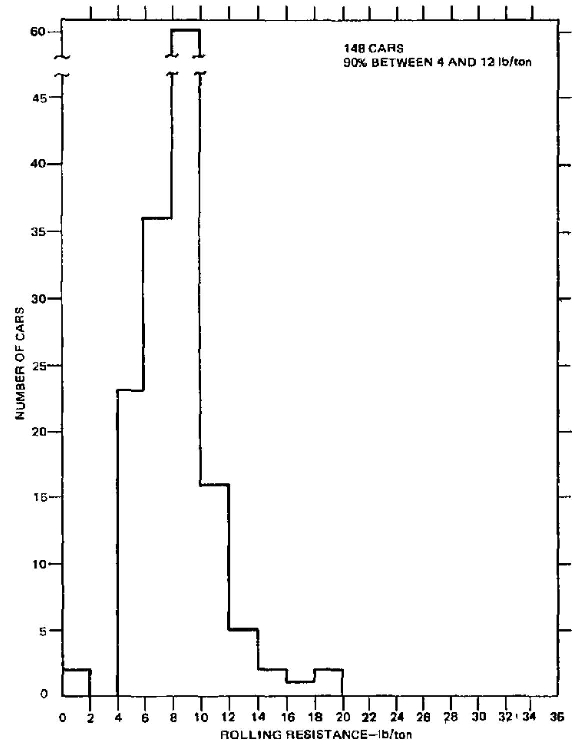



FIGURE 3-14 HISTOGRAM OF ROLLING RESISTANCE FROM ENGLEWOOD YARD DATA, SECTION C (IMMEDIATELY BEFORE TANGENT POINT RETARDER

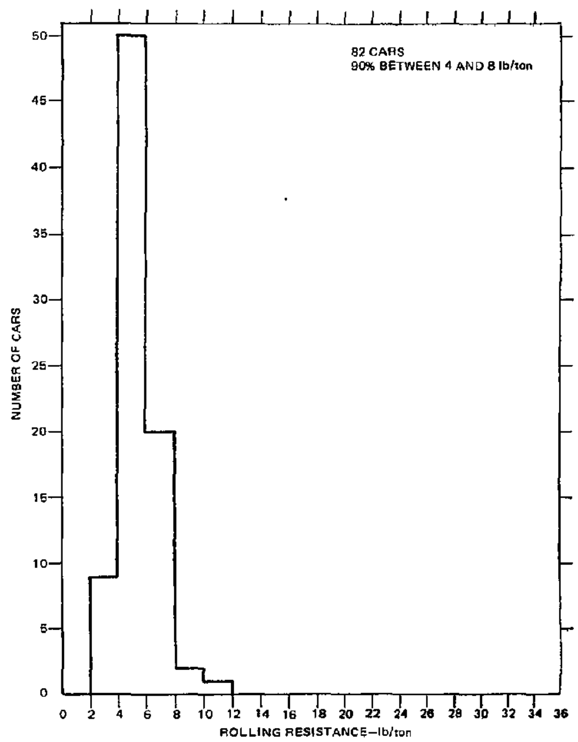



FIGURE 3-15 HISTOGRAM OF ROLLING RESISTANCE FROM ENGLEWOOD YARD DATA, SECTION D (IMMEDIATELY AFTER TANGENT POINT RETARDER)

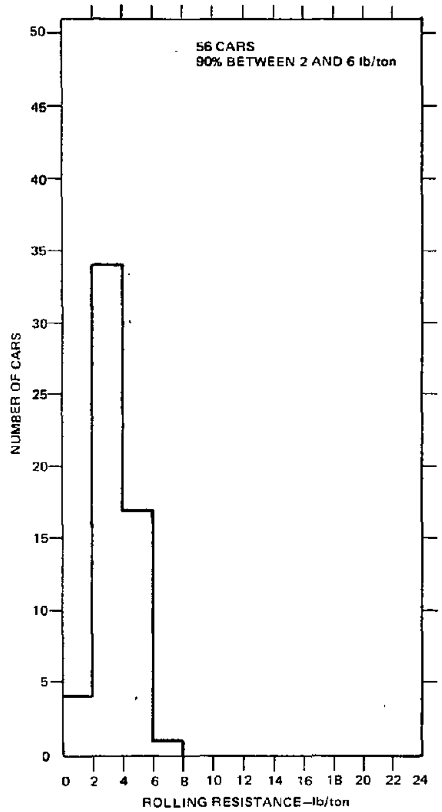



FIGURE 3-16 HISTOGRAM OF ROLLING RESISTANCE FROM ENGLEWOOD YARD DATA, SECTION E (APPROXIMATELY 600 FEET DOWN CLASSIFICATION TRACK)

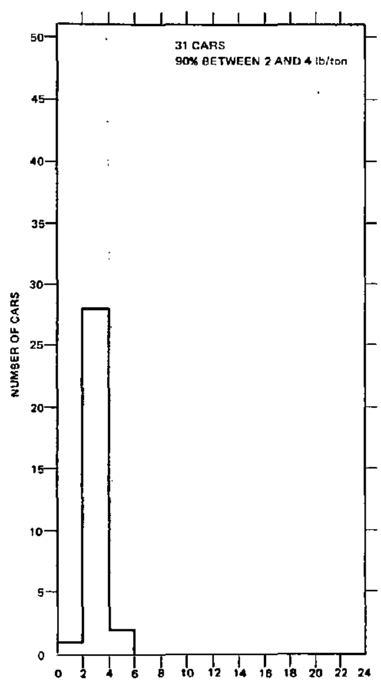



FIGURE 3-17 HISTOGRAM OF ROLLING RESISTANCE FROM ENGLEWOOD YARD DATA, SECTION F (APPROXIMATELY 1,000 FEET DOWN CLASSIFICATION TRACK)

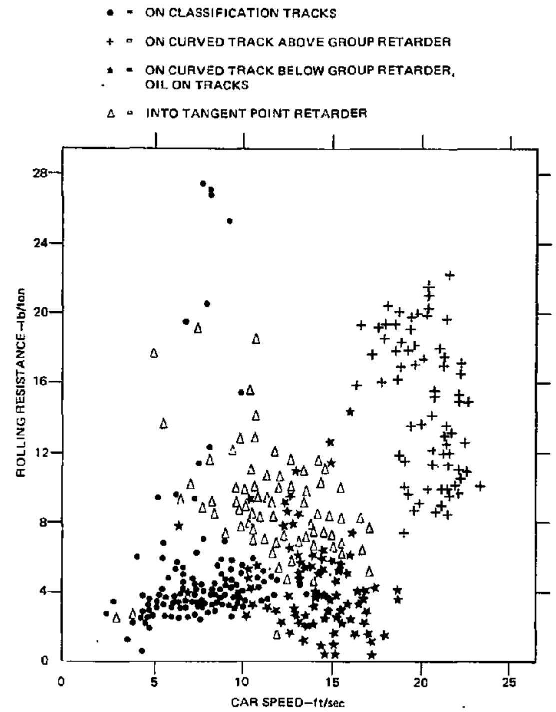



FIGURE 3-18 ROLLING RESISTANCE AS A FUNCTION OF CAR SPEED FOR ENGLEWOOD YARD

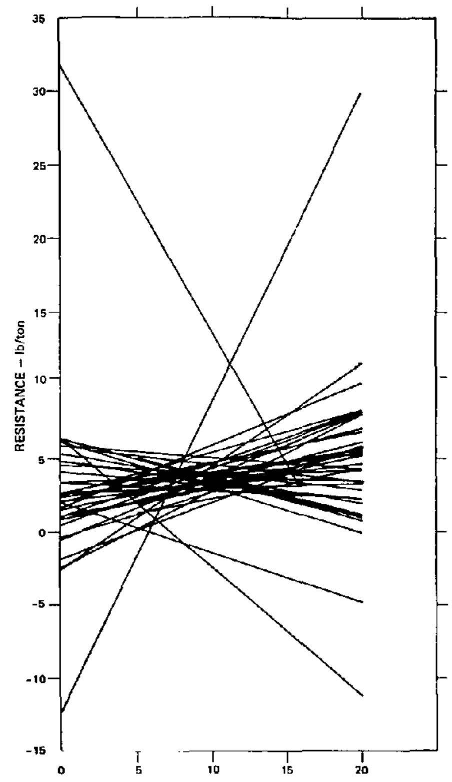



FIGURE 3-19 TOTAL ROLLING RESISTANCE AS AN INSTANTANEOUS FUNCTION OF VELOCITY FOR FITTED RELATIONSHIPS FOR ENGLEWOOD YARD DATA

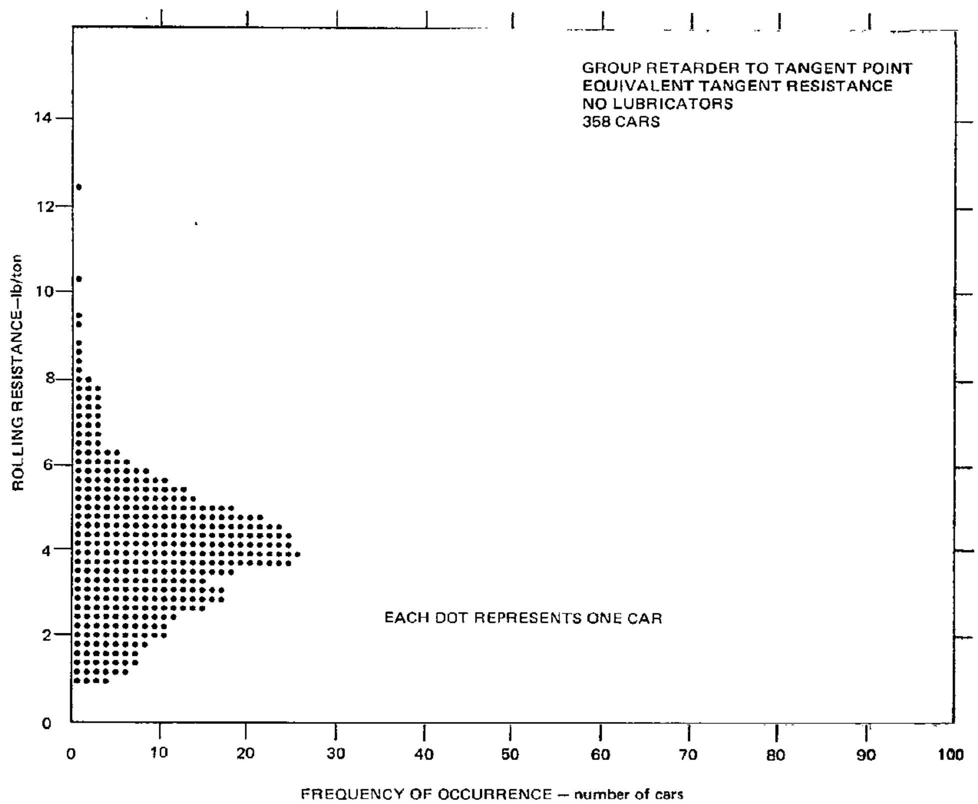



FIGURE 3-20 ROLLING RESISTANCE HISTOGRAM FROM MORRISVILLE YARD

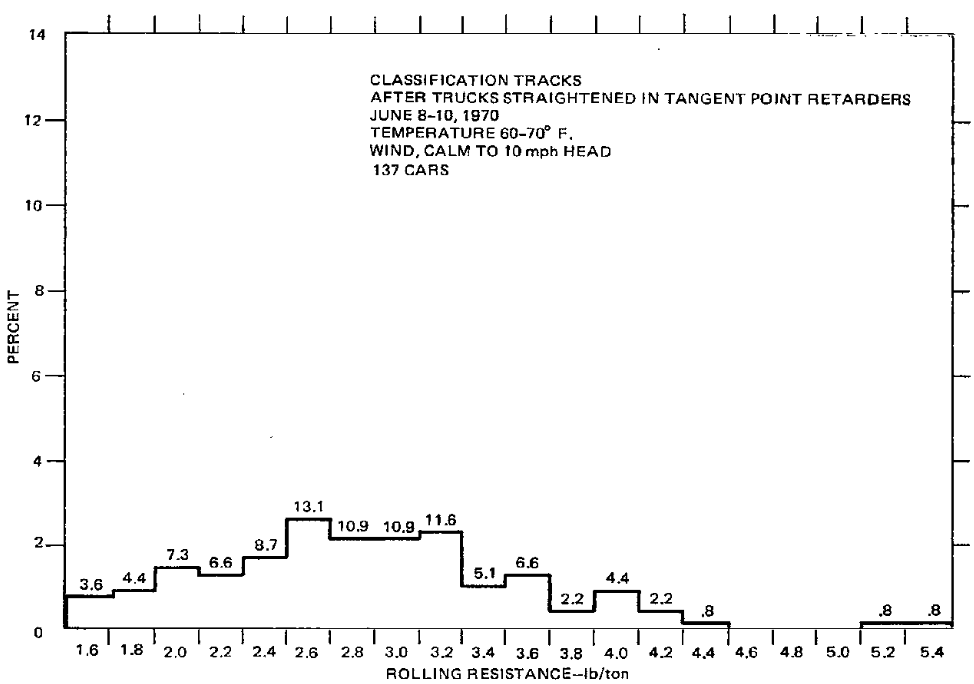



FIGURE 3-21 ROLLING RESISTANCE HISTOGRAM FROM CITY OF INDUSTRY YARD

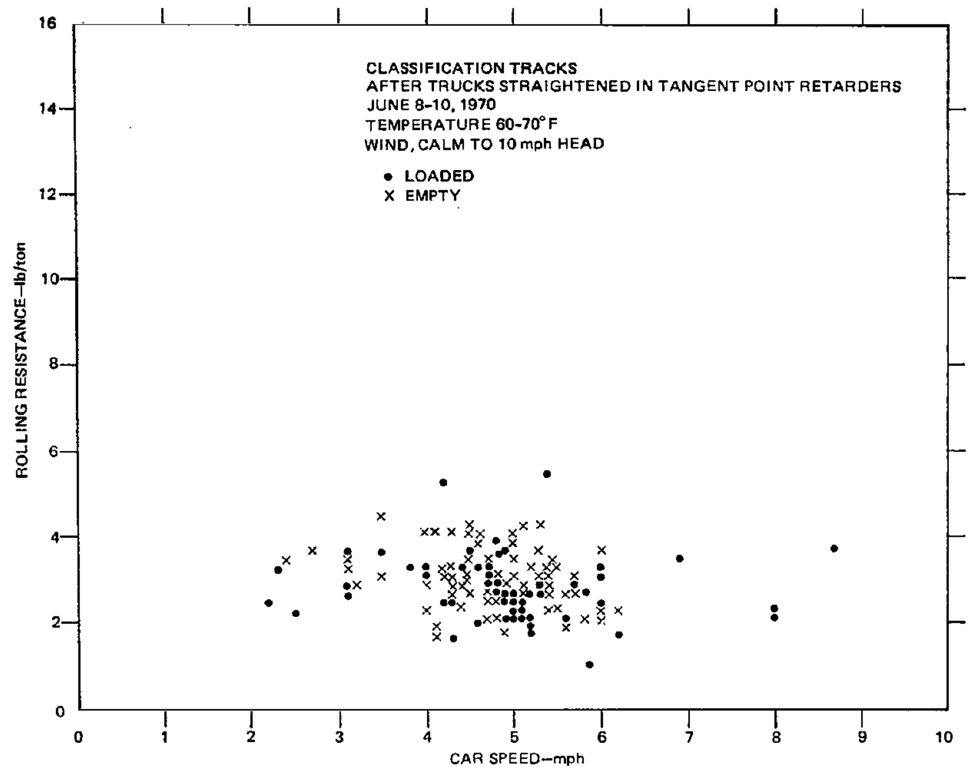



FIGURE 3-22 ROLLING RESISTANCE AS A FUNCTION OF CAR SPEED FOR CITY OF INDUSTRY YARD

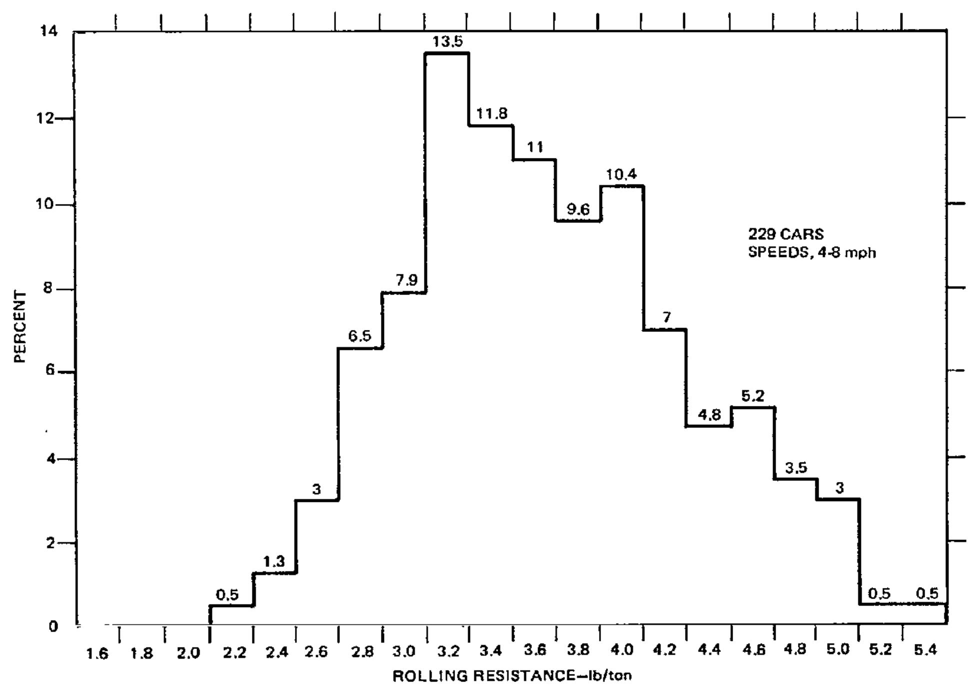



FIGURE 3-23 ROLLING RESISTANCE HISTOGRAM FROM WEST COLTON YARD

# CHAPTER 4: NEW ROLLING RESISTANCE DATA

## 4.1 INTRODUCTION

During this study, SRI collected new rolling resistance data from Hinkle, DeWitt, Northtown, Argentine, and Linwood yards. These yards were selected on the basis of the following criteria:

- Agreement of the railroad to cooperate.
- Availability of data from the process control (PC) system.
- Diverse climate and geographical locations.

Exhibit 4-1 summarizes the characteristics of these yards, and Figure 4-1 shows their locations.

Data sets for winter and summer were desired to examine rolling resistance under extreme temperature conditions; some yards, however, provided data that had been collected during the winter and spring.

For Hinkle and DeWitt yards, SRI was able to extract from the PC computer rolling resistance data for the following four measurement sections:

- The crest to master retarder (measurement section 1).
- The master retarder to group retarder (measurement section 2).
- The group retarder to tangent point (measurement section 3).
- On the classification track (measurement section 4).

Exhibit 4-1

SUMMARY OF YARD CHARACTERISTICS

Hinkle Yard (Union Pacific)

- GRS yard
- Located in eastern Oregon, near Pendleton

DeWitt Yard (CONRAIL)

- GRS yard
- Located in Syracuse, New York

Northtown Yard (Burlington Northern)

- GRS yard
- Located in Minneapolis, Minnesota

Argentine Yard (Santa Fe)

- WABCO yard
- Located in Kansas City, Kansas

Linwood Yard (Southern)

- GRS yard
- Located in North Carolina, near Charlotte

Northtown and Linwood yards provided data from measurement sections 1 and 2, and Argentine Yard provided data on measurement sections 2 and 3.

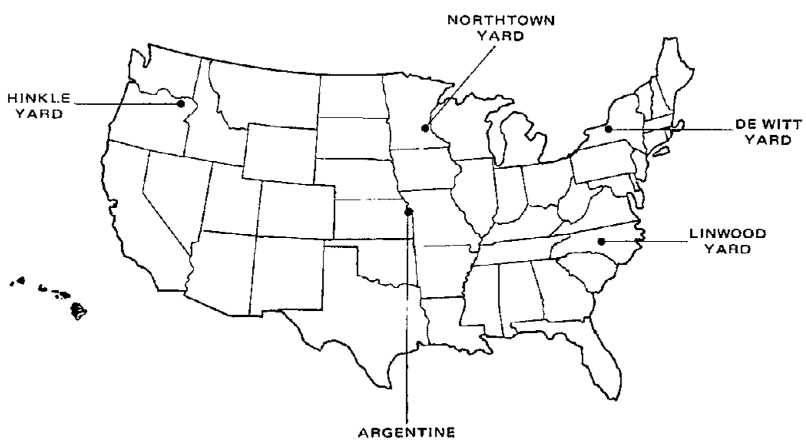



FIGURE 4-1 LOCATION OF RAILROAD CLASSIFICATION YARDS SELECTED FOR THIS STUDY

In some cases, the rolling resistances were not provided directly by the PC computer but were calculated by SRI software developed uniquely for the yard. The software processed raw velocity data provided by the PC computer (e.g., velocity data at the entrance or exit of retarders, track circuits on the classification track) to calculate rolling resistances. Appendix D describes the software developed for each yard.

Table 4-1 summarizes the parameters on which data were obtained from each of the yards under the three categories of UMLER car characteristics, cut statistics, and track characteristics. The track characteristic parameters pertain principally to measurement sections 3 and 4 and were obtained for Hinkle and DeWitt yards because those were the only yards that provided data for both measurement sections. Temperature, wind, and precipitation data usually were provided by the PC computer; however, in some cases, this information was obtained from "Local Climatological Data: Monthly Summary" (obtained from National Oceanic Atmospheric Administration) for the nearest airport. If the weather-related data were not automatically recorded by the PC computer with the cut statistics, SRI manually encoded this information at the time the cut was humped.

Because the yards in this study had PC computer systems, they necessarily all had continuous (welded) rail. In addition, all the yards had oilers at the exit of the group retarders; and Argentine Yard had an additional flange oiler at the hump crest. Therefore, SRI could not compare the effects of jointed and continuous rail or the effects of the presence and absence of oilers.

The rolling resistance values presented in this chapter are the average energy losses per foot of travel over the measurement section and include the effects of track switches and curvature, car speed and weight, temperature, wind, and like factors. If the rolling resistances are used for a particular section of the hump grade, the yard designer thus need not add these factors.

## 4.2 HINKLE YARD

### 4.2.1 Physical Description

Union Pacific's Hinkle Yard is located in Hermiston, in eastern Oregon. As Figure 4-2

Table 4-1

YARD DATA FILES

| Parameters | Yards: Hinkle | DeWitt | Northtown | Argentine | Linwood |
|---|---|---|---|---|---|
| UMLER car characteristics | X | X | X | X | X |
| Bulkhead cross-sectional area | X | X | X | X | X |
| Car type | X | X | X | X | X |
| Bearings (roller/journal) | X | X | X | X | X |
| Cut statistics | | | | | |
| Wind direction | X | X | X | | X |
| Wind speed | X | X | X | X | X |
| Precipitation (wet/dry) | X | X | X | X | X |
| Temperature (°F) | X | X | X | X | X |
| Headwind component* | X | X | | | |
| Sidewind component* | X | X | | | |
| Car humped weight | X | X | X | X | X |
| Car weight class | X | X | X | X | X |
| Average car velocity | X | X | X | | X |
| Car rolling resistance | X | X | X | X | X |
| Track characteristics* | | | | | |
| Total curvature traversed (sum of central angles) | X | X | | | |
| Total curved length of track | X | X | | | |
| Number of changes in car direction | X | X | | | |
| Number of consecutive track links | X | X | | | |
| Total length of track | X | X | | | |
| Number of switches | X | X | | | |

Note: All the yards in this study had oilers and welded rail.

*Parameters used only for regression analysis.

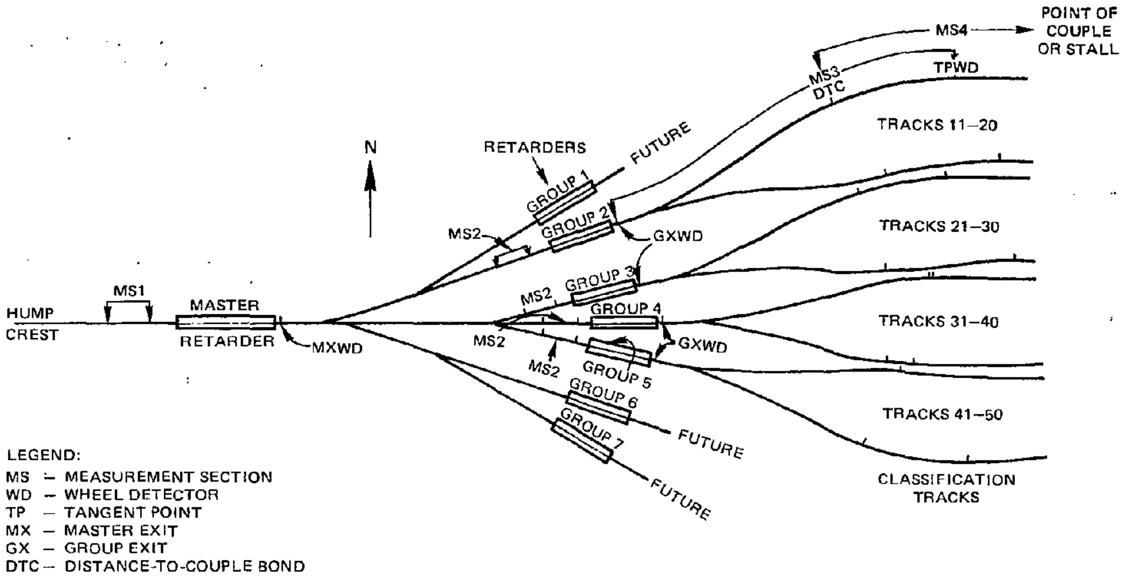



FIGURE 4-2 HINKLE YARD CONFIGURATION

indicates, Hinkle Yard has one master retarder and four group retarders. Railcars are humped into the four groups of 40 classification tracks (10 tracks per group) at a rate of 2 mph. The signaling and PC systems were installed by GRS.

Velocity measurements stored by the PC computer system are recorded:

- From the hump crest to the master retarder (measurement section 1).
- From the master retarder to the group retarder (measurement section 2).
- From the group retarder to the tangent point (measurement section 3).
- From the distance-to-couple bond to the point of coupling (measurement section 4).

Rolling resistance data and the associated parameters that might influence rolling resistance were extracted for the four measurement sections (denoted as MS1 through MS4 in Figure 4-2). Measurement sections 1, 2, and 4 are an integral part of Hinkle Yard's PC computer system, and car rolling resistances are automatically measured. Thus, SRI extracted these data as recorded by the PC computer. Car rolling resistances in measurement section 3 were calculated by using PC computer-recorded velocities, the length and grade of the measurement section, and the rate of acceleration.

Measurement section 1 consists of approximately 80 feet of straight track between the first and third wheel detectors before the master retarder. The orientation of the measurement section is 90 degrees (measured clockwise from north) on a 3% grade. The midpoint of the section is 200 feet from the crest.

Measurement section 2 also consists of about 80 feet of straight track between the first and third wheel detectors before each group retarder. The orientation, grade, and the distance from the crest (DFC) to the midpoint of the measurement section for each group retarder are tabulated as follows:

| Group Retarder Number | Track Orientation (degrees) | Grade (%) | DFC (feet) |
|---|---|---|---|
| 2 | 71 | 1.030 | 771 |
| 3 | 77 | 0.962 | 796 |
| 4 | 90 | 0.943 | 820 |
| 5 | 103 | 0.943 | 820 |

Measurement section 3 includes 40 sections of track that vary in length from 325 to 615 feet. Each section of track starts at the group exit wheel detector (GXWD) and ends at the tangent point wheel detector (TPWD) located on the classification track. Each track section has:

- An oiler located before the first switch after the group retarder.
- Some curvature.
- Either a 7-5-7 lap switch and/or No. 7 switch(es).
- An average orientation ranging from 67 to 109 degrees.
- An average grade from the GXWD to the midpoint of the measurement section ranging from 0.106 to 0.185%.

- An average grade from the GXWD to the TPWD ranging from 0.042 to 0.134%.

Measurement section 4 starts at the distance-to-couple (DTC) bond, which is located after the clearance point before the TPWD on the classification track. Therefore, a portion of measurement section 4 overlaps measurement section 3. The extent of the overlap and the degree of track curvature are determined by the length of track between the DTC bond and the TPWD. After the TPWD, all the classification tracks are straight and have an orientation of 90 degrees and a grade of 0.08%. Because this section ends at the point of coupling or stall of the car, the length of measurement section 4 varies with each car. Consequently, the average orientation, grade, and DFC also vary with each car.

#### 4.2.2 Important Rolling Resistance Factors During the Periods Analyzed

A Hinkle Yard data file was created containing 9,660 observations with UMLER matches recorded during the following three periods:

(1) October 25 to November 21, 1979 (3,120 cars).

(2) December 5, 1979, to January 30, 1980 (3,920 cars).

(3) June 16 to August 25, 1980 (2,620 cars).

The statistics and descriptive information presented here, however, are for only the winter and summer periods (time periods 2 and 3). Table 4-2 presents the distribution of car rollability observations.

Weather--Eastern Oregon has a dry, semiarid climate--considerably different from the damp climate of western Oregon. Only 37 observations were made at Hinkle Yard when the weather was wet. The wind velocity measured at the master retarder usually was less than 5 ft/sec and averaged 6.4 and 9.4 ft/sec in the winter and summer, respectively. Figure 4-3 presents the distribution of rolling resistances data for various wind directions. The average temperature during the observation periods was 36 °F in the winter and 71 °F in the summer. Because the winter temperatures were mild, no data were obtained for subzero temperatures, as shown in Table 4-3.

Table 4-3

DISTRIBUTION OF HINKLE YARD ROLLING RESISTANCE DATA FOR VARIOUS TEMPERATURE RANGES

| Temperature (°F) | Relative Frequency (%) Winter | Summer |
|---|---|---|
| 0 and below | 0.0 | 0.0 |
| 1-5 | 0.0 | 0.0 |
| 6-10 | 0.0 | 0.0 |
| 11-15 | 1.4 | 0.0 |
| 16-20 | 2.6 | 0.0 |
| 21-25 | 5.6 | 0.0 |
| 26-30 | 13.3 | 0.0 |
| 31-40 | 56.3 | 0.0 |
| 41-50 | 17.5 | 1.8 |
| 51-70 | 3.3 | 41.6 |
| Greater than 70 | 0.0 | 56.6 |
| Total | 100.0% | 100.0% |

Car Population--For quantification of the dependence of rolling resistance on certain characteristics of the car itself, the following parameters were identified for each rolling resistance observation:

- Car type
- Car weight class
- Car weight
- Truck center length
- Bearing type.

Table 4-2

HINKLE YARD DATA COLLECTION PERIODS

| Winter Month | Number of Observations | Relative Frequency (%) | Summer Month (1980) | Number of Observations | Relative Frequency (%) |
|---|---|---|---|---|---|
| December 1979 | 309 | 72.2 | June | 32 | 11.5 |
| January 1980 | 119 | 27.8 | July | 137 | 49.1 |
| | | | August | 110 | 39.4 |
| Total | 428 | 100.0 | | 279 | 100.0 |

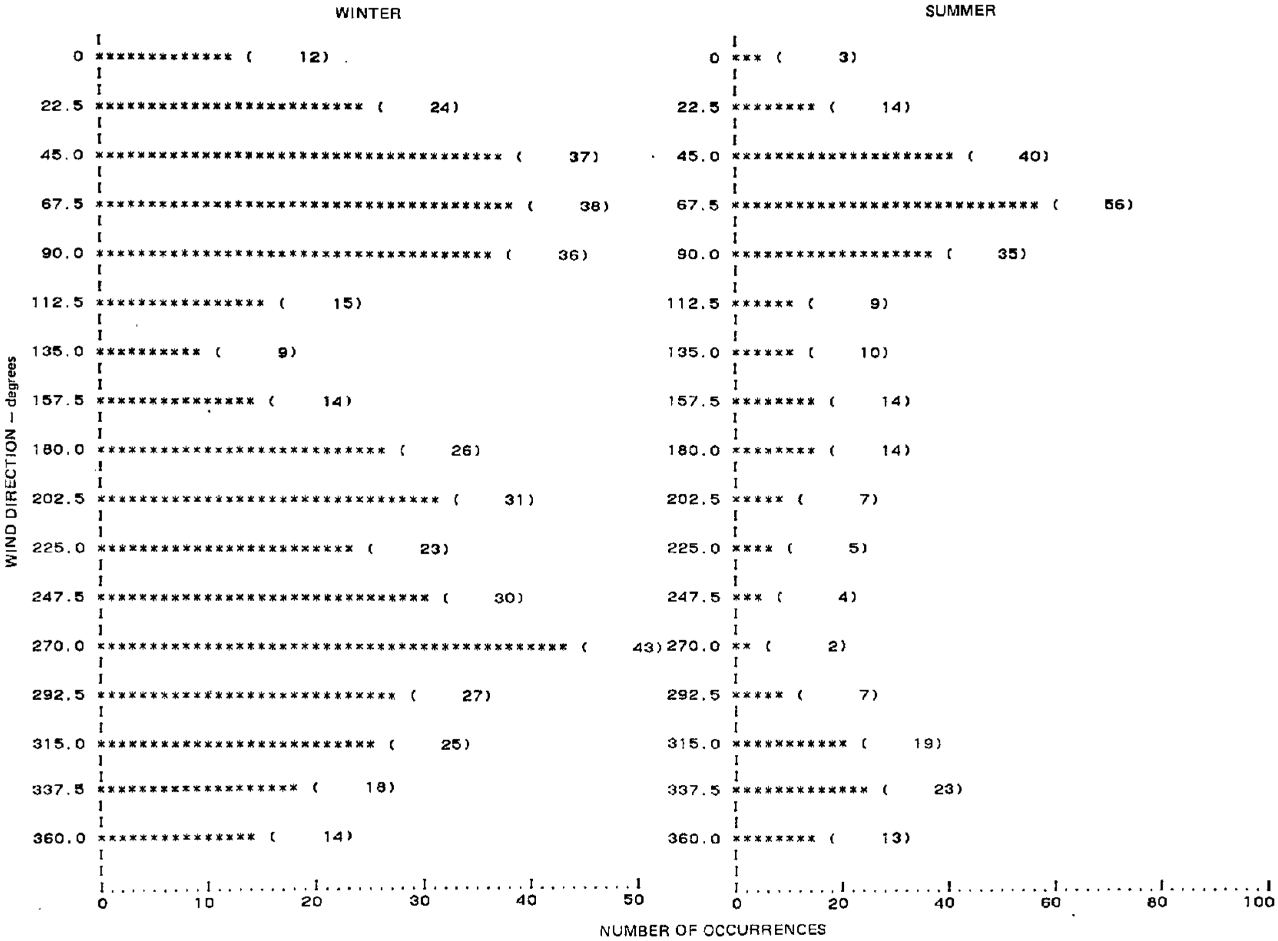



FIGURE 4-3 DISTRIBUTION OF HINKLE YARD ROLLING RESISTANCE DATA FOR VARIOUS WIND DIRECTIONS

The car population at Hinkle Yard during the study periods comprised the car types identified in Figures 4-4 and 4-5. Boxcars predominated, comprising 33.9 and 27.6% of the winter and summer railcar populations, respectively.

Each car was classified as light, medium, heavy, or extra heavy on the basis of the following loaded car weight ranges:

- Light car, 0 to 35 tons.
- Medium car, 35 to 65 tons.
- Heavy car, 65 to 100 tons.
- Extra heavy car, more than 100 tons.

The predominant car weight was light, but the distribution of cars by weight classification differed between winter and summer, as Table 4-4 indicates. The average weight of the winter car population was lighter: 62 tons compared with 69 tons in the summer. Table 4-5 compares the winter and summer loaded car weights.

The truck center length (TRCNTL) for 54% of the observations was obtained from the UMLER file. The car wheelbase (IWBASE), however, was recorded for every observation by the Hinkle Yard PC computer. The following calibration equation provided an estimate of the truck center length when UMLER data were unavailable:

$$TRCNTL = \hat{\alpha} + \hat{\beta} * IWBASE \qquad (4.1)$$

where

TRCNTL = truck center length as contained in UMLER
IWBASE = car wheelbase as provided by the PC computer
$\hat{\alpha}$, $\hat{\beta}$ = coefficients estimated by regression.

The coefficients estimated by regression were:

$$\hat{\alpha} = -5.98$$

$$\hat{\beta} = 1.00615 \quad .$$

```
            I
            **********  (      35)
            I  EQUIPPED BOX CARS
            I
            ****************************  (     110)
            I  UNEQUIPPED BOX CARS
            I
            *****  (      16)
            I  EQUIPPED GONDOLAS
            I
            ***********  (      44)
            I  FLAT CARS
            I
            *******  (      22)
            I  UNEQUIPPED GONDOLA
            I
            ****  (      13)
         C  I  UNEQUIPPED HOPPER
         A  I
         R  ****************  (      63)
            I  SPECIAL TYPE CARS
         T  I
         Y  **  (      5)
         P  I  MAINTENANCE OF WAY
         E  I
            ****  (      10)
            I  CABOOSES
            I
            *****************  (      66)
            I  REFRIGERATOR CARS
            I
            ********  (      29)
            I  TANK CARS
            I
            ***  (      9)
            I  VEHICULAR
            I
            I.........I.........I.........I.........I.........I
            0        40        80       120       160       200
                              NUMBER OF CARS
```

FIGURE 4-4 DISTRIBUTION OF HINKLE YARD CARS BY UMLER CAR TYPE DURING THE WINTER OBSERVATIONS

```
            I
            ****************  (      30)
            I  EQUIPPED BOX CARS
            I
            ************************  (      47)
            I  UNEQUIPPED BOX CARS
            I
            *******  (      12)
            I  EQUIPPED GONDOLAS
            I
            ***********  (      21)
            I  FLAT CARS
            I
            *******  (      12)
            I  UNEQUIPPED GONDOLA
            I
            *****  (      8)
         C  I  UNEQUIPPED HOPPER
         A  I
         R  ******************************  (      59)
            I  SPECIAL TYPE CARS
         T  I
         Y  ****  (      5)
         P  I  MAINTENANCE OF WAY
         E  I
            ******  (      9)
            I  CABOOSES
            I
            ***********************  (      43)
            I  REFRIGERATOR CARS
            I
            ************  (      23)
            I  TANK CARS
            I
            ****  (      6)
            I  VEHICULAR
            I
            I.........I.........I.........I.........I.........I
            0        20        40        60        80       100
                              NUMBER OF CARS
```

FIGURE 4-5 DISTRIBUTION OF HINKLE YARD CARS BY UMLER CAR TYPE DURING THE SUMMER OBSERVATIONS

Table 4-6 presents the distribution of winter and summer car populations by length. Eighty-six percent of the cars were known to have roller bearings, and 9 to 10% had plain or journal bearings. Data on bearings were unavailable for the remaining percentage of cars.

### 4.2.3 Rolling Resistance Information for Design

Figures 4-6 and 4-7 are histograms of rolling resistance at the four measurement sections. Tables 4-7 and 4-8 indicate the mean, standard deviation, standard error, 95% confidence interval, minimum, and maximum for the rolling resistances and average velocities at each of the four measurement sections.

One of the rolling resistance models most commonly used for yard design is to assume that the hardest rolling car begins with a high rolling resistance value on the hump and gradually becomes easier rolling on its journey to the classification track. The data in Figure 4-6 and Table 4-7, however, contradicts this model.

Figure 4-6 indicates that the nominal rolling resistance values are initially low on the crest to master retarder measurement section, increase in the master retarder to group retarder measurement section, and then decrease into the classification area. This is verified by examination of the mean rolling resistance values given in Tables 4-7 and 4-8.

Figure 4-6 also indicates that the variance in the rolling resistance values is initially small on the crest to master retarder section, increases in the master retarder to group retarder section, and then decreases in the group retarder to tangent point and classification areas. This is verified by the standard deviation and the minimum and maximum values for each measurement section in Table 4-7. This spread can be explained, at least in part, by the error characteristics of the way the rollability data were collected (see Appendix C).

At first, these histograms appear to be counterintuitive. However, closer examination provided the following explanation. Rolling resistance increases with car velocity, so that the increase or decrease in the mean and variance of the rolling resistance values should be highly correlated with the increase or decrease in the mean and variance of the car speeds for the four measurement sections. The data in Table 4-7 verify this.

## 4.3 DE WITT YARD

### 4.3.1 Physical Description

De Witt is a CONRAIL yard located in Syracuse, New York. As shown in Figure 4-8, it has one master retarder and six group retarders. Railcars are humped into the six groups of classification tracks at a rate of 2 mph. The signaling

Table 4-4

DISTRIBUTION OF HINKLE YARD CARS BY WEIGHT CLASSIFICATION
(Percent)

| | Winter | | Summer | |
|---|---|---|---|---|
| Weight Class | Relative Frequency | Cumulative Frequency | Relative Frequency | Cumulative Frequency |
| Light | 42.8% | 42.8% | 35.1% | 35.1% |
| Medium | 16.6 | 59.3 | 19.7 | 54.8 |
| Heavy | 23.1 | 82.5 | 21.5 | 76.3 |
| Extra heavy | 17.5 | 100.0 | 23.7 | 100.0 |

Table 4-5

DISTRIBUTION OF HINKLE YARD CARS BY WEIGHT
(Percent)

| | Winter | | Summer | |
|---|---|---|---|---|
| Car Weight (tons) | Relative Frequency | Cumulative Frequency | Relative Frequency | Cumulative Frequency |
| 20 | 1.6% | 1.6% | 1.8% | 1.8% |
| 30 | 26.9 | 28.5 | 20.8 | 22.6 |
| 40 | 21.3 | 49.8 | 21.1 | 43.7 |
| 50 | 6.8 | 56.5 | 6.1 | 49.8 |
| 60 | 7.0 | 63.6 | 3.2 | 53.0 |
| 70 | 4.2 | 67.8 | 4.3 | 57.3 |
| 80 | 5.4 | 73.1 | 8.6 | 65.9 |
| 90 | 6.3 | 79.4 | 7.2 | 73.1 |
| 100 | 3.7 | 83.2 | 3.9 | 77.1 |
| 110 | 3.7 | 86.9 | 5.7 | 82.8 |
| 120 | 3.5 | 90.4 | 2.2 | 84.9 |
| 130 | 9.3 | 99.8 | 13.6 | 98.6 |
| 140 | 0.2 | 100.0 | 0.7 | 99.3 |
| 150 | 0.0 | 100.0 | 0.4 | 99.6 |
| 160 | 0.0 | 100.0 | 0.4 | 100.0 |

and PC systems were installed by GRS.

Velocity measurements stored by the PC computer systems are recorded:

- From the hump crest to the master retarder (measurement section 1).
- From the master retarder to the group retarder (measurement section 2).
- From the group retarder to the tangent point (measurement section 3).

Table 4-6

DISTRIBUTION OF HINKLE YARD CARS BY TRUCK CENTER LENGTH
(Percent)

| | Winter | | Summer | |
|---|---|---|---|---|
| Length (feet) | Relative Frequency | Cumulative Frequency | Relative Frequency | Cumulative Frequency |
| 20 | 0.9% | 0.9% | 1.4% | 1.4% |
| 25 | 4.2 | 5.1 | 6.1 | 7.5 |
| 30 | 10.5 | 15.7 | 12.2 | 19.7 |
| 35 | 2.8 | 18.5 | 5.4 | 25.1 |
| 40 | 39.7 | 58.2 | 32.6 | 57.7 |
| 45 | 29.4 | 87.6 | 30.5 | 88.2 |
| 50 | 4.7 | 92.3 | 6.5 | 94.6 |
| 55 | 1.4 | 93.7 | 1.1 | 95.7 |
| 60 | 1.9 | 95.6 | 1.4 | 97.1 |
| 65 | 4.4 | 100.0 | 2.9 | 100.0 |

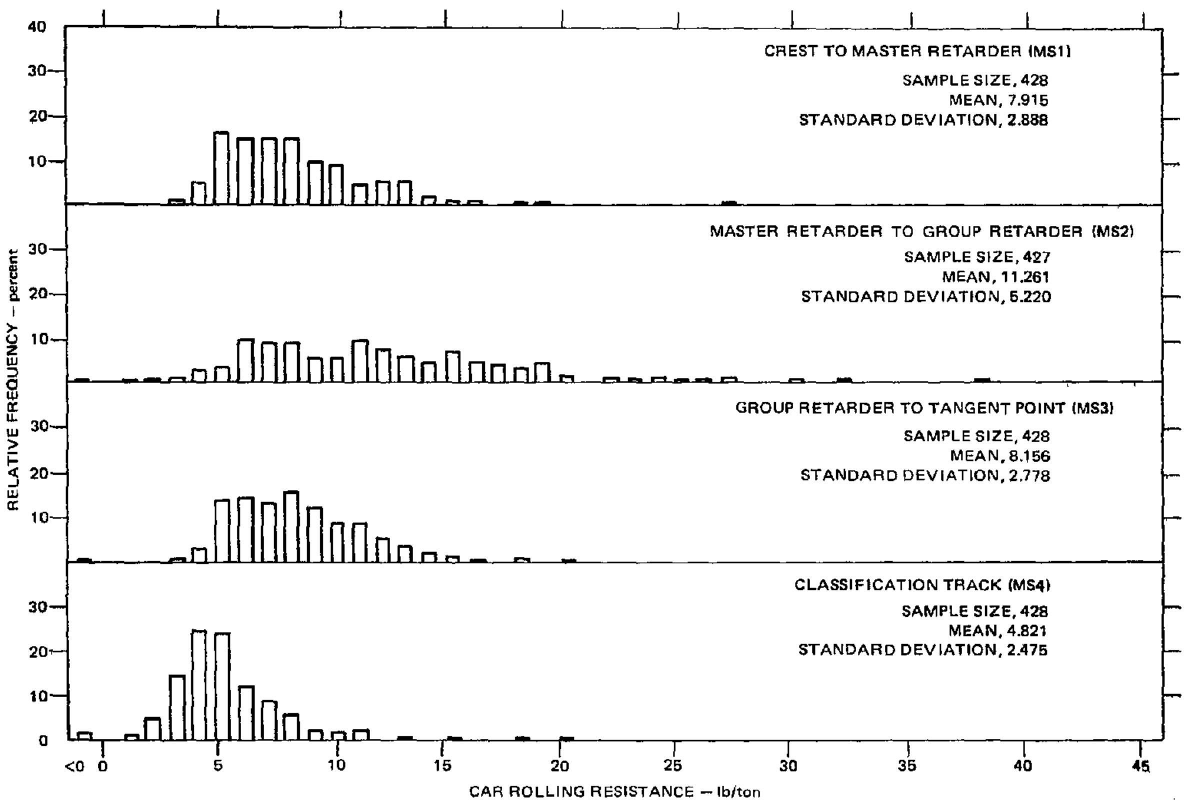



FIGURE 4-6 DISTRIBUTION OF HINKLE YARD CAR ROLLING RESISTANCES BY MEASUREMENT SECTION DURING THE WINTER OBSERVATIONS

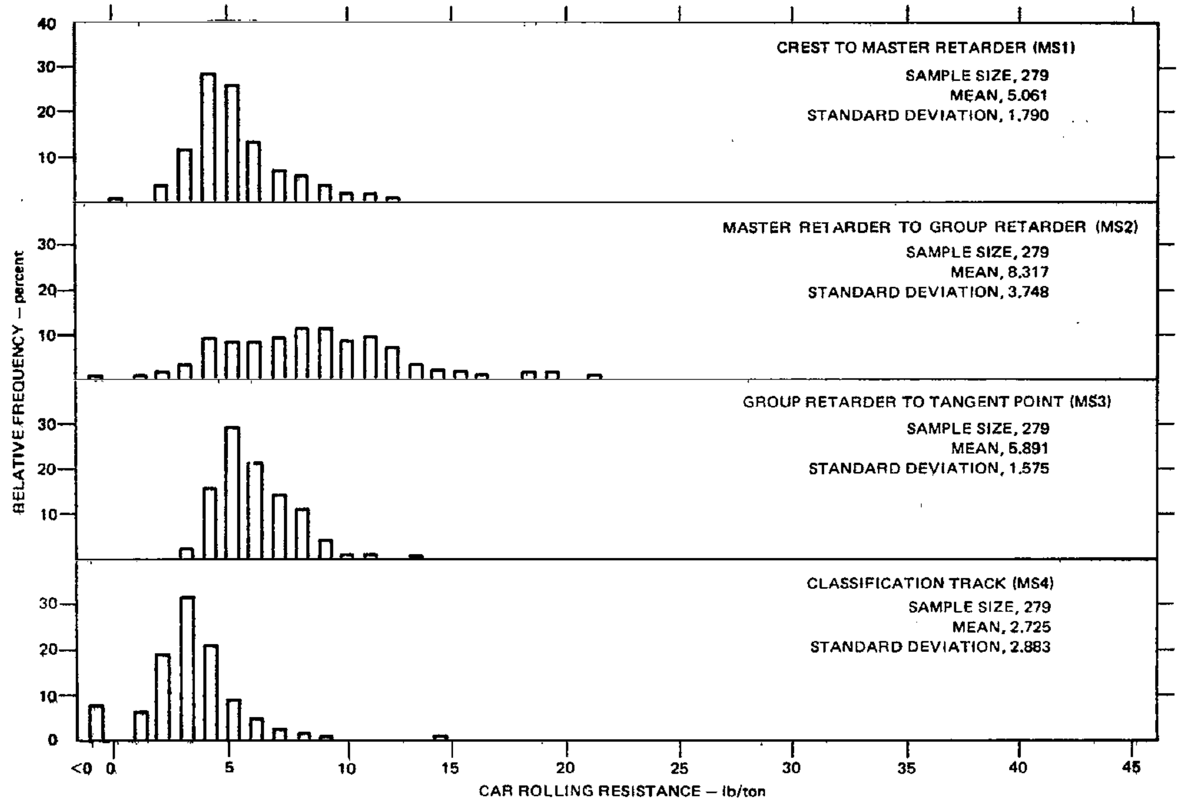



FIGURE 4-7 DISTRIBUTION OF HINKLE YARD CAR ROLLING RESISTANCES BY MEASUREMENT SECTION DURING THE SUMMER OBSERVATIONS

Table 4-7

ROLLING RESISTANCE AND VELOCITY STATISTICS AT HINKLE YARD MEASUREMENT SECTIONS FROM THE WINTER OBSERVATIONS

| Measurement Section | Rolling Resistance (lb/ton) | | | | | | Average Velocity (ft/sec) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD* | SE* | 95% CI | Minimum | Maximum | Mean | SD* | SE* | 95% CI | Minimum | Maximum |
| Crest to master retarder (MS1) | 7.915 | 2.888 | .140 | 7.640–8.189 | 2 | 27 | 18.161 | .617 | .030 | 18.102–18.219 | 14 | 19 |
| Master retarder to group retarder (MS2) | 11.261 | 5.220 | .253 | 10.764–11.757 | -19 | 38 | 25.050 | 2.049 | .099 | 24.855–25.245 | 19 | 31 |
| Group retarder to tangent-point (MS3) | 8.156 | 2.778 | .134 | 7.892–8.420 | - 1 | 22 | 13.273 | 2.202 | .107 | 13.063–13.482 | 8 | 18 |
| Classification area (MS4) | 4.821 | 2.475 | .120 | 4.586–5.056 | -11 | 20 | 9.081 | 1.996 | .097 | 8.891–9.271 | 4 | 15 |

*SD, standard deviation.
SE, standard error of mean.
CI, confidence interval for mean.

- From the distance-to-couple bond to the point of coupling (measurement section 4).

Car rolling resistance is measured and stored by the PC computer for three measurement sections (shown as MS1, MS2, and MS4 in Figure 4-8). SRI calculated the car rolling resistance for measurement section 3.

Measurement section 1 consists of approximately 53 feet of straight track between the first and third wheel detectors before the master retarder.

Table 4-8

ROLLING RESISTANCE AND VELOCITY STATISTICS AT HINKLE YARD MEASUREMENT SECTIONS FROM THE SUMMER OBSERVATIONS

| Measurement Section | Rolling Resistance (lb/ton) Mean | SD* | SE* | 95% CI | Minimum | Maximum | Average Velocity (ft/sec) Mean | SD* | SE* | 95% CI | Minimum | Maximum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Crest to master retarder (MS1) | 5.061 | 1.790 | .107 | 4.850-5.272 | 0 | 12 | 18.665 | .402 | .024 | 18.618-18.712 | 17 | 19 |
| Master retarder to group retarder (MS2) | 8.317 | 3.748 | .224 | 7.875-8.758 | -15 | 21 | 23.640 | 1.767 | .106 | 23.432-23.849 | 18 | 31 |
| Group retarder to tangent point (MS3) | 5.891 | 1.575 | .094 | 5.705-6.077 | 3 | 13 | 11.650 | 2.199 | .132 | 11.391-11.909 | 7 | 18 |
| Classification area (MS4) | 2.725 | 2.883 | .173 | 2.385-3.065 | -13 | 14 | 8.823 | 2.303 | .141 | 8.545-9.101 | 4 | 16 |

*SD, standard deviation.
SE, standard error of mean.
CI, confidence interval for mean.

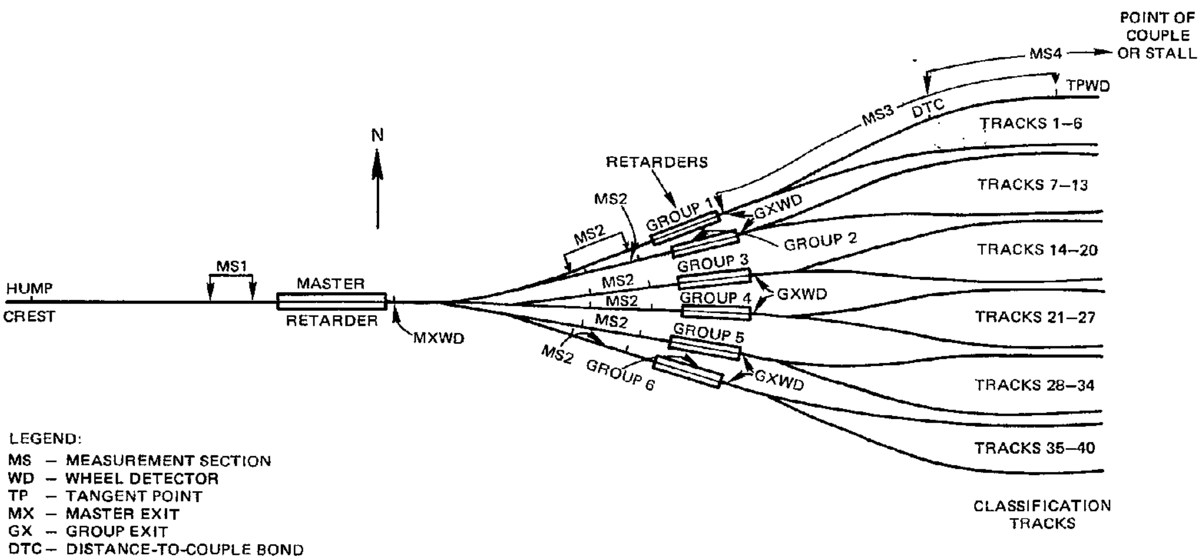



FIGURE 4-8 DE WITT YARD CONFIGURATION

The orientation of the measurement section is 90 degrees (measured clockwise from north) on a 2.28% grade. The midpoint of the section is 272 feet from the crest.

Measurement section 2 consists of approximately 80 feet of straight track between the first and third wheel detectors before each group retarder. The orientation, grade, and distance from the crest (DFC) to the midpoint of the measurement section differ for each group as follows:

| Group Retarder Number | Track Orientation (degrees) | Grade (%) | DFC (feet) |
|---|---|---|---|
| 1 | 69 | 1.3644 | 777 |
| 2 | 76 | 1.3644 | 789 |
| 3 | 83 | 0.9219 | 801 |
| 4 | 93 | 0.9219 | 800 |
| 5 | 101 | 1.3644 | 791 |
| 6 | 109 | 1.3644 | 776 |

Measurement section 3 comprises 40 sections of track varying in length from 280 to 480 feet. Each section of track starts at the group exit wheel detector (GXWD) and ends at the tangent point wheel detector (TPWD) located on the classification track. Each track section has the following features:

- An oiler located before the fan after the group retarder.
- Some curvature.
- A combination of Nos. 6, 8, and 10 switches.
- An average orientation ranging from 71 to 108 degrees.
- An average grade from the GXWD to the midpoint of the measurement section ranging from 0 to 0.063%.
- An average grade from the GXWD to the TPWD ranging from 0 to 0.173%.

Measurement section 4 begins at the distance-to-couple (DTC) bond, which is located after the clearance point and usually before the TPWD. Thus, a portion of measurement section 4 overlaps measurement section 3. The extent of the overlap and the degree of track curvature are determined by the length of track between the DTC bond and the TPWD (0 to 178 feet). After the TPDW, all the classification tracks are straight and have an orientation of 90 degrees and a grade of 0.0 to 8%. The section ends at the point of coupling or stall of the car, so the length of measurement section 4 varies with each car. The average orientation, grade, and DFC also vary with each car.

#### 4.3.2 Important Rolling Resistance Factors During the Periods Analyzed

Data consisting of 20 trains of cut statistics, were obtained for two time periods: February 27 and 28, 1980 (winter), and August 16 through 18, 1980 (summer). The rollability observations for the winter and summer periods numbered 560 and 465 cars, respectively.

In processing the first few trains of DeWitt Yard data, SRI found that a significant amount of the data included two or more cars humped together. Also, in view of the relatively small sample available, single car data with no UMLER matches could not be discarded. Therefore, separate data files were created that included:

- Single-car cuts with UMLER matches
- Single-car cuts with no UMLER matches
- Multiple-car cuts with no UMLER matches.

Statistics and descriptive information are presented here for only the single-car cuts. The regression analysis described in Chapter 5 was based on the same data.

A preliminary analysis of DeWitt Yard rollability data for winter was based on a sample of 801 cars. Plots, frequency distributions, histograms, and statistical descriptions were derived through SPSS for car rolling resistances in the four measurement sections and for the associated parameters. In this preliminary analysis, some data were determined to be in error for some car observations. Those data were classified as "missing," and a second SPSS file for regression analysis was established.

Mr. Jim Wetzel of CONRAIL informed SRI that he had been working with GRS personnel to solve problems in process control at DeWitt Yard. While investigating why the rolling resistance values for cars going to Group 3 tracks were inaccurate, they had discovered errors in the PC computer program, including:

- The original grade profile was incorrect.
- The precise location of wheel detectors was incorrect.
- A signal for erroneous wheelbase measurements (e.g., 1 foot) was overridden, providing some incorrect velocity measurements.
- The car weight category parameter used for control in the program matched the actual weight category only 60% of the time.
- Some wind speeds were highly erroneous (e.g., 300 ft/sec).

A statistical comparison of rollability measurements taken on Group 3 tracks with measurements taken on the other tracks confirmed Mr. Wetzel's observation. Consequently, measurements from Group 3 were excluded from the summer observations.

Weather--During both the summer and winter observation periods, there was no recorded precipitation. The wind velocity, measured at the master retarder, was considerably higher during the winter, averaging 13 ft/sec in the winter and 6 ft/sec in the summer. The general direction of the wind varied considerably between summer and winter, as depicted in Figure 4-9. The PC system recorded temperatures according to six temperature range codes. Based on these ranges, the average temperature for the observations was estimated at 19 °F in the winter and 66 °F in the summer. Because of the short data collection periods and the wide-range temperature categories, however, the distribution of temperatures may not be representative of the 1980 winter and summer months in Syracuse. Table 4-9 presents the distribution of rolling resistance observations for the six temperature ranges.

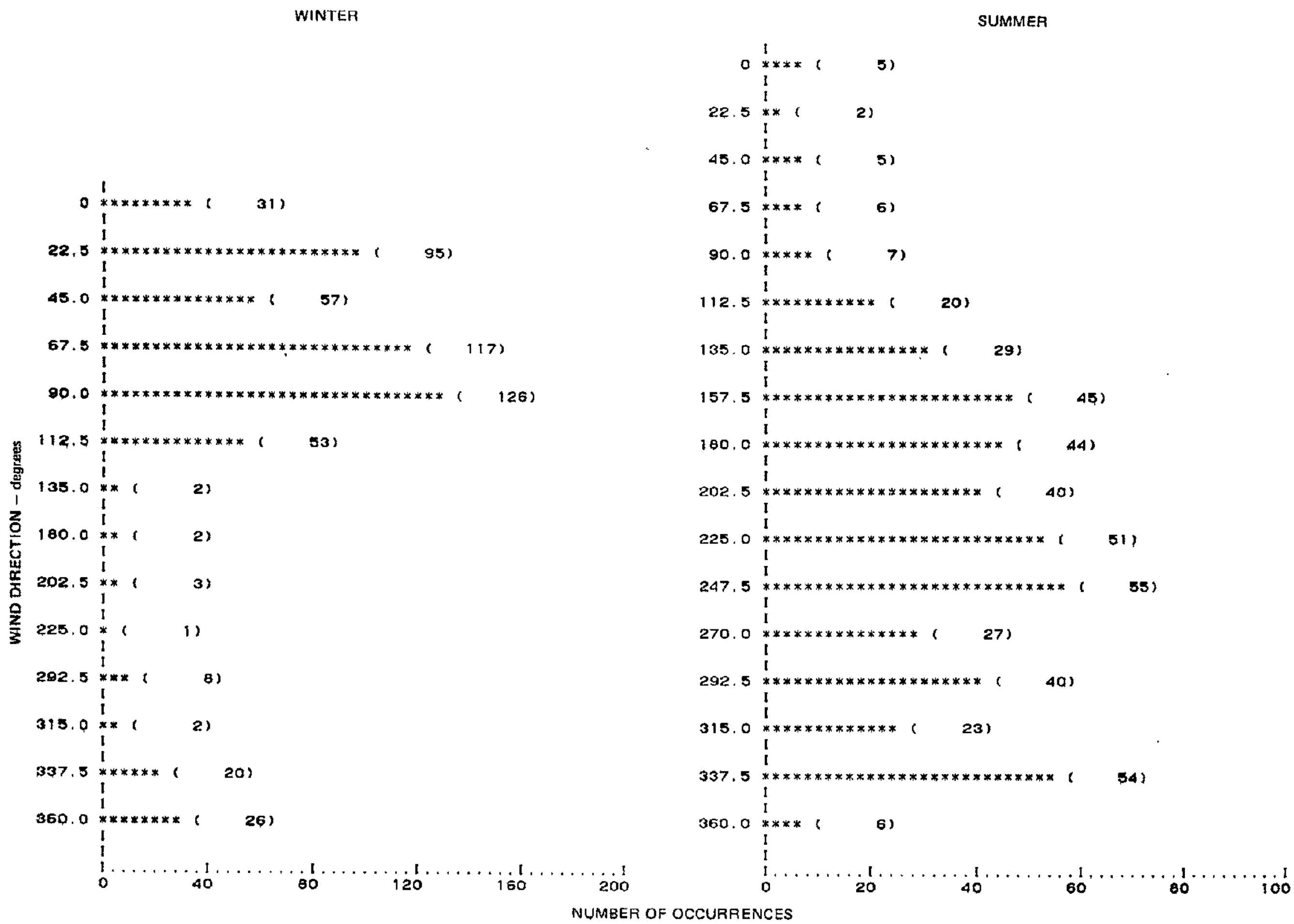



FIGURE 4-9 DISTRIBUTION OF DE WITT ROLLING RESISTANCE DATA FOR VARIOUS WIND DIRECTIONS

Table 4-9

DISTRIBUTION OF DE WITT YARD ROLLING RESISTANCE DATA FOR VARIOUS TEMPERATURE RANGES

| Temperature (°F) | Relative Frequency (%) Winter | Summer |
|---|---|---|
| Less than 0 | 0.9 | 0.0 |
| 0 - 20 | 58.5 | 0.0 |
| 20 - 40 | 40.6 | 0.0 |
| 40 - 60 | 0.0 | 21.5 |
| 60 - 80 | 0.0 | 76.3 |
| Greater than 80 | 0.0 | 2.2 |
| Total | 100.0% | 100.0% |

Car Population--The following parameters were identified for each rolling resistance observation so that the dependence of rolling resistance on certain aspects of the car itself could be quantified:

- Car type
- Car weight class
- Car weight
- Truck center length
- Bearing type.

Car type, truck center length, and bearing type were obtained from a 1977 UMLER file. The UMLER file contained relatively few cars that had been renumbered to CONRAIL IDs, however. In only 68% of the cases did the UMLER file and car observation match. Consequently, in a substantial number of observations data on these parameters were missing.

The car population at DeWitt Yard comprised the car types indicated in Figures 4-10 and 4-11. As in Hinkle Yard, boxcars were predominant, comprising a larger percentage of the winter than the summer population.

```
CAR TYPE
I
*********** (     41)
I  EQUIPPED BOX CARS
I
************************** (       99)
I  UNEQUIPPED BOX CARS
I
** (      2)
I  EQUIPPED GONDOLA
I
*************** (      60)
I  FLAT CARS
I
******* (      25)
I  UNEQUIPPED GONDOLA
I
** (      5)
I  UNEQUIPPED HOPPER
I
******************** (       78)
I  SPECIAL TYPE CARS
I
** (      2)
I  MAINTENANCE OF WAY
I
*** (      7)
I  CABOOSES
I
********** (     36)
I  REFRIGERATOR CARS
I
******* (      25)
I  TANK CARS
I
**** (     12)
I  VEHICULAR FLAT CARS
I
**************************************** (      151)
I
I
I.........I.........I.........I.........I.........I
0        40        80       120       160       200
                  NUMBER OF CARS
```

FIGURE 4-10 DISTRIBUTION OF DE WITT CARS BY UMLER CAR TYPE DURING THE WINTER OBSERVATIONS

```
CAR TYPE
I
******** (      27)
I  EQUIPPED BOX CARS
I
***************** (      62)
I  UNEQUIPPED BOX CARS
I
** (      2)
I  EQUIPPED GONDOLA
I
******* (      24)
I  FLAT CARS
I
***** (      15)
I  UNEQUIPPED GONDOLA
I
**** (      10)
I  UNEQUIPPED HOPPER
I
****************** (       69)
I  SPECIAL TYPE CARS
I
** (      3)
I  MAINTENANCE OF WAY
I
*** (      6)
I  CABOOSES
I
********* (      33)
I  REFRIGERATOR CARS
I
****** (      18)
I  TANK CARS
I
**** (      10)
I  VEHICULAR FLAT CARS
I
********************************************** (      180)
I
I
I.........I.........I.........I.........I.........I
0        40        80       120       160       200
                  NUMBER OF CARS
```

FIGURE 4-11 DISTRIBUTION OF DE WITT CARS BY UMLER CAR TYPE DURING THE SUMMER OBSERVATIONS

The DeWitt Yard PC computer classified every car as either light, medium, heavy, or extra heavy according to the following loaded car weights:

- Light, 0 to 35 tons
- Medium, 35 to 65 tons
- Heavy, 65 to 100 tons
- Extra heavy, more than 100 tons.

The distribution of cars by weight class was considerably different during the winter and summer, as shown in Table 4-10. Some of these differences may be due to inaccuracies discovered in the DeWitt PC system program for weight categorization during the summer data collection period. The inaccuracy in weight classification resulted in an incorrect "effective" gravity factor used during the calculation of some rolling resistances during the summer period.

Table 4-11 presents a more accurate distribution of these cars by loaded weight. The average car weight of the car population in the winter was 7 tons lighter than that in the summer (57.9 as opposed to 65.2 tons).

The truck center length (TRCNTL) parameter was frequently missing. For 67% of the observations, however, the DeWitt Yard PC system had recorded the cut wheelbase (IWBASE). An estimate of truck center length for cars having missing values was performed with calibration equation 4.1. The coefficients estimated by regression were:

$$\hat{\alpha} = -6.037$$

$$\hat{\beta} = 1.0056 \; .$$

Table 4-12 presents the distribution of winter and summer car populations by length. Forty-nine percent of the winter car population had roller bearings, and 22% had plain or journal bearings. The equivalent figures for the summer car population were 43 and 16%, respectively. Information on bearings was unavailable for the remaining percentages.

### 4.3.3 Rolling Resistance Information for Design

Figures 4-12 and 4-13 are histograms of winter and summer rolling resistances at the four measurement sections:

- Crest to master retarder (measurement section 1).
- Master retarder to group retarder (measurement section 2).
- Group retarder to tangent point (measurement section 3).
- Classification track (measurement section 4).

Table 4-10

DISTRIBUTION OF DE WITT YARD CARS BY WEIGHT CLASSIFICATION
(Percent)

| | Winter | | Summer | |
|---|---|---|---|---|
| Weight Class | Relative Frequency | Cumulative Frequency | Relative Frequency | Cumulative Frequency |
| Light | 32.1% | 32.1% | 35.9% | 35.9% |
| Medium | 38.4 | 70.5 | 15.9 | 51.2 |
| Heavy | 16.1 | 86.6 | 27.1 | 78.3 |
| Extra heavy | 13.4 | 100.0 | 21.7 | 100.0 |

Table 4-11

DISTRIBUTION OF DE WITT YARD CARS BY WEIGHT
(Percent)

| | Winter | | Summer | |
|---|---|---|---|---|
| Car Weight (tons) | Relative Frequency | Cumulative Frequency | Relative Frequency | Cumulative Frequency |
| 0 | 0.7% | 0.7% | 0.4% | 0.4% |
| 20 | 0.9 | 1.6 | 1.5 | 1.9 |
| 30 | 30.2 | 31.8 | 29.0 | 31.0 |
| 40 | 1.8 | 33.6 | 7.5 | 38.5 |
| 50 | 32.0 | 65.5 | 9.5 | 48.0 |
| 60 | 2.0 | 67.5 | 4.7 | 52.7 |
| 70 | 2.9 | 70.4 | 3.7 | 56.3 |
| 80 | 12.9 | 83.2 | 17.0 | 73.3 |
| 90 | 1.6 | 84.8 | 6.2 | 79.6 |
| 100 | 2.1 | 87.0 | 2.2 | 81.7 |
| 110 | 2.7 | 89.6 | 3.2 | 84.9 |
| 120 | 8.8 | 98.4 | 10.3 | 95.3 |
| 130 | 1.6 | 100.0 | 4.5 | 99.8 |
| 140 | 0.0 | 100.0 | 0.2 | 100.0 |

Tables 4-13 and 4-14 present descriptive statistics for the rolling resistances and average velocities at each of the four measurement sections for the winter and summer populations. Figures 4-12 and 4-13 are similar to the Hinkle Yard rolling resistance histograms showing low rolling resistance values on measurement section 1, an increase in the values on measurement section 2, followed by decreasing values on measurement sections 3 and 4 for both populations. Figures 4-11 and 4-12 also indicate a larger variance in the rolling resistances for the winter population than for the summer population. This is verified by examining the standard deviation and the 95% confidence intervals for each population in Tables 4-13 and 4-14. These tables also indicate a possible correlation in the increase or decrease of mean rolling resistance values and the increase or decrease of mean car velocities for the four measurement sections for both populations.

Table 4-12

DISTRIBUTION OF DE WITT YARD CARS BY TRUCK CENTER LENGTH
(Percent)

| Length (feet) | Winter Relative Frequency | Winter Cumulative Frequency | Summer Relative Frequency | Summer Cumulative Frequency |
|---|---|---|---|---|
| 20 | 2.4% | 2.4% | 2.3% | 2.3% |
| 25 | 6.3 | 8.7 | 7.4 | 9.7 |
| 30 | 14.5 | 23.2 | 18.8 | 28.5 |
| 35 | 6.6 | 29.8 | 8.4 | 36.9 |
| 40 | 29.0 | 58.8 | 23.5 | 60.4 |
| 45 | 21.1 | 79.9 | 26.2 | 86.6 |
| 50 | 1.8 | 81.8 | 0.7 | 87.2 |
| 55 | 3.2 | 85.0 | 3.0 | 90.3 |
| 60 | 3.2 | 88.1 | 1.3 | 91.6 |
| 65 | 11.6 | 99.7 | 8.4 | 100.0 |
| 70 | 0.3 | 100.0 | 0.0 | 100.0 |

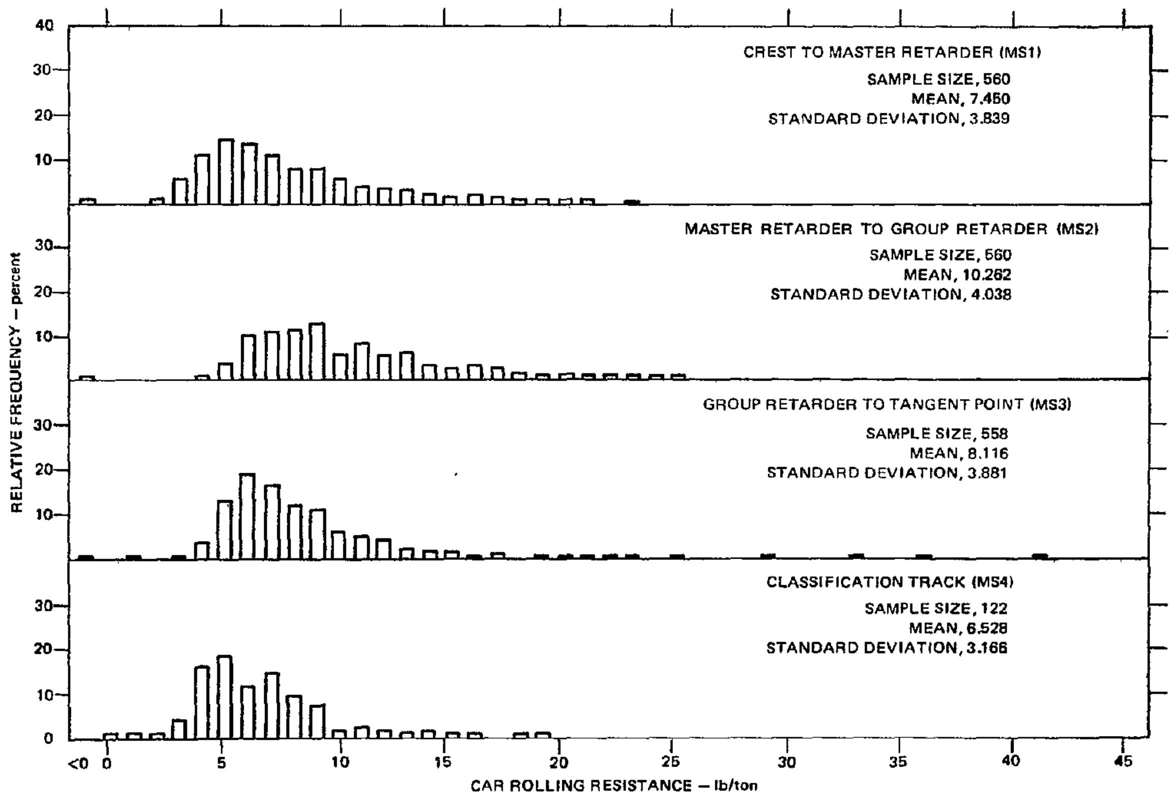



FIGURE 4-12 DISTRIBUTION OF DEWITT YARD CAR ROLLING RESISTANCES BY MEASUREMENT SECTION DURING THE WINTER OBSERVATIONS

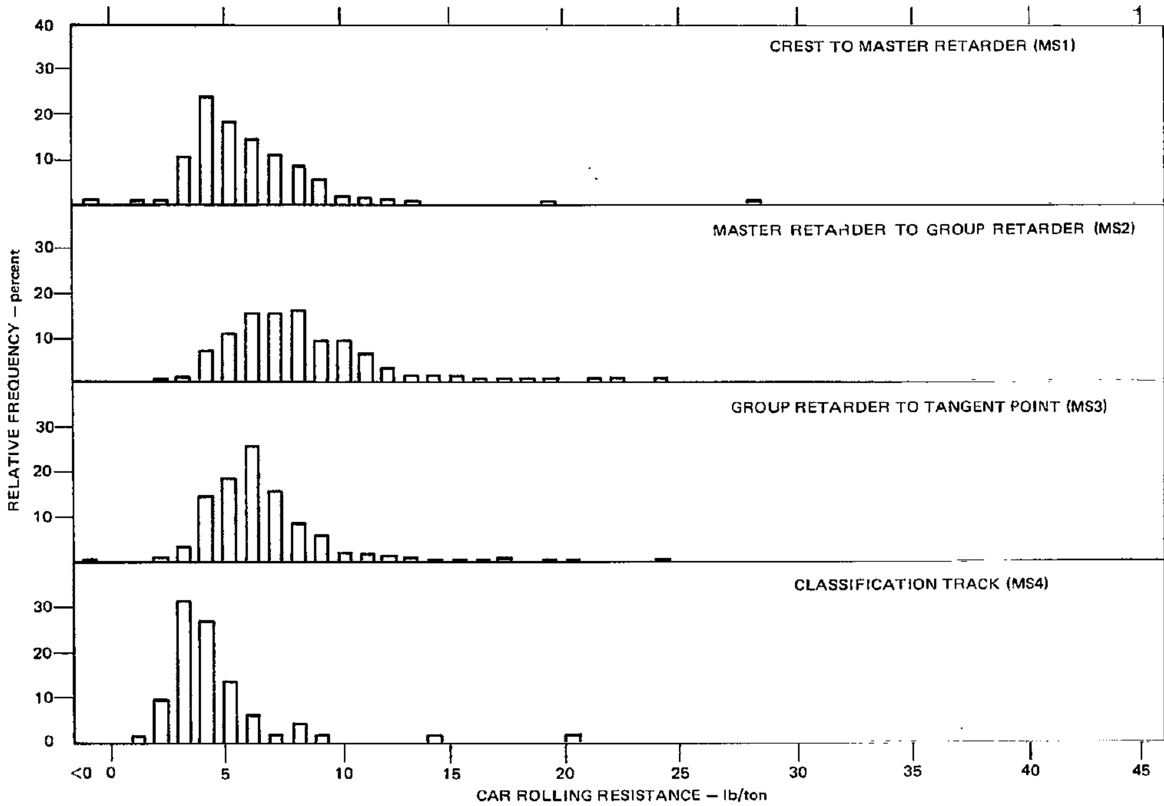



FIGURE 4-13 DISTRIBUTION OF DEWITT YARD CAR ROLLING RESISTANCES BY MEASUREMENT SECTION DURING THE SUMMER OBSERVATIONS

Table 4-13

ROLLING RESISTANCE AND VELOCITY STATISTICS AT DE WITT YARD MEASUREMENT SECTIONS DURING THE WINTER OBSERVATIONS

| Measurement Section | Rolling Resistance (lb/ton) | | | | | | Average Velocity (ft/sec) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD* | SE* | 95% CI | Minimum | Maximum | Mean | SD* | SE* | 95% CI | Minimum | Maximum |
| Crest to master retarder (MS1) | 7.450 | 3.839 | .162 | 7.132–7.769 | -14 | 23 | 19.895 | .872 | .037 | 19.823–19.968 | 16 | 22 |
| Master retarder to group retarder (MS2) | 10.262 | 4.038 | .171 | 9.927–10.597 | - 5 | 26 | 20.692 | 1.861 | .079 | 20.537–20.847 | 15 | 25 |
| Group retarder to tangent point (MS3) | 8.116 | 3.881 | .164 | 7.793–8.438 | -17 | 41 | 15.043 | 2.287 | .097 | 14.853–15.233 | 7 | 22 |
| Classification area (MS4) | 6.528 | 3.166 | .287 | 5.960–7.095 | 1 | 19 | 10.921 | 2.560 | .231 | 10.464–11.378 | 5 | 18 |

*SD, standard deviation.
SE, standard error of mean.
CI, confidence interval for mean.

Table 4-14

ROLLING RESISTANCE AND VELOCITY STATISTICS AT DE WITT YARD MEASUREMENT SECTIONS DURING THE WINTER OBSERVATIONS

| Measurement Section | Rolling Resistance (lb/ton) | | | | | | Average Velocity (ft/sec) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD* | SE* | 95% CI | Minimum | Maximum | Mean | SD* | SE* | 95% CI | Minimum | Maximum |
| Crest to master retarder (MS1) | 5.666 | 2.523 | .117 | 5.436–5.896 | -10 | 28 | 20.313 | .621 | .029 | 20.256–20.370 | 15 | 21 |
| Master retarder to group retarder (MS2) | 7.808 | 2.803 | .130 | 7.552–8.063 | 2 | 24 | 20.479 | .956 | .044 | 20.392–20.566 | 17 | 24 |
| Group retarder to tangent point (MS3) | 6.367 | 2.473 | .116 | 6.139–6.595 | - 1 | 24 | 11.777 | 2.906 | .136 | 11.509–12.045 | 6 | 18 |
| Classification area (MS4) | 4.410 | 2.833 | .349 | 3.713 - 5.106 | 1 | 20 | 7.202 | 2.638 | .325 | 6.554 - 7.851 | 2 | 13 |

*SD, standard deviation.
SE, standard error of mean.
CI, confidence interval for mean.

## 4.4 NORTHTOWN YARD*

### 4.4.1 Physical Description

Northtown, a Burlington Northern yard located in Minneapolis, Minnesota, has one master retarder and eight group retarders (see Figure 4-14). Railcars are humped in a southerly direction into 63 classification tracks at a rate of 2 mph. GRS installed the signaling and PC systems.

Velocity measurements were recorded by the PC computer at the following measurement sections:

- From the hump crest to the master retarder (measurement section 1).
- From the master retarder to the group retarder (measurement section 2).

Rolling resistance data and the parameters that might influence rolling resistance were extracted for measurement sections 1 and 2 (MS1 and MS2 on Figure 4-14). The PC system automatically records rolling resistances for these measurement sections. The PC system also calculates a second rolling resistance that takes into consideration the wind effect. Thus, this discussion presents rolling resistance statistics calculated with and without the wind effect.

Northtown Yard data exist only on computer printouts and thus were manually processed into machine-readable form. SRI extracted pertinent data for a small sample of cars from the hardcopy cut statistics. The data selected were for single-car cuts humped into an outside group of tracks (Group 1, Tracks 1 through 7) and into a center group of tracks (Group 4, Tracks 24 through 31).

Measurement section 1 consists of approximately 80 feet of straight track between the first and fourth wheel detectors before the master retarder. The measurement section is on a 4% grade, and its midpoint is 190 feet from the crest.

Measurement section 2 also consists of approximately 90 and 80 feet of straight track between the first and fourth wheel detectors before the Group 1 and Group 4 retarders, respectively. The grade and the distance from the crest (DFC) to the midpoint of the measurement section differ for each group as follows:

| Group Retarder Number | Grade (%) | DFC (feet) |
|---|---|---|
| 1 | 0.9 | 665 |
| 4 | 0.57 | 784 |

### 4.4.2 Important Rolling Resistance Factors During the Periods Analyzed

Computer printout data (cut statistics) were obtained for a sample of trains humped during January and February 1980 (winter) and during July 1980 (summer).

Northtown yard personnel had adjusted certain factors (e.g., length between wheel detectors) in the rollability calculation to improve the performance of the system. That was the basis for SRI's decision to process data on a small sample of single-car cuts humped onto Tracks 1 through 7 and Tracks 24 through 31--groups of tracks where possible irregularities in rolla-

*Just before the printing of this report, Dr. Dennis C. Henry of Gustavus Adolphus College, a consultant to Burlington Northern, indicated to SRI that the rolling resistance values at Northtown Yard were treated as a "tuning parameter" and arbitrarily adjusted to improve yard operations. Thus, the Northtown Yard data are unreliable.

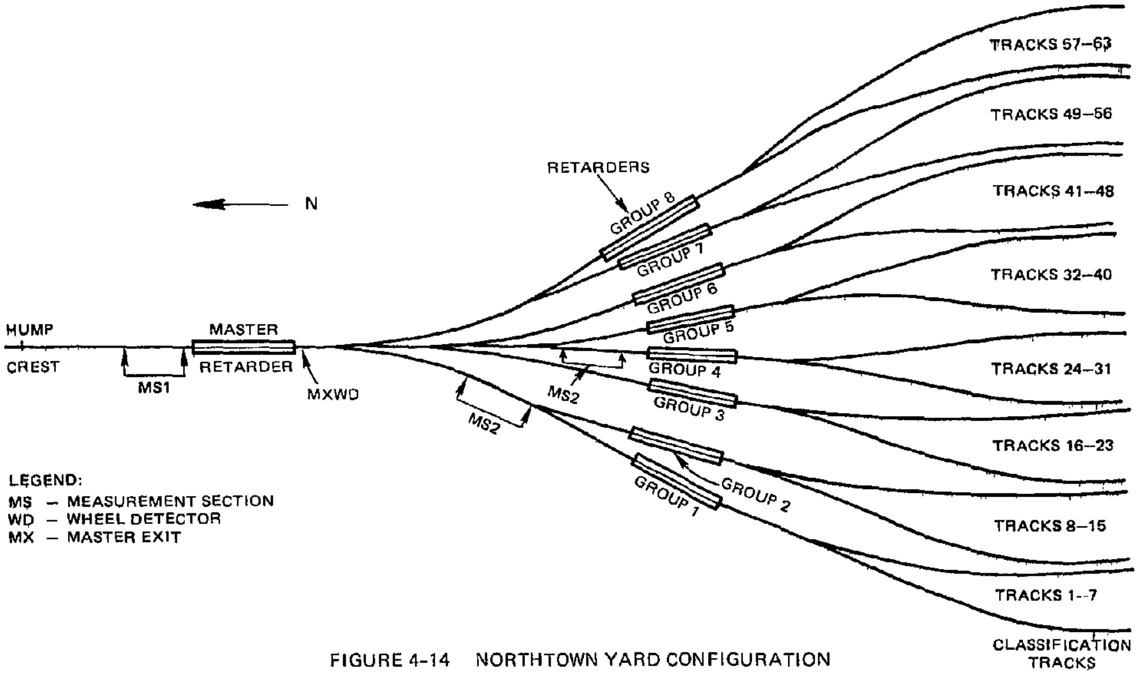



FIGURE 4-14 NORTHTOWN YARD CONFIGURATION

bility values were not likely. This sample comprised data on a maximum 125 cars for each temperature range in the two time periods. The sample included cars both successfully and unsuccessfully matched to the UMLER car file.

Weather--According to Northtown Yard personnel, 15-mph headwinds are not unusual on a normal day. Winter temperatures were the coldest among all the yards studied.

Car rollability observations were made on 734 and 464 cars during the winter and summer periods, respectively. An almost equal number of observations were randomly selected from temperature ranges between -15 and 95 °F. Temperatures were recorded by the PC computer in temperature ranges of 10-degree intervals. Based on these ranges, the average temperatures for the observations were 16 °F in the winter and 77 °F in the summer; thus, the range of temperatures did not overlap in the winter and summer. Table 4-15 indicates the distribution of rolling resistance observations for the temperature ranges.

There was no precipitation during the summer observations, and only 12% of the cars were humped during wet weather in the winter. The wind velocity was substantially higher during the winter at Northtown Yard: The average wind velocity in the winter was 7.8 mph, whereas it was 4.1 mph in the summer. Because wind is a major factor at Northtown Yard, rolling resistance distributions by wind velocity are presented in Table 4-16. The wind seemed to oppose the cars more in the winter than in the summer, but the direction of the wind did vary, as depicted in Figure 4-15.

Table 4-15

DISTRIBUTION OF NORTHTOWN YARD ROLLING RESISTANCE DATA FOR VARIOUS TEMPERATURE RANGES

| Temperature (°F) | Relative Frequency (%) Winter | Summer |
|---|---|---|
| -15 – -5 | 14.4 | 0.0 |
| - 5 – 5 | 17.0 | 0.0 |
| 5 – 15 | 17.0 | 0.0 |
| 15 – 25 | 17.4 | 0.0 |
| 25 – 35 | 17.0 | 0.0 |
| 35 – 45 | 17.0 | 0.0 |
| 45 – 55 | 0.0 | 0.0 |
| 55 – 65 | 0.0 | 17.5 |
| 65 – 75 | 0.0 | 25.9 |
| 75 – 85 | 0.0 | 29.5 |
| 85 – 95 | 0.0 | 27.2 |
| Total | 100.0% | 100.0% |

Car Population--SRI attempted to identify the following parameters for each rolling resistance observation:

Table 4-16

DISTRIBUTION OF NORTHTOWN YARD ROLLING RESISTANCE DATA FOR VARIOUS VELOCITIES OF WIND

| Wind Velocity (ft/sec) | Relative Frequency (%) Winter | Summer |
|---|---|---|
| | 6.5 | 6.7 |
| 1 | 5.7 | 8.0 |
| 3 | 3.7 | 18.8 |
| 4 | 5.9 | 8.2 |
| 6 | 3.5 | 23.3 |
| 7 | 6.4 | 8.6 |
| 9 | 9.0 | 12.1 |
| 10 | 6.3 | 3.2 |
| 12 | 16.6 | 4.7 |
| 13 | 7.5 | 0.9 |
| 15 | 4.4 | 1.3 |
| 16 | 3.0 | 3.4 |
| 18 | 1.9 | 0.0 |
| 19 | 0.4 | 0.0 |
| 21 | 2.5 | 0.0 |
| 22 | 7.2 | 0.9 |
| 23 | 3.5 | 0.0 |
| 25 | 5.2 | 0.0 |
| 26 | 0.1 | 0.0 |
| 28 | 0.7 | 0.0 |
| | 100.0 | 100.0 |

- Car type
- Car weight class
- Car weight
- Truck center length
- Bearing type.

The data on car type, truck center length, and bearing type in the UMLER file matched those recorded for 79% of the car observations. Figures 4-16 and 4-17 indicate that, again, the predominant type of car was the boxcar, which comprised a greater percentage of the winter than the summer population. In addition, a substantial number of cars were special types.

The Northtown Yard PC computer classified cars as light, medium, heavy, or extra heavy according to the following loaded car weights:

- Light, 0 to 35 tons
- Medium, 35 to 60 tons
- Heavy, 60 to 100 tons
- Extra heavy, more than 100 tons.

The distribution of cars by weight class was somewhat different for the two observation periods, as shown in Table 4-17, but the average weight of the cars in summer and winter was about 64 tons. Table 4-18 presents the distribution of loaded weights for the car populations.

The truck center length (TRCNTL) was obtained from the UMLER file for only 35% of the observations. The car wheelbase (IWBASE), however, was recorded for every observation by the Northtown Yard PC computer. When UMLER data were unavailable, SRI estimated the truck center length using calibration equation 4.1, which included the following coefficients estimated by regression:

$$\hat{\alpha} = -1.953$$

$$\hat{\beta} = .96294.$$

Table 4-19 presents the distribution of winter and summer car populations by length. Sixty-one percent of the winter cars had roller bearings, and 23% had plain or journal bearings. Only 49% of the summer cars had roller bearings, with 20% having plain or journal bearings. Data on bearings were unavailable for the remaining cars.

### 4.4.3 Rolling Resistance Information for Design

The preliminary analysis of Northtown Yard data collected in winter revealed that car rolling resistance measurements were 5 to 10 lb/ton higher than expected. Northtown Yard personnel explained that such great rolling resistances are due to high headwinds. Consequently, additional rolling resistance statistics were encoded from the cut statistics that were modified by the yard's PC computer to exclude the wind effect.

Figures 4-18 and 4-19 are histograms of unmodified car rolling resistances calculated in winter and summer by the PC computer. Although these values are significantly higher than those for other yards, the variance of the summer rolling resistance values is somewhat smaller on measurement section 1 than on measurement section 2. This is verified by examining the standard deviation and the 95% confidence interval values for each measurement section in Tables 4-20 and 4-21.

Figures 4-20 and 4-21 are histograms of winter and summer car rolling resistances modified by the Northtown Yard PC computer to take into account the effect of wind. The relationships the PC computer used to extract the wind effect from the unmodified rolling resistances were:

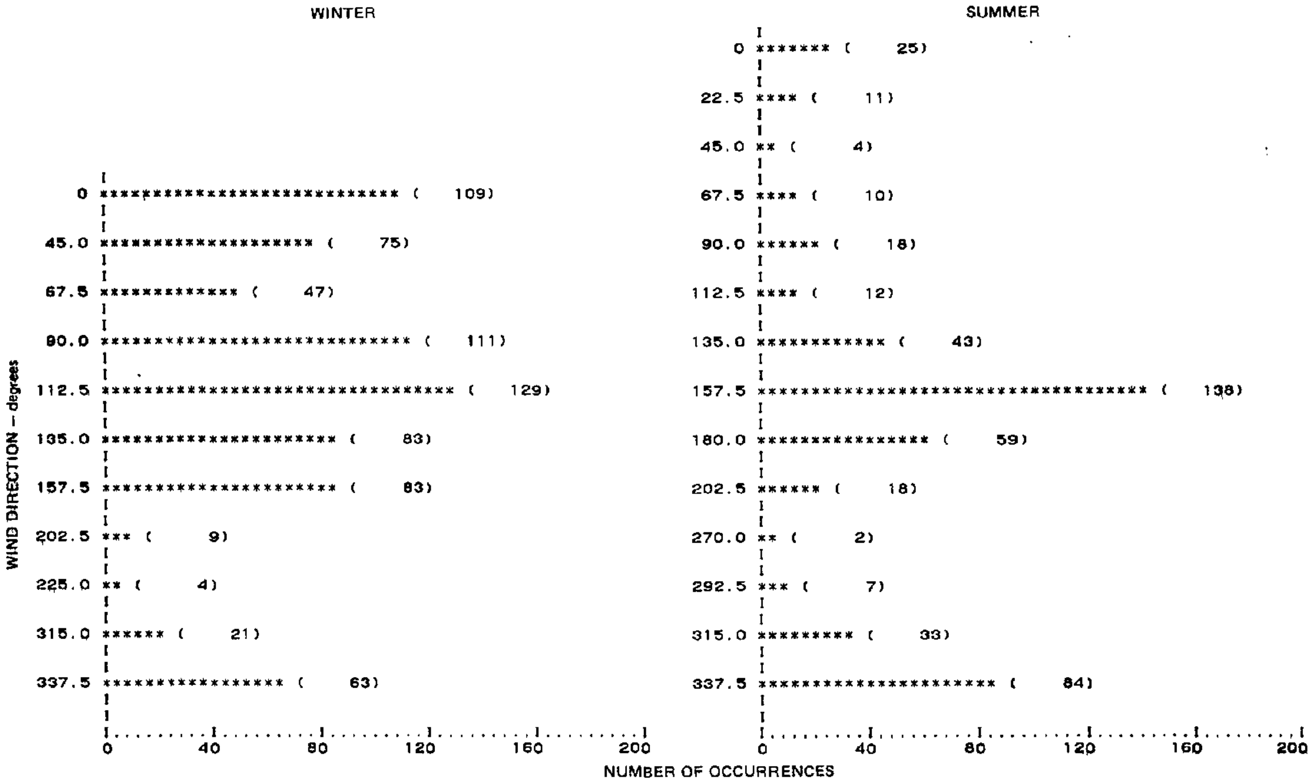



FIGURE 4-15 DISTRIBUTION OF NORTHTOWN YARD ROLLING RESISTANCE DATA FOR VARIOUS WIND DIRECTIONS

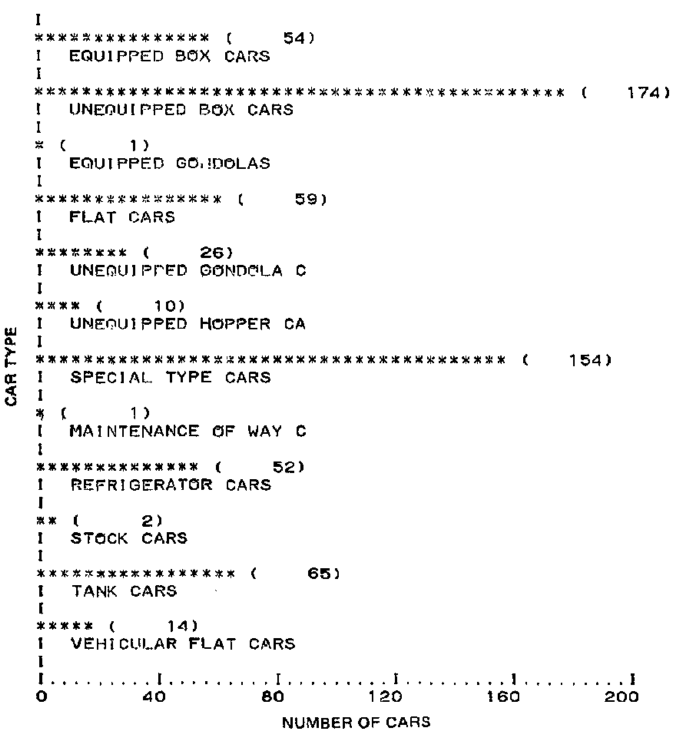



FIGURE 4-16 DISTRIBUTION OF NORTHTOWN YARD CARS BY UMLER CAR TYPE DURING THE WINTER OBSERVATIONS

$$RRMOD = RR + WINDT$$

$$WINDT = \left[\frac{V_h^2 * BHAREA}{W}\right] * \left[\pm 1 + \left|\frac{SKIN - V_h}{1.46}\right|\right]$$

$$V_h = V_{car} \pm (\cos\theta)(V_w) \quad ,$$

where

RRMOD = rolling resistance modified (i.e., effect of headwind removed)

RR = raw or unmodified rolling resistance, directly as measured

WINDT = correction to be applied to rolling resistance due to wind

$V_h$ = relative wind speed opposing car

BHAREA = car bulkhead area

W = car weight

SKIN = skin friction effect

$V_{car}$ = car velocity

$V_w$ = wind velocity

$\Theta$ = angle between car direction and wind direction.

Table 4-22 presents statistics for the modified car rolling resistance values. A comparison of

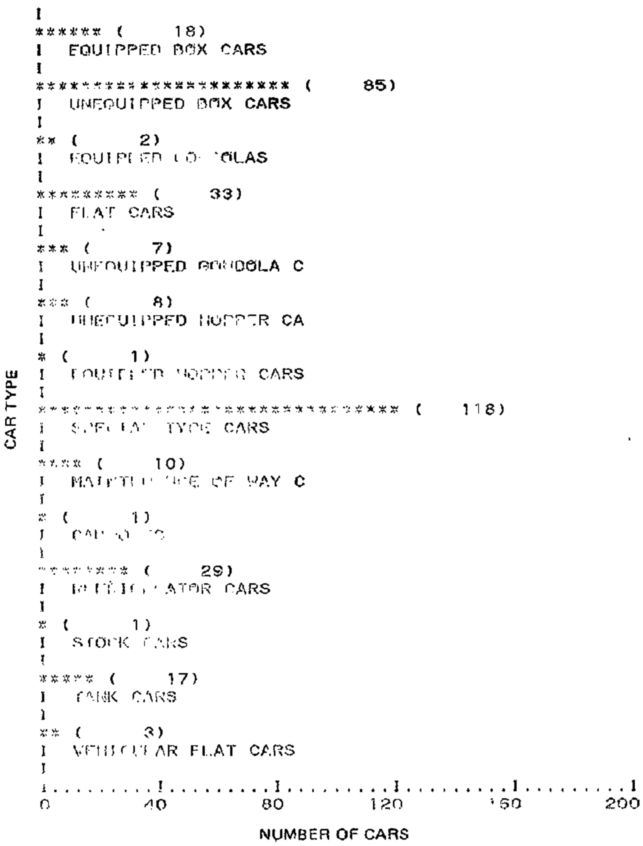



FIGURE 4-17 DISTRIBUTION OF NORTHTOWN YARD CARS BY UMLER CAR TYPE DURING THE SUMMER OBSERVATIONS

the modified and unmodified rolling resistance values reveals a slight reduction in the mean car rolling resistance after modification in measurement section 1 (i.e., 1.5 lb/ton in the winter and 1.1 lb/ton in the summer) and a greater reduction in mean car rolling resistance after modification in measurement section 2 (i.e., 2.7 lb/ton in the winter and 1.9 lb/ton in the summer). Even after modification, however, the car rolling resistance values remain 5 to 10 lb/ton higher than those recorded at the other yards.

Rolling resistance at Northtown Yard is consistently harder than at other yards. At this time, this discrepancy cannot be explained. It may be due to severe headwinds, track conditions, or a bias in the measurement sections.

## 4.5 ARGENTINE YARD

### 4.5.1 Physical Description

Argentine is a Santa Fe Railway yard located in Kansas City. It was constructed in 1969. As Figure 4-22 shows, Argentine Yard has one master retarder and six group retarders. Railcars are humped into 48 classification tracks (8 tracks per group). A flange oiler is located at the crest. The signaling and PC systems were installed by WABCO.

Velocity measurements were obtained on cards from the PC computer for the following measurement sections:

- From the master retarder to the group retarder (measurement section 2).
- From the group retarder to the tangent point (measurement section 3).

Rolling resistances were calculated for measurement sections 2 and 3 (MS2 and MS3 in Figure 4-22). In the calculation, PC computer-recorded velocities and lengths, the grades of the measurement sections, and a rate of acceleration were used. Associated parameters that might influence rolling resistance were extracted for the two measurement sections.

Measurement section 2 consists of 277 to 354 feet of straight and curved track between the exit of the master retarder (MXWD) and the wheel detectors located approximately 100 feet from the group retarder. The measurement section grade and the total lengths differ for each group as follows:

Table 4-17

DISTRIBUTION OF NORTHTOWN YARD CARS BY WEIGHT CLASSIFICATION
(Percent)

| | Winter | | Summer | |
|---|---|---|---|---|
| Weight Class | Relative Frequency | Cumulative Frequency | Relative Frequency | Cumulative Frequency |
| Light | 44.1% | 44.1% | 40.9% | 40.9% |
| Medium | 19.8 | 63.9 | 13.6 | 54.5 |
| Heavy | 17.8 | 81.7 | 26.7 | 81.3 |
| Extra heavy | 18.3 | 100.0 | 18.8 | 100.0 |

Table 4-18

DISTRIBUTION OF NORTHTOWN YARD CARS BY WEIGHT
(Percent)

| Car Weight (tons) | Winter Relative Frequency | Winter Cumulative Frequency | Summer Relative Frequency | Summer Cumulative Frequency |
|---|---|---|---|---|
| 20 | 4.4% | 4.4% | 2.8% | 2.8% |
| 30 | 30.9 | 35.3 | 30.2 | 33.0 |
| 40 | 11.7 | 46.9 | 9.6 | 42.6 |
| 50 | 4.9 | 51.9 | 6.5 | 49.1 |
| 60 | 4.7 | 56.5 | 4.1 | 53.5 |
| 70 | 4.8 | 61.3 | 6.7 | 60.0 |
| 80 | 9.9 | 71.2 | 10.2 | 70.2 |
| 90 | 7.7 | 78.9 | 6.7 | 77.0 |
| 100 | 4.0 | 82.9 | 6.1 | 83.0 |
| 110 | 4.0 | 86.8 | 5.9 | 88.9 |
| 120 | 4.1 | 90.9 | 6.3 | 95.2 |
| 130 | 8.4 | 99.3 | 4.6 | 99.8 |
| 140 | 0.5 | 99.9 | 0.2 | 100.0 |
| 150 | 0.1 | 100.0 | 0.0 | 100.0 |

Table 4-19

DISTRIBUTION OF NORTHTOWN YARD CARS BY TRUCK CENTER LENGTH
(Percent)

| Length (feet) | Winter Relative Frequency | Winter Cumulative Frequency | Summer Relative Frequency | Summer Cumulative Frequency |
|---|---|---|---|---|
| 20 | 0.4% | 0.4% | 0.9% | 0.9% |
| 25 | 4.2 | 4.6 | 6.7 | 7.5 |
| 30 | 14.7 | 19.3 | 14.0 | 21.6 |
| 35 | 8.9 | 28.2 | 8.0 | 29.5 |
| 40 | 31.1 | 59.3 | 22.4 | 51.9 |
| 45 | 29.8 | 89.1 | 33.8 | 85.8 |
| 50 | 5.9 | 95.0 | 8.0 | 93.8 |
| 55 | 1.5 | 96.5 | 0.6 | 94.4 |
| 60 | 0.8 | 97.3 | 1.9 | 96.3 |
| 65 | 2.6 | 99.9 | 3.7 | 100.0 |
| 70 | 0.1 | 100.0 | 0.0 | 100.0 |

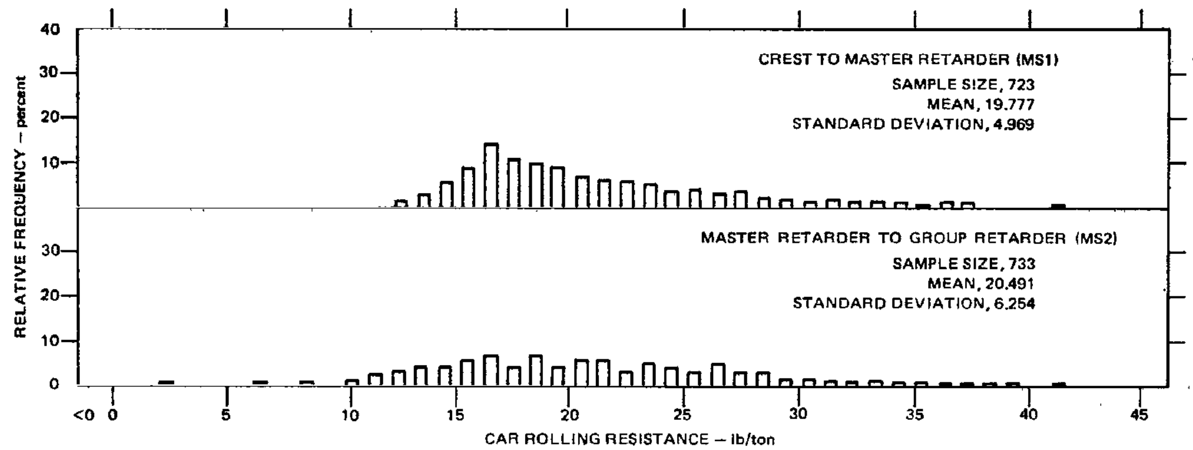



FIGURE 4-18 DISTRIBUTION OF NORTHTOWN YARD CAR ROLLING RESISTANCES BY MEASUREMENT SECTION DURING THE WINTER OBSERVATIONS

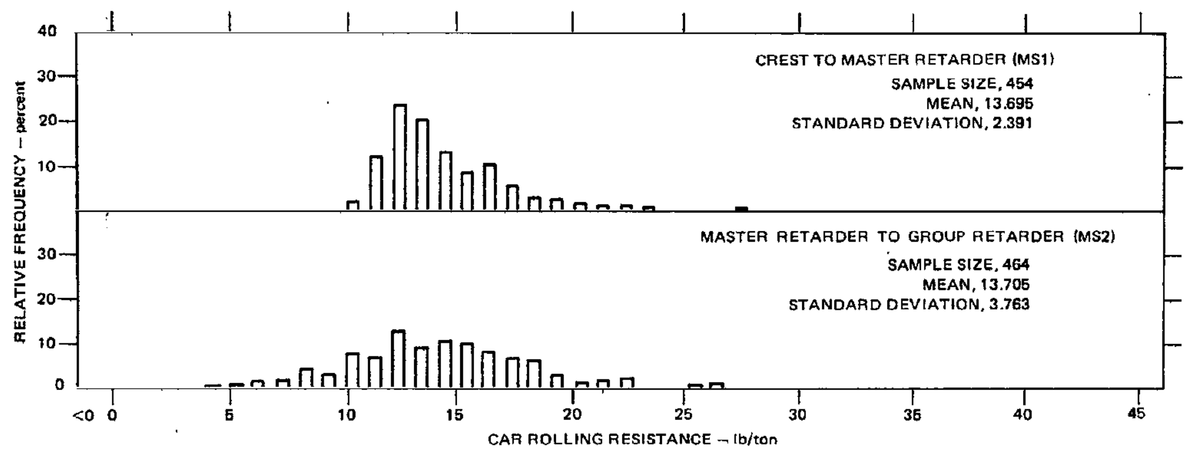



FIGURE 4-19 DISTRIBUTION OF NORTHTOWN YARD CAR ROLLING RESISTANCES BY MEASUREMENT SECTION DURING THE SUMMER OBSERVATIONS

Table 4-20

ROLLING RESISTANCE AND VELOCITY STATISTICS AT NORTHTOWN YARD MEASUREMENT SECTIONS DURING THE WINTER OBSERVATIONS

| Measurement Section | Rolling Resistance (lb/ton) | | | | | | Average Velocity (ft/sec) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD* | SE* | 95% CI | Minimum | Maximum | Mean | SD* | SE* | 95% CI | Minimum | Maximum |
| Crest to master retarder (MS1) | 19.777 | 4.969 | .185 | 19.415-20.140 | 12 | 41 | 16.888 | .985 | .037 | 16.816-16.960 | 13 | 18 |
| Master retarder to group retarder (MS2) | 20.491 | 6.254 | .231 | 20.037-20.944 | 2 | 41 | 19.841 | 1.647 | .061 | 19.721-19.960 | 11 | 25 |

*SD, standard deviation.
SE, standard error of mean.
CI, confidence interval for mean.

Table 4-21

ROLLING RESISTANCE AND VELOCITY STATISTICS AT NORTHTOWN YARD MEASUREMENT SECTIONS DURING THE SUMMER OBSERVATIONS

| Measurement Section | Rolling Resistance (lb/ton) | | | | | | Average Velocity (ft/sec) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD* | SE* | 95% CI | Minimum | Maximum | Mean | SD* | SE* | 95% CI | Minimum | Maximum |
| Crest to master retarder (MS1) | 13.695 | 2.392 | .112 | 13.474–13.915 | 10 | 27 | 17.943 | .506 | .024 | 17.896–17.990 | 15 | 19 |
| Master retarder to group retarder (MS2) | 13.705 | 3.763 | .175 | 13.361–14.048 | 4 | 26 | 19.345 | 1.497 | .069 | 19.208–19.481 | 15 | 23 |

*SD, standard deviation.
SE, standard error of mean.
CI, confidence interval for mean.

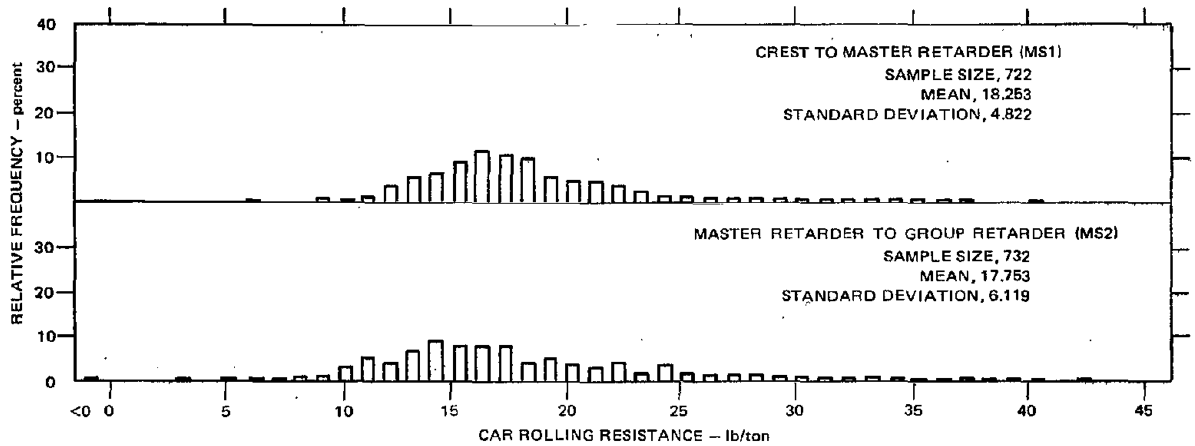



FIGURE 4-20 DISTRIBUTION OF NORTHTOWN YARD MODIFIED CAR ROLLING RESISTANCES (EFFECT OF HEADWIND REMOVED) BY MEASUREMENT SECTIONS DURING THE WINTER OBSERVATIONS

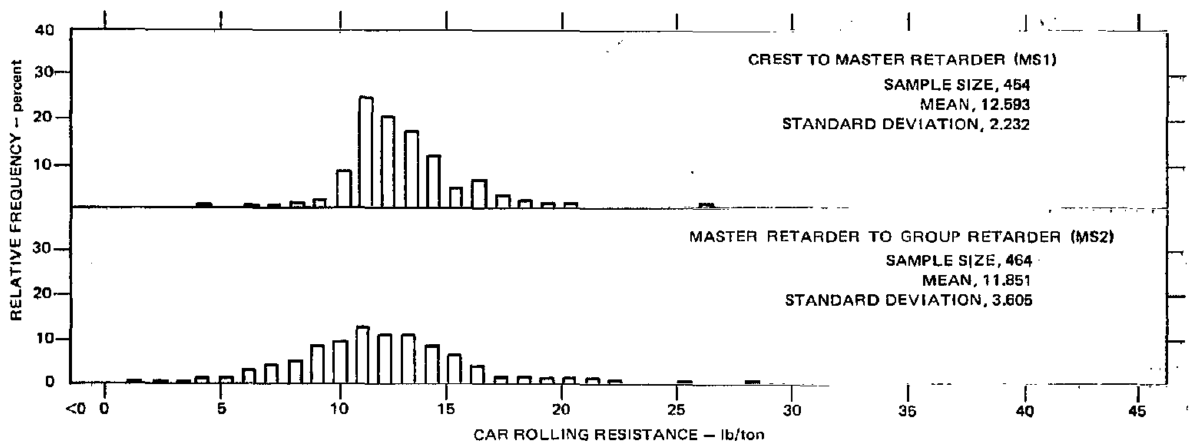



FIGURE 4-21 DISTRIBUTION OF NORTHTOWN YARD MODIFIED CAR ROLLING RESISTANCES (EFFECT OF HEADWIND REMOVED) BY MEASUREMENT SECTIONS DURING THE SUMMER OBSERVATIONS

Table 4-22

MODIFIED ROLLING RESISTANCE (EFFECT OF HEADWIND REMOVED) STATISTICS AT NORTHTOWN YARD MEASUREMENT SECTIONS
(Pounds per Ton)

| Measurement Section | Winter | | | | | | Summer | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD* | SE* | 95% CI | Minimum | Maximum | Mean | SD* | SE* | 95% CI | Minimum | Maximum |
| Crest to master retarder (MS1) | 18.253 | 4.822 | .179 | 17.901-18.605 | 6 | 40 | 12.593 | 2.232 | .105 | 12.387-12.799 | 4 | 26 |
| Master retarder to group retarder (MS2) | 17.753 | 6.119 | .226 | 17.309-18.197 | -3 | 42 | 11.851 | 3.605 | .167 | 11.523-12.180 | 1 | 28 |

*SD, standard deviation.
SE, standard error of mean.
CI, confidence interval for mean.

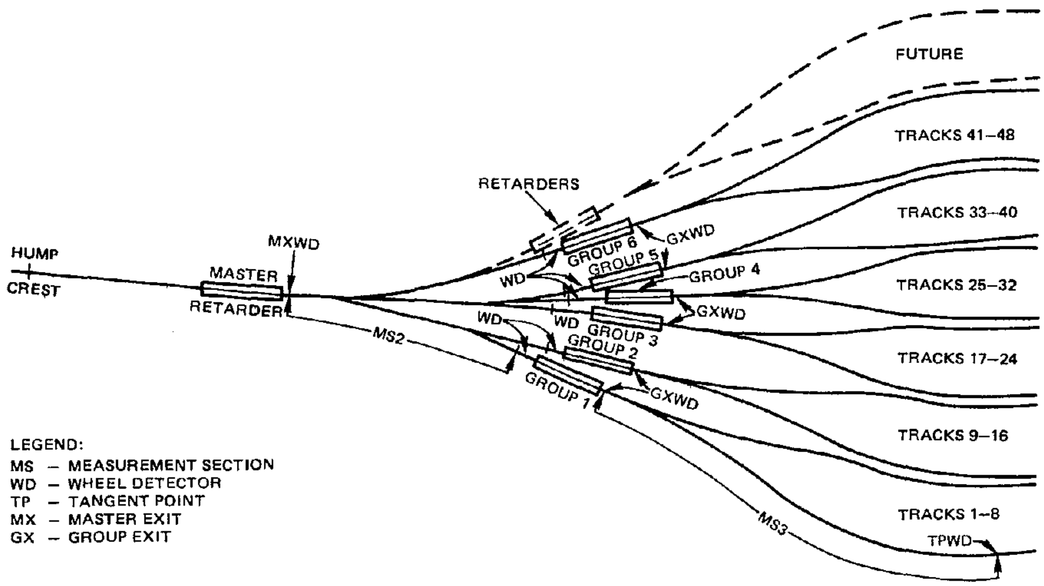



FIGURE 4-22 ARGENTINE YARD CONFIGURATION

| Group Retarder Number | Grade (%) | Length (feet) |
|---|---|---|
| 1 | 1.11 | 277 |
| 2 | 1.11 | 294 |
| 3 | 1.06 | 342 |
| 4 | 1.19 | 354 |
| 5 | 1.01 | 333 |
| 6 | 1.08 | 310 |

Measurement section 3 includes track from the exit of the group retarder (GXWD) to the tangent point wheel detector (TPWD) located on the classification track. The lengths of the measurement sections vary between 523 and 666 feet. Each track section includes some curvature, an oiler at the exit of the group retarder, and an average grade ranging from 0.08 to 0.24%.

### 4.5.2 Important Rolling Resistance Factors During the Periods Analyzed

Classification yard calibration information for 3,272 observations was obtained for the time periods April 2 through 14, 1980 (winter), and June 29 through July 13, 1980 (summer). The car rollability observations obtained for these two 2-week periods numbered 1,338 and 1,307 cars, respectively.

The data were on only single-car cuts. An Argentine Yard data file was created containing 2,645 observations that had UMLER matches. Statistics and descriptive information are presented here for the winter and summer UMLER matches.

Weather--During the observation periods, recorded precipitation occurred on 9.5% of the winter observations and none was recorded during the summer observations.* Wind velocity and direction measurements were unavailable for Argentine Yard.

The winter temperatures at Argentine Yard were moderate, but some very high temperatures were reached in the summer (observations were recorded during 110 °F temperatures). The average temperatures for the observations were 53 °F and 93 °F in the winter and summer, respectively. In view of the short sample data collection periods, however, the distribution of temperatures may not be representative of the 1980 winter and summer months in the Kansas City area. Table 4-23 shows the distribution of rolling resistance observations for various temperatures.

Car Population--The following parameters were identified for each rolling resistance observation so that the dependence of rolling resistance on certain aspects of the car itself could be quantified:

- Car type
- Car weight class
- Car weight
- Truck center length
- Bearing type.

Table 4-23

DISTRIBUTION OF ARGENTINE YARD ROLLING RESISTANCE DATA FOR VARIOUS TEMPERATURES

| Temperature (°F) | Relative Frequency (%) Winter | Relative Frequency (%) Summer |
|---|---|---|
| 30 | 5.5 | 0.0 |
| 40 | 17.0 | 0.0 |
| 50 | 21.3 | 0.0 |
| 60 | 47.5 | 0.0 |
| 70 | 8.6 | 0.0 |
| 80 | 0.0 | 19.4 |
| 90 | 0.0 | 38.9 |
| 100 | 0.0 | 16.4 |
| 110 | 0.0 | 25.2 |
| Total | 100.0% | 100.0% |

Car type, truck center length, and bearing type were obtained from the UMLER file. As Figures 4-23 and 4-24 demonstrate, the car population at Argentine Yard was like that of the other yards, the most predominant type of car being the boxcar; it comprised approximately 40% of the car population.

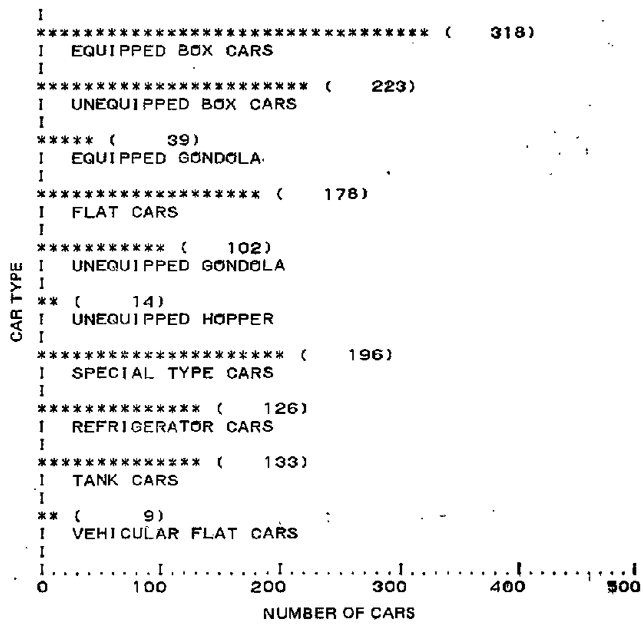



FIGURE 4-23 DISTRIBUTION OF ARGENTINE YARD CARS BY UMLER CAR TYPE DURING THE WINTER OBSERVATIONS

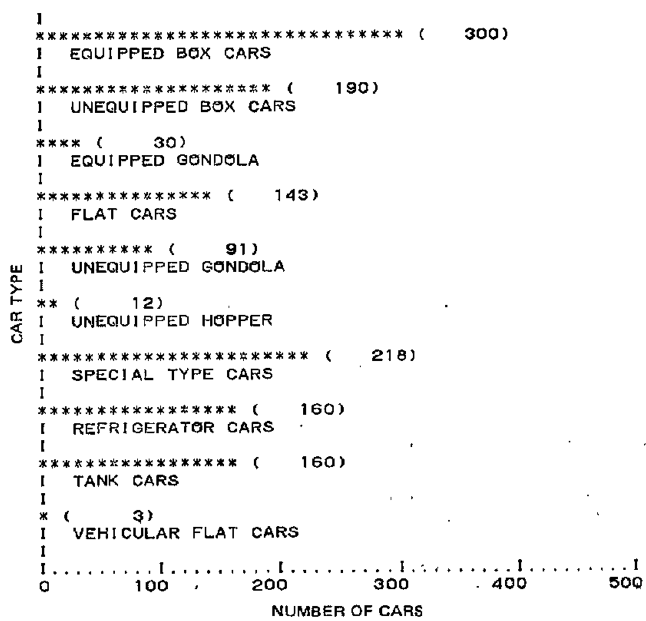



FIGURE 4-24 DISTRIBUTION OF ARGENTINE YARD CARS BY UMLER CAR TYPE DURING THE SUMMER OBSERVATIONS

*The precipitation and supplemental temperature information were obtained from "Local Climatological Data" recorded at the National Weather Service Office at the Kansas City International Airport; these data were unavailable from the cards provided by the PC computer.

The yard PC computer classified every car as light, medium, heavy, or extra heavy according to the following loaded weights:

- Light, 0 to 30 tons
- Medium, 30 to 50 tons
- Heavy, 50 to 100 tons
- Extra heavy, more than 100 tons.

Tables 4-24 and 4-25 indicate that the two car populations differed little in distribution by weight class and loaded weight. Compared with the other yards, Argentine Yard had relatively few light (or empty) cars. The average car weight for both populations was 59 tons.

The truck center length (TRCNTL) parameter was missing for 46% of the cars. The PC computer had recorded the car length (first axle to last) for all observations. Therefore, SRI could estimate truck center length using calibration equation 4.1 and the following coefficients estimated by regression:

$$\hat{\alpha} = -5.389$$

$$\hat{\beta} = 1.020.$$

Table 4-24

DISTRIBUTION OF ARGENTINE YARD CARS BY WEIGHT CLASSIFICATION
(Percent)

| | Winter | | Summer | |
|---|---|---|---|---|
| Weight Class | Relative Frequency | Cumulative Frequency | Relative Frequency | Cumulative Frequency |
| Light | 15.8% | 15.8% | 13.9% | 13.9% |
| Medium | 40.1 | 55.9 | 45.1 | 59.0 |
| Heavy | 28.6 | 84.5 | 23.9 | 82.9 |
| Extra heavy | 15.5 | 100.0 | 17.1 | 100.0 |

Table 4-25

DISTRIBUTION OF ARGENTINE YARD CARS BY WEIGHT
(Percent)

| | Winter | | Summer | |
|---|---|---|---|---|
| Car Weight (tons) | Relative Frequency | Cumulative Frequency | Relative Frequency | Cumulative Frequency |
| 20 | 3.9% | 3.9% | 3.3% | 3.3% |
| 30 | 27.9 | 31.8 | 28.8 | 32.1 |
| 40 | 20.4 | 52.2 | 21.8 | 53.9 |
| 50 | 7.3 | 59.5 | 7.5 | 61.4 |
| 60 | 4.5 | 64.1 | 3.6 | 65.0 |
| 70 | 4.0 | 68.0 | 3.2 | 68.2 |
| 80 | 5.9 | 73.9 | 5.2 | 73.4 |
| 90 | 7.0 | 81.0 | 7.7 | 81.1 |
| 100 | 6.9 | 87.9 | 4.6 | 85.8 |
| 110 | 3.3 | 91.2 | 2.8 | 88.5 |
| 120 | 2.5 | 93.7 | 3.2 | 91.8 |
| 130 | 6.2 | 99.9 | 7.7 | 99.5 |
| 140 | 0.1 | 99.9 | 0.5 | 100.0 |

The distribution of winter and summer car populations by length is given in Table 4-26. Most of the cars had roller bearings (77% of the winter population and 81% of the summer population); the remaining cars had plain bearings.

### 4.5.3 Rolling Resistance Information for Design

Figures 4-25 and 4-26 are histograms of winter and summer rolling resistance for measurement sections 2 and 3.

Descriptive statistics for the rolling resistances are presented in Table 4-27 for the winter and summer populations. Data were insufficient for accurate computation of the average velocities within the measurement sections.

Similar to the other rolling resistance histograms, Figures 4-25 and 4-26 show a greater variance and higher rolling resistance values on measurement section 2 than on measurement sec-

Table 4-26

DISTRIBUTION OF ARGENTINE YARD CARS BY TRUCK CENTER LENGTH

| Length (feet) | Winter | | Summer | |
|---|---|---|---|---|
| | Relative Frequency | Cumulative Frequency | Relative Frequency | Cumulative Frequency |
| 15 | 0.2% | 0.2% | 0.0% | 0.0% |
| 20 | 0.2 | 0.5 | 0.4 | 0.4 |
| 25 | 2.8 | 3.3 | 2.9 | 3.4 |
| 30 | 10.3 | 13.6 | 9.1 | 12.5 |
| 35 | 2.8 | 16.4 | 1.8 | 14.3 |
| 40 | 46.3 | 62.7 | 49.9 | 64.2 |
| 45 | 21.1 | 83.9 | 21.6 | 85.8 |
| 50 | 2.7 | 86.5 | 2.4 | 88.3 |
| 55 | 3.5 | 90.0 | 4.8 | 93.0 |
| 60 | 2.2 | 92.3 | 3.1 | 96.1 |
| 65 | 7.6 | 99.9 | 3.9 | 100.0 |
| 70 | 0.0 | 99.9 | 0.0 | 100.0 |
| 75 | 0.1 | 100.0 | 0.0 | 100.0 |

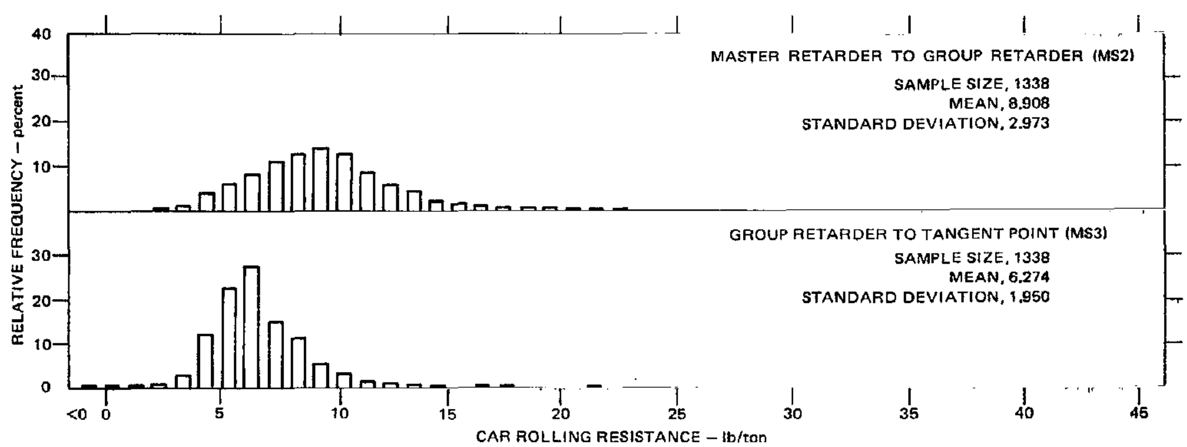



FIGURE 4-25 DISTRIBUTION OF ARGENTINE YARD CAR ROLLING RESISTANCES BY MEASUREMENT SECTION DURING THE WINTER OBSERVATIONS

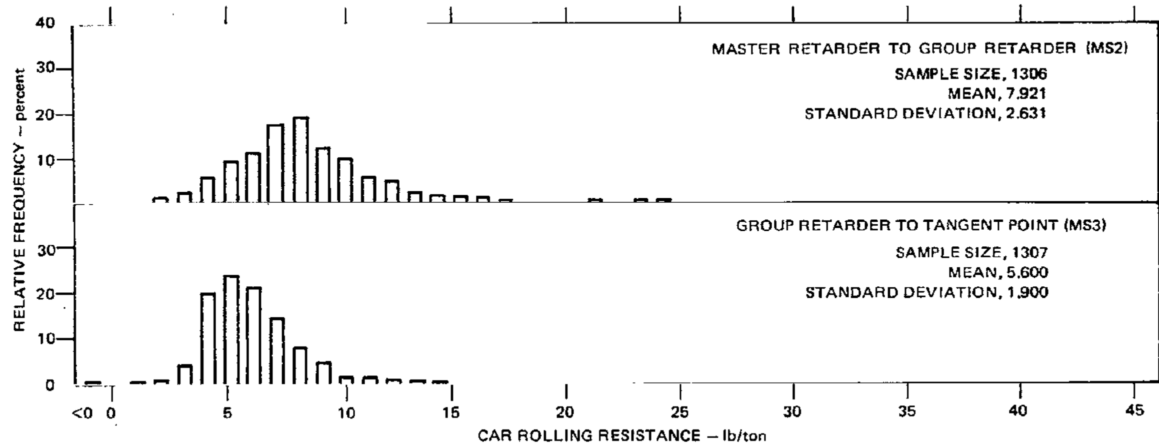



FIGURE 4-26 DISTRIBUTION OF ARGENTINE YARD CAR ROLLING RESISTANCES BY MEASUREMENT SECTION DURING THE SUMMER OBSERVATIONS

Table 4-27

ROLLING RESISTANCE STATISTICS AT ARGENTINE YARD MEASUREMENT SECTIONS
(Feet per Second)

| Measurement Section | Winter Mean | Winter SD* | Winter SE* | Winter 95% CI | Winter Minimum | Winter Maximum | Summer Mean | Summer SD* | Summer SE* | Summer 95% CI | Summer Minimum | Summer Maximum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Master retarder to group retarder (MS2) | 8.908 | 2.973 | .081 | 8.748–9.067 | 2 | 22 | 7.921 | 2.631 | .073 | 7.778–8.064 | 2 | 24 |
| Group retarder to tangent point (MS3) | 6.274 | 1.950 | .053 | 6.170–6.379 | -2 | 21 | 5.600 | 1.900 | .053 | 5.497–5.703 | -1 | 33 |

*SD, standard deviation.
SE, standard error of mean.
CI, confidence interval for mean.

tion 3. The histograms also show a slightly larger variance in the rolling resistances for the winter than for the summer population. This is verified by examining the standard deviation (SD) and the 95% confidence intervals for each population in Table 4-27.

## 4.6 LINWOOD YARD

### 4.6.1 Physical Description

Linwood (or Spencer) Yard is a Southern Railway hump yard located at Linwood, North Carolina. As Figure 4-27 indicates, Linwood Yard has one master retarder and eight group retarders. Railcars are humped into a northeastern direction onto eight groups of classification tracks, usually at a rate of 2.25 to 2.5 mph. The signaling and PC systems were installed by GRS.

Velocity measurements are recorded by the PC computer at two measurement sections:

- From the hump crest to the master retarder (measurement section 1).
- From the master retarder to the group retarder (measurement section 2).

Linwood Yard data were obtained on computer printout and thus had to be manually processed into machine-readable form. SRI extracted pertinent data for a small sample of cars from hardcopy cut statistics; the sample comprised every tenth car of arriving trains, providing it was a single-car cut with rolling resistance data.

Measurement section 1 consists of approximately 60 feet of straight track between the first and third wheel detectors before the master retarder.The orientation of the measurement section is 45 degrees (measured clockwise from north) on a 3.22% grade. The midpoint of the section is 229 feet from the crest.

The tracks between the master retarder and group retarders contain combination No. 10 and No. 8 turnout lap switches. However, measurement section 2 consists of approximately 80 feet of straight track between the first and third wheel detectors before each group retarder. The measurement sections are all on a 0.8% grade.

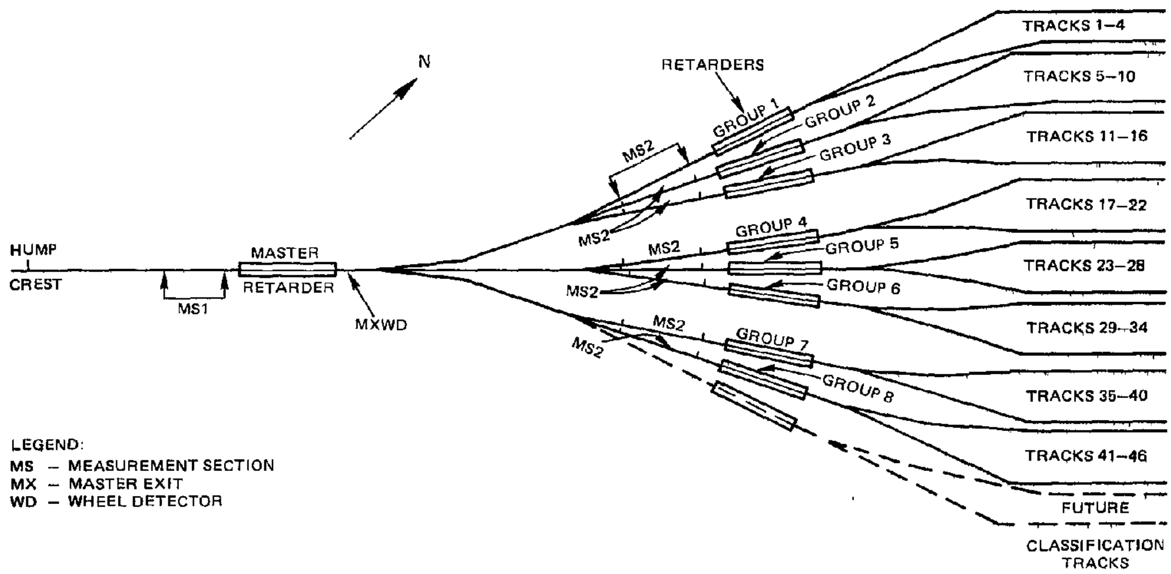



FIGURE 4-27 LINWOOD YARD CONFIGURATION

### 4.6.2 Important Rolling Resistance Factors During the Periods Analyzed

Hard-copy listings of cut statistics were obtained for two time periods: November 15-21, 1980 (Period 1), and February 11-15, 1981 (Period 2).

A Linwood Yard data file was created containing 1,048 and 744 cut statistics from Periods 1 and 2, respectively. The data included single-car cuts with UMLER matches and single-car cuts with no UMLER match.

Statistics and descriptive information are presented here for the sampled cut statistics. Period 1 observations are presented for cars successfully matched to the UMLER car file. The UMLER file was unavailable for processing the second sample of observations. Consequently, those observations are presented regardless of UMLER match.

Weather--At Linwood Yard, car rollability observations with UMLER matches for the Period 1 numbered 804 cars.

During Periods 1 and 2, there was recorded precipitation for 30% and 6% of the observations, respectively. The wind velocity averaged 7 ft/sec in Period 1 and 10 ft/sec in Period 2. The wind direction was recorded in 16 (22.5 degree) categories (i.e., N, NNE, ENE, and so on). During both periods, the general recorded directions of the wind were South and West, as depicted in Figure 4-28.

The PC computer recorded temperatures using six temperature range codes. Based on these ranges, the average temperatures for the observations were estimated at 60 $^{o}$F and 56 $^{o}$F in Periods 1 and 2, respectively. In view of the brief data collection periods and the wide temperature categories, the distribution of temperatures may not be typical of the weather in this part of the United States during the winter months. Table 4-28 presents the distribution of rolling resistance observations for the six temperature ranges.

Table 4-28

DISTRIBUTION OF LINWOOD ROLLING RESISTANCE DATA FOR VARIOUS TEMPERATURE RANGES

| Temperature ($^{o}$F) | Relative Frequency (%) Period 1 | Period 2 |
|---|---|---|
| Less than 0 | 0.0 | 0.0 |
| 0 - 20 | 0.0 | 0.0 |
| 20 - 40 | 0.0 | 14.0 |
| 40 - 60 | 35.2 | 51.9 |
| 60 - 80 | 52.8 | 25.1 |
| Greater than 80 | 12.0 | 9.0 |
| Total | 100.0% | 100.0% |

Car Population--The following parameters were identified for each rolling resistance observation for quantification of the dependence of rolling resistance on certain aspects of the car itself:

- Car type
- Car weight class
- Car weight
- Truck center length
- Bearing type.

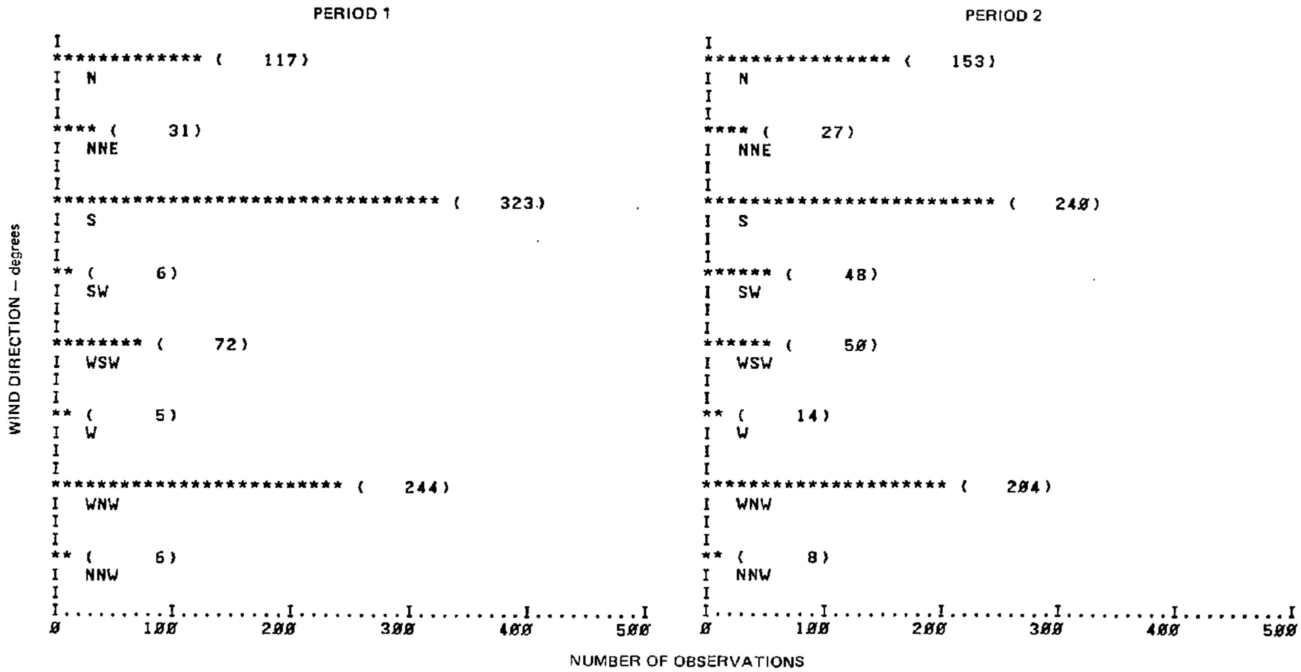



FIGURE 4-28 DISTRIBUTION OF LINWOOD YARD ROLLING RESISTANCE DATA FOR VARIOUS WIND DIRECTIONS

The car type, truck center length, and bearing type were available for Period 1 observations only.

Figure 4-29 indicates the various car types in the Linwood Yard population during Period 1. Again, the most predominant type of car was the boxcar, which comprised 40% of the population during that period.

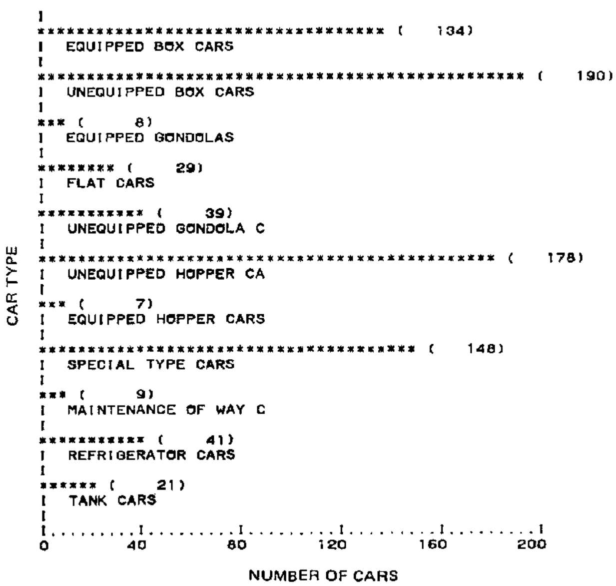



FIGURE 4-29 DISTRIBUTION OF LINWOOD YARD CARS BY UMLER CAR TYPE (Period 1 Observations)

The Linwood Yard PC computer classified every car as light, medium, heavy, or extra heavy according to the following loaded car weights:

- Light car, 0 – 35 tons
- Medium car, 35 – 60 tons
- Heavy car, 60 – 100 tons
- Extra heavy car, more than 100 tons.

Table 4-29 shows the distribution of cars by weight class for the two populations, and Table 4-30 distributes these cars by loaded weight. The average weights of cars in the two car populations were 65 tons and 60 tons.

The truck center length was missing for 18% of the UMLER matches. The cut wheelbase, used to estimate the missing truck center length for the other yards, was not obtained for Linwood Yard observations. Consequently, the distribution of the 657 Linwood Yard cars of known truck center length is given in Table 4-31. Seventy-seven percent of the car population during Period 1 had roller bearings, and 23% had plain or journal bearings.

4.6.3 Rolling Resistance Information for Design

Figures 4-30 and 4-31 are histograms of Linwood

Table 4-29

DISTRIBUTION OF LINWOOD YARD CARS BY WEIGHT CLASSIFICATION
(Percent)

| Weight Class | Period 1 Relative Frequency | Period 1 Cumulative Frequency | Period 2 Relative Frequency | Period 2 Cumulative Frequency |
|---|---|---|---|---|
| Light | 26.9% | 26.9% | 14.7% | 14.7% |
| Medium | 29.5 | 56.3 | 45.7 | 60.3 |
| Heavy | 19.8 | 76.1 | 21.4 | 81.7 |
| Extra heavy | 23.9 | 100.0 | 18.3 | 100.0 |

Table 4-30

DISTRIBUTION OF LINWOOD YARD CARS BY WEIGHT
(Percent)

| Car Weight (tons) | Period 1 Relative Frequency | Period 1 Cumulative Frequency | Period 2 Relative Frequency | Period 2 Cumulative Frequency |
|---|---|---|---|---|
| 20 | 3.9% | 3.9% | 3.6% | 3.6% |
| 30 | 34.2 | 38.1 | 37.1 | 40.8 |
| 40 | 10.5 | 48.6 | 13.6 | 54.4 |
| 50 | 4.2 | 52.7 | 4.3 | 58.7 |
| 60 | 4.9 | 57.7 | 4.6 | 63.3 |
| 70 | 3.5 | 61.2 | 3.8 | 67.1 |
| 80 | 5.1 | 66.2 | 3.5 | 70.6 |
| 90 | 6.4 | 72.6 | 6.6 | 77.2 |
| 100 | 7.1 | 79.7 | 5.3 | 82.5 |
| 110 | 5.5 | 85.2 | 5.1 | 87.6 |
| 120 | 6.4 | 91.6 | 4.3 | 91.9 |
| 130 | 7.4 | 99.0 | 7.2 | 99.1 |
| 140 | 0.6 | 99.6 | 0.9 | 100.0 |
| 160 | 0.1 | 99.7 | 0.0 | 100.0 |
| 170 | 0.1 | 99.9 | 0.0 | 100.0 |
| 190 | 0.1 | 100.0 | 0.0 | 100.0 |

Yard car rolling resistances for the two measurement sections.

Tables 4-32 and 4-33 present the descriptive statistics for the rolling resistances and average velocities at each of the two measurement sections for the two populations.

Unlike the other rolling resistance histograms, Figures 4-30 and 4-31 show slightly higher rolling resistance values on measurement section 1 than on measurement section 2. A comparison of average car velocities for the two measurement sections at Linwood Yard with those at other yards, however, reveals a similar increase in car speed from measurement section 1 to measurement section 2.

Table 4-31

DISTRIBUTION OF LINWOOD YARD CARS
BY TRUCK CENTER LENGTH

Period 1
(Percent)

| Length (feet) | Relative Frequency | Cumulative Frequency |
|---|---|---|
| 25 | 4.7% | 4.7% |
| 30 | 13.1 | 17.8 |
| 35 | 9.4 | 27.2 |
| 40 | 45.8 | 73.1 |
| 45 | 18.6 | 91.6 |
| 50 | 2.1 | 93.8 |
| 55 | 2.3 | 96.0 |
| 60 | 2.0 | 98.0 |
| 65 | 1.4 | 99.4 |
| 75 | 0.6 | 100.0 |

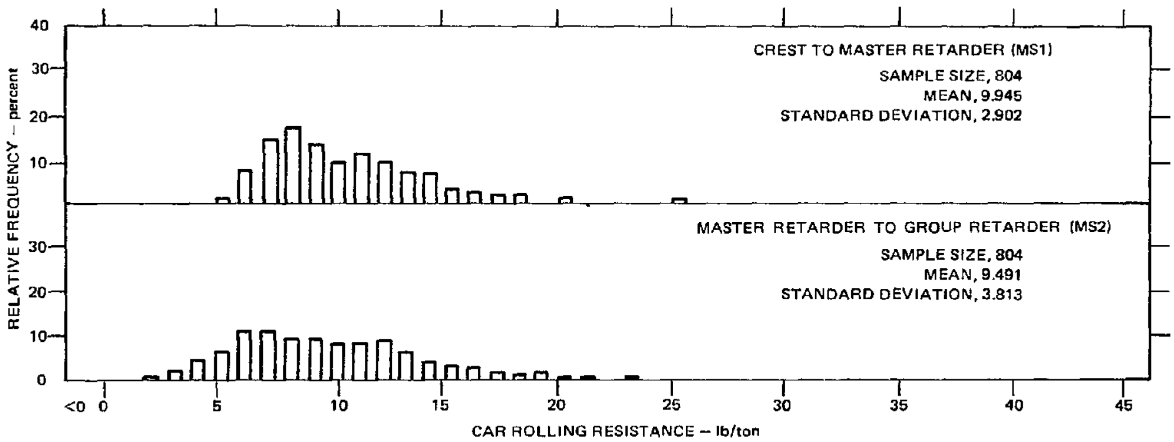



FIGURE 4-30 DISTRIBUTION OF LINWOOD YARD CAR ROLLING RESISTANCE BY MEASUREMENT SECTION DURING PERIOD 1 OBSERVATIONS

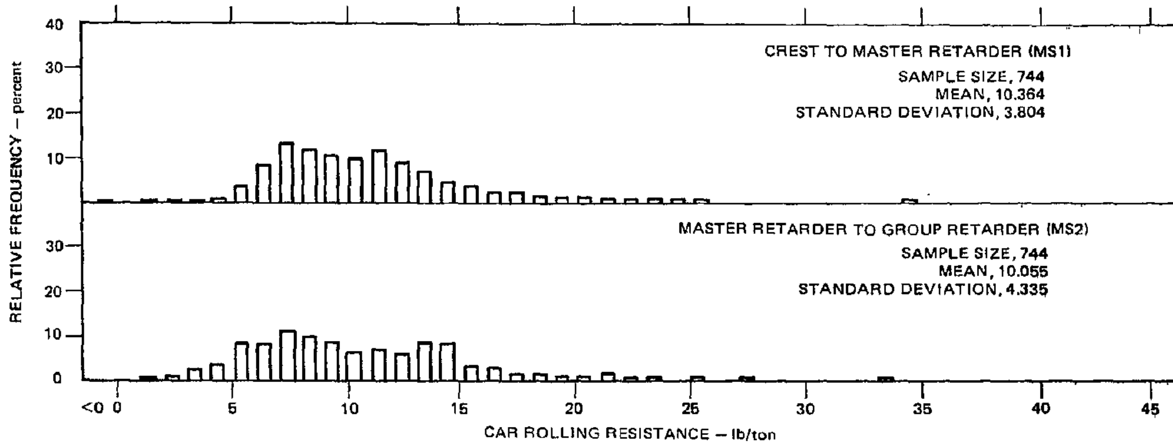



FIGURE 4-31 DISTRIBUTION OF LINWOOD YARD CAR ROLLING RESISTANCE BY MEASUREMENT SECTION DURING PERIOD 2 OBSERVATIONS

Table 4-32

ROLLING RESISTANCE AND VELOCITY STATISTICS AT LINWOOD YARD MEASUREMENT SECTIONS DURING PERIOD 1

| Measurement Section | Rolling Resistance (lb/ton) | | | | | | Average Velocity (ft/sec) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD* | SE* | 95% CI | Minimum | Maximum | Mean | SD* | SE* | 95% CI | Minimum | Maximum |
| Crest to master retarder (MS1) | 9.945 | 2.902 | .102 | 9.744–10.145 | 5 | 25 | 18.386 | .673 | .024 | 18.339–18.433 | 15 | 19 |
| Master retarder to group retarder (MS2) | 9.491 | 3.813 | .134 | 9.227–9.755 | 2 | 23 | 21.350 | 1.811 | .064 | 21.225–21.476 | 16 | 27 |

*SD, standard deviation.
SE, standard error of mean.
CI, confidence interval for mean.

Table 4-33

ROLLING RESISTANCE AND VELOCITY STATISTICS AT LINWOOD YARD MEASUREMENT SECTION DURING PERIOD 2

| Measurement Section | Rolling Resistance (lb/ton) | | | | | | Average Velocity (ft/sec) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SD* | SE* | 95% CI | Minimum | Maximum | Mean | SD* | SE* | 95% CI | Minimum | Maximum |
| Crest to master retarder (MS1) | 10.364 | 3.804 | 0.139 | 10.091–10.637 | -1 | 34 | 18.308 | 0.826 | 0.030 | 18.249–18.367 | 13 | 20 |
| Master retarder to group retarder (MS2) | 10.055 | 4.335 | 0.159 | 9.743–10.367 | 1 | 33 | 21.232 | 2.283 | 0.084 | 21.067–21.397 | 8 | 28 |

*SD, standard deviation.
SE, standard error of mean.
CI, confidence interval for mean.

# CHAPTER 5: STATISTICAL ANALYSIS OF CAUSAL FACTORS

## 5.1 GENERAL

This chapter presents SRI's findings on the influence of the factors that traditionally have been believed to influence rolling resistance: car weight, car type, bearing type, truck center length, car speed, wind velocity, temperature, moisture, switches and curves, distance from crest, and presence of oilers. The type of rail is also believed to influence rolling resistance, but this factor could not be assessed because all the yards had welded rail (common to all modern yards with PC systems).

The linear regression technique was used, which indicated how the mean rolling resistance varied as a function of these factors--the independent variables. Because of its emphasis on the mean, linear regression does not provide much information on the distributional characteristics of rolling resistance when all these factors are held constant.* Nonetheless, knowledge of how mean rolling resistance varies with these factors can be useful in applying correction factors to the distributional characteristics obtained, as in Chapter 6.**

The regression analysis results presented here, unless specified otherwise, include only first-order terms, with rolling resistance as the dependent variable. Details on this analysis, including the complete calibrated computing formulas, are presented in Appendix B. Appendix B also presents regression results considering first-order interactions among the independent variables and considering resistance force as the dependent variable. The interaction term and resistance force regressions did not add an appreciable amount of information. Therefore, the results presented in this chapter should be sufficient for most design purposes.

Isolating the influence of any single factor on rolling resistance is difficult because all factors influence rolling resistance simultaneously. Although the regression technique generally indicates the effects of the various factors, the multidimensional equation that results from the analysis can still be difficult to grasp. Therefore, for the quantified relationships, an artifice called "nominal car" or "nominal conditions" was used. Use of this artifice permitted selection of nominal values for all factors except the one being studied, which was allowed to vary. (Appendix B presents the complex multiple-variable relationships revealed in these analyses.)

*The distribution of the "error" in regression terminology.

**Ignoring any heteroskedasticity. (See Appendix B for a discussion of terminology.)

These analyses were performed using data only from Hinkle and DeWitt yards. The data from the other yards did not provide the necessary complete quantification of the factors being examined. In addition, a small but nonetheless statistically significant difference existed in the rolling resistances between these two yards. This difference was about 0.5 lb/ton; it persisted even when the explanatory power of all the available factors was taken into account.* This residual difference could represent a bias in the data provided by the PC systems and by plans in one or both yards, or it could represent some unknown factor varying between the two yards that was omitted from the analysis.

## 5.2 CAR WEIGHT

An inverse relationship exists between rolling resistance and car weight: As cars become lighter, they roll harder. Figure 5-1 depicts

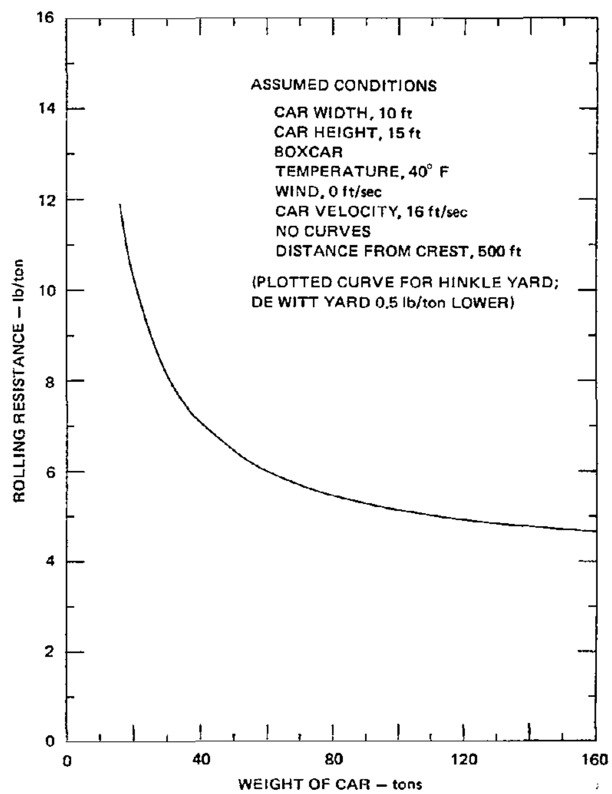



FIGURE 5-1 ROLLING RESISTANCE AS A FUNCTION OF CAR WEIGHT

*The quantification of these factors should be capable of explaining most, if not all, regional differences between the two yards.

this relationship for the nominal conditions indicated. For example, an "average" 30-ton boxcar has a rolling resistance of approximately 8.3 lb/ton, whereas an "average" 80-ton boxcar has a rolling resistance of approximately 5.4 lb/ton.

### 5.3 CAR TYPE

Relative to the boxcar (the nominal car), on the average:

- Gondola cars roll about 1.2 lb/ton harder.
- Flatcars roll about 0.55 lb/ton harder.
- Tank cars roll about 0.66 lb/ton harder.

The other car types considered--hoppers, refrigerator cars, and vehicular cars--were not significantly different from the reference boxcar.*

### 5.4 BEARING TYPE

The traditional assumption has been that cars with roller bearings roll easier than cars with journal bearings. In this study, however, no statistically significant difference was found between the cars. Moreover, cars with journal bearings constituted about 17% of the regression sample--more than sufficient to detect any statistically significant difference.

### 5.5 TRUCK CENTER LENGTH

The truck center length had no statistically significant effect on rolling resistance. This applied even on curves,** where conventional wisdom has been that cars with long wheelbases roll harder because of a binding effect.

### 5.6 CAR SPEED

Rolling resistance depends greatly on car speed; that is, rolling resistance increases with car speed.

Figure 5-2 shows this speed relationship for the nominal conditions indicated. Although a $V^2$

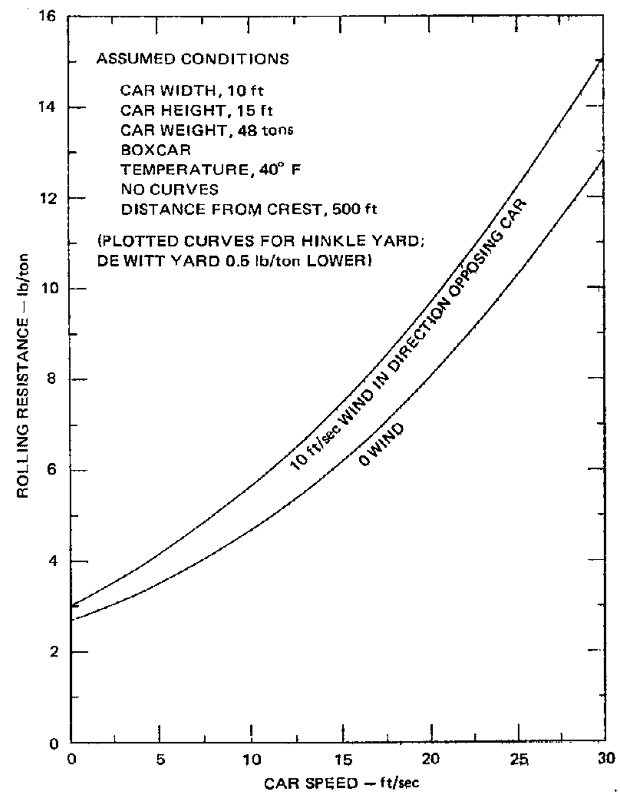



FIGURE 5-2 ROLLING RESISTANCE AS A FUNCTION OF CAR VELOCITY

(velocity squared) dependence* exists, the actual curvilinearity appears to be small under zero ambient wind conditions and even with a 10-ft/sec headwind. Thus, for most yard applications curvilinearity can be ignored when headwinds are slight. (The wind effect is discussed in Section 5.7 below.)

If a linear relationship is assumed, each foot-per-second increase in velocity appears to increase rolling resistance by approximately 0.32 lb/ton for the zero-wind condition, and by 0.40 lb/ton for the 10-ft/sec headwind.

### 5.7 WIND VELOCITY

A headwind can contribute significantly to the rolling resistance of a nominal car.** This

*Cabooses were omitted from the analysis because data on them were incomplete in every instance. Maintenance-of-way and special types of cars were also omitted because their characteristics were too variable within their categories. No distinction was made between equipped and unequipped hoppers or between equipped and unequipped gondolas.

**See the interaction term regression in Appendix B. In particular, note the lack of significance of the interaction between truck center length and the curve variables.

*The $V^2$ dependence is statistically significant and consists of (1) a component due to headwind (even in zero wind conditions, a car moving at 15 ft/sec has a 15-ft/sec relative headwind) and (2) a $V^2$ term with all headwind effects removed. There is also a statistically significant first-power V term.

**This term is proportional to the square of the headwind, times the car's cross-sectional area, divided by the car's weight (details in Appendix B).

effect is shown in Figure 5-3 for the nominal conditions indicated, where negative values of wind velocity are headwind and impede the motion of the car. Each foot-per-second headwind contributes approximately 0.2 lb/ton to rolling resistance for the nominal conditions, although more precise values as a function of wind velocity can be obtained from Figure 5-3.

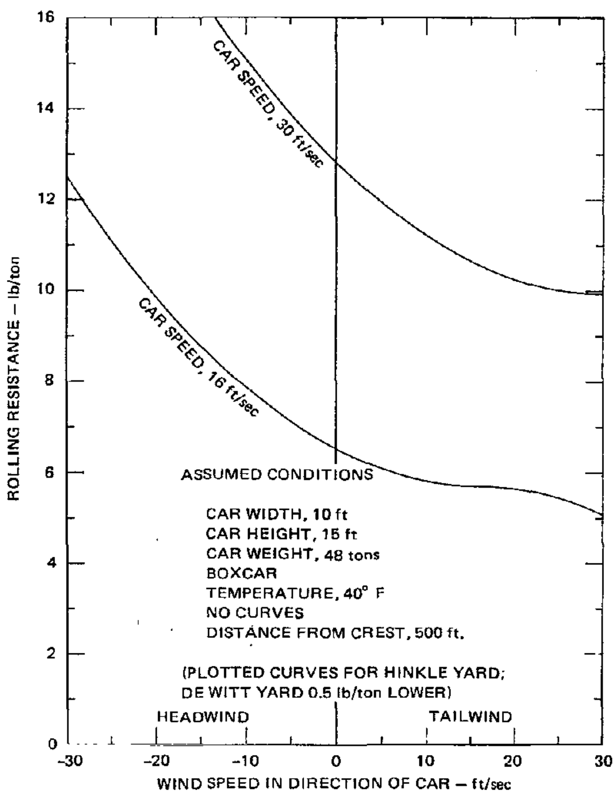



FIGURE 5-3 ROLLING RESISTANCE AS A FUNCTION OF WIND VELOCITY

## 5.8 TEMPERATURE

Cars roll more easily with increasing temperature. The available data sample did not include extreme cold temperatures. A very slight, but nonetheless statistically significant, variation with $T^2$ (temperature squared) was noted, as shown in Figure 5-4.* In the temperature ranges investigated, on the average a car rolls 0.39 lb/ton heavier for every drop of 10 °F in temperature.

## 5.9 MOISTURE

It has been assumed that cars roll easier in the rain, but that deep snow, particularly when it covers the rail, impedes a car's rolling. The available data indicated whether moisture was

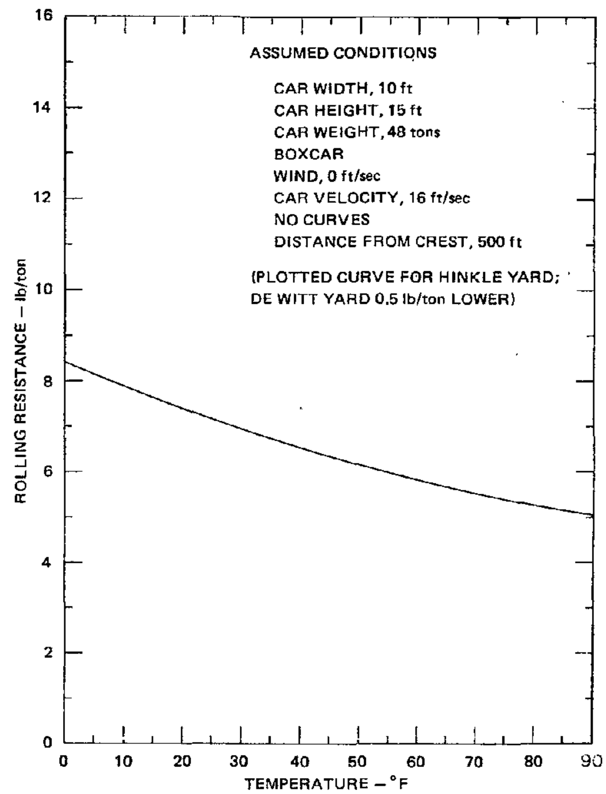



FIGURE 5-4 ROLLING RESISTANCE AS A FUNCTION OF TEMPERATURE

present, but did not differentiate between rain and snow. In addition, only about 3.4% of the data were collected on days when moisture was present. A discrepancy could also exist between what was automatically recorded in the cut statistics and the moisture conditions on the ground. No significant effect of moisture was found. To what extent these difficulties are responsible for the lack of a significant moisture effect cannot be determined.

## 5.10 SWITCHES AND CURVES

The effect of switches and curves could not be reliably isolated. Although their effect appears to be significant, a reliable quantification of their individual action was not possible because the measurement sections that provided the switch and curve data were the same in most cases; thus, the effects of each variable could not be reliably isolated. Further, these sections were located just after the oilers, further confounding the analysis. Appendix B presents a more extensive discussion of this problem and certain findings on the effect of curves based on the interaction term analysis.

## 5.11 DISTANCE FROM CREST

A statistically significant counterintuitive trend was found for the effect of distance from the crest on rolling resistance: Rolling resis-

*There is also a statistically significant T first-power term.

tance increased farther from the crest. As Figure 5-5 indicates, the effect was slight, but it was evident in all the analyses. The effect may be related to the statistical difficulties encountered with switches and curves. Nonetheless, it does not support the commonly held hypothesis that cars roll easier farther from the crest.

5.12 PRESENCE OF OILERS

No significant effect of oilers on rolling resistance was found. However, the oilers were one of the variables confounding the effects of switches and curves, so their effect may have been hidden.

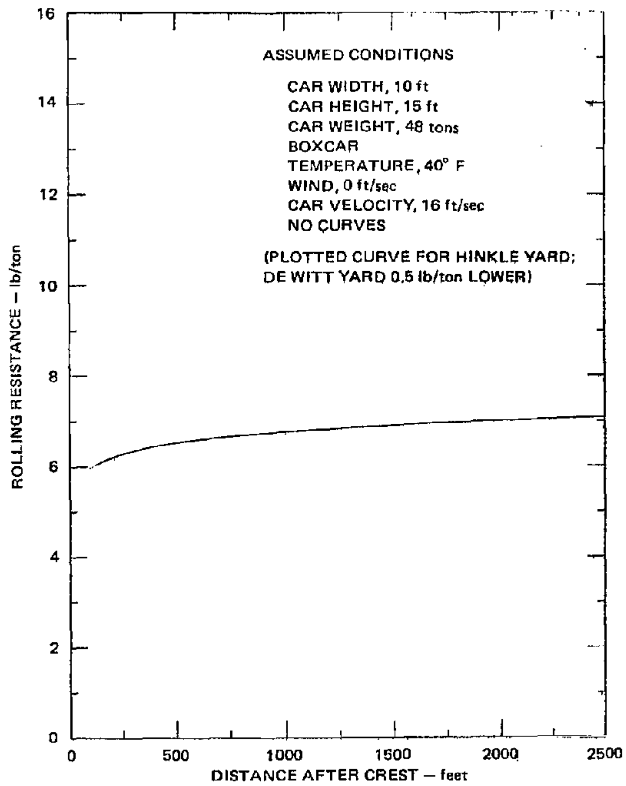



FIGURE 5-5 ROLLING RESISTANCE AS A FUNCTION OF DISTANCE FROM CREST

This chapter presents a general method for estimating the rolling resistance distribution of the total car population of a yard, to be used for design or other purposes. The emphasis is not on explaining rolling resistance, but on obtaining a practical estimate of rolling resistance distribution. This method is based on the only large sample of rolling resistance data available in this study, that from Hinkle Yard. The approach may be repeated by users who can obtain a sufficiently large sample of data for other yards.

A synopsis of the underlying concept for estimating a rolling resistance distribution is as follows. The rolling resistance data from Hinkle Yard can be separated by four categories of weight and eight ranges in temperature, as indicated by the matrix in Exhibit 6-1. Each cell in the matrix contains four histograms of rolling resistance for the four measurement sections, corresponding to the specific weight category and temperature. Table 6-1, Parts 1 through 32, are the histograms for each cell in Exhibit 6-1; their position in the matrix is indicated in the exhibit.

Exhibit 6-1

MATRIX SEPARATING HINKLE YARD DATA BY WEIGHT AND TEMPERATURE

| TEMPERATURE (°F) | WEIGHT* Light | Medium | Heavy | Extra Heavy |
|---|---|---|---|---|
| 11 to 15 | Table 7.2 Part 1 | Table 7.2 Part 2 | Table 7.2 Part 3 | Table 7.3 Part 4 |
| 16 to 20 | Table 7.2 Part 5 | Table 7.2 Part 6 | Table 7.2 Part 7 | Table 7.2 Part 8 |
| 21 to 25 | Table 7.2 Part 9 | Table 7.2 Part 10 | Table 7.2 Part 11 | Table 7.2 Part 12 |
| 26 to 30 | Table 7.2 Part 13 | Table 7.2 Part 14 | Table 7.2 Part 15 | Table 7.2 Part 16 |
| 31 to 40 | Table 7.2 Part 17 | Table 7.2 Part 18 | Table 7.2 Part 19 | Table 7.2 Part 20 |
| 41 to 50 | Table 7.2 Part 21 | Table 7.2 Part 22 | Table 7.2 Part 23 | Table 7.2 Part 24 |
| 51 to 70 | Table 7.2 Part 25 | Table 7.2 Part 26 | Table 7.2 Part 27 | Table 7.2 Part 28 |
| >70 | Table 7.2 Part 29 | Table 7.2 Part 30 | Table 7.2 Part 31 | Table 7.2 Part 32 |

*WEIGHT CATEGORIES:
LIGHT, 0-35 TONS
MEDIUM, 36-65 TONS
HEAVY, 66-100 TONS
EXTRA HEAVY, > 100 TONS.

Assume that a designer wants to estimate a set of histograms for the four measurements sections (MS1 through MS4) for a new yard that had only heavy cars and a temperature range of 31 to 40 °F. Referring to Exhibit 6-1, the designer would find that the estimated histograms are identical to those in Table 6-1, Part 19. If the new yard had only heavy cars and the temperature were between 26 to 30 °F and 31 to 40 °F, the estimated set of histograms would be obtained by combining the corresponding histogram in Table 6-1, Parts 15 and 19, in equal proportion.

This rationale can be extended to the general case in which frequency distributions of car weights and temperature ranges exist for the new yard; based on these proportions, exemplified in these frequency distributions, the corresponding histograms in Table 1, Parts 1 through 32, are appropriately combined. Although the concept is simple, the specific formulas and procedures require the detailed explanation that follows.

## 6.1 TECHNICAL APPROACH

In this method, the three most common factors considered to affect rolling resistance are explicitly considered: car weight, temperature, and wind.

Raw rolling resistance observations were available in the Hinkle Yard data base at four measurement sections:

- From the crest to the master retarder (measurement section 1),
- From the master retarder to the group retarder (measurement section 2),
- From the group retarder to the tangent point (measurement section 3),
- From the tangent point to the classification tracks (measurement section 4).

Because the distribution is estimated at these four locations, two location-dependent factors are implicitly considered:

- The distance from hump crest
- Switches and curves (as contained in measurement section 3).

RR denotes the raw value of rolling resistance as obtained directly. First, $RR_c$, the raw rolling resistance with removal of the decelerating effect of any headwind (or accelerating effect of a tailwind),* must be computed by using the regression results reported in Chapter 5 and Appendix B.

*The headwind effect must be removed to avoid bias in the rolling resistance distributions obtained here to the prevailing wind conditions at Hinkle Yard.

Table 6-1

DISTRIBUTIONAL SUMMARY OF HINKLE YARD FALL,
WINTER, AND SUMMER DATA: CORRECTED
ROLLING RESISTANCES

Part 1

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 11-15<br>WEIGHT: LIGHT | | | | |
| SAMPLE SIZE | 18 | 18 | 18 | 18 |
| MEAN RESIS. LB/T | 9.4790 | 11.4257 | 9.6546 | 8.1202 |
| STD. DEV. LB/T | 2.7204 | 3.1750 | 2.6087 | 2.1054 |
| MIN. VAL. LB/T | 5.92 | 3.79 | 2.84 | 5.10 |
| MAX. VAL. LB/T | 14.99 | 17.74 | 12.85 | 13.55 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 0 |
| PCT. 2- 4 LB/T | 0 | 5.56 | 5.56 | 0 |
| PCT. 4- 6 LB/T | 5.56 | 0 | 5.56 | 16.67 |
| PCT. 6- 8 LB/T | 27.78 | 0 | 11.11 | 38.89 |
| PCT. 8-10 LB/T | 27.78 | 16.67 | 16.67 | 33.33 |
| PCT. 10-12 LB/T | 11.11 | 33.33 | 44.44 | 5.56 |
| PCT. 12-14 LB/T | 22.22 | 27.78 | 16.67 | 5.56 |
| PCT. 14-16 LB/T | 5.56 | 5.56 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | 11.11 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Part 2

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 11-15<br>WEIGHT: MEDIUM | | | | |
| SAMPLE SIZE | 12 | 12 | 12 | 12 |
| MEAN RESIS. LB/T | 8.4576 | 10.2554 | 9.9528 | 6.9727 |
| STD. DEV. LB/T | 1.4685 | 2.5439 | 1.7408 | 1.9338 |
| MIN. VAL. LB/T | 6.45 | 6.10 | 5.77 | 5.56 |
| MAX. VAL. LB/T | 11.00 | 13.85 | 12.21 | 12.36 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 0 |
| PCT. 2- 4 LB/T | 0 | 0 | 0 | 0 |
| PCT. 4- 6 LB/T | 0 | 0 | 8.33 | 33.33 |
| PCT. 6- 8 LB/T | 41.67 | 25.00 | 0 | 50.00 |
| PCT. 8-10 LB/T | 41.67 | 8.33 | 33.33 | 8.33 |
| PCT. 10-12 LB/T | 16.67 | 41.67 | 50.00 | 0 |
| PCT. 12-14 LB/T | 0 | 25.00 | 8.33 | 8.33 |
| PCT. 14-16 LB/T | 0 | 0 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | 0 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

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Table 6-1 (continued)

Part 3

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 11-15 | | | | |
| WEIGHT: HEAVY | | | | |
| SAMPLE SIZE | 17 | 17 | 17 | 17 |
| MEAN RESIS. LB/T | 6.1567 | 7.3727 | 6.9504 | 3.9515 |
| STD. DEV. LB/T | 1.0944 | 2.6191 | 1.2742 | .7935 |
| MIN. VAL. LB/T | 4.89 | 3.68 | 5.31 | 2.42 |
| MAX. VAL. LB/T | 8.30 | 11.70 | 9.57 | 6.05 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 0 |
| PCT. 2- 4 LB/T | 0 | 5.88 | 0 | 47.06 |
| PCT. 4- 6 LB/T | 52.94 | 35.29 | 29.41 | 47.06 |
| PCT. 6- 8 LB/T | 41.18 | 17.65 | 52.94 | 5.88 |
| PCT. 8-10 LB/T | 5.88 | 23.53 | 17.65 | 0 |
| PCT. 10-12 LB/T | 0 | 17.65 | 0 | 0 |
| PCT. 12-14 LB/T | 0 | 0 | 0 | 0 |
| PCT. 14-16 LB/T | 0 | 0 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | 0 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Part 4

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 11-15 | | | | |
| WEIGHT: XHEAVY | | | | |
| SAMPLE SIZE | 19 | 19 | 19 | 19 |
| MEAN RESIS. LB/T | 6.3407 | 7.0046 | 6.2620 | 4.7648 |
| STD. DEV. LB/T | 1.0356 | 1.7713 | 1.0261 | 1.9179 |
| MIN. VAL. LB/T | 4.64 | 2.99 | 3.71 | 2.84 |
| MAX. VAL. LB/T | 8.23 | 9.85 | 8.28 | 11.27 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 0 |
| PCT. 2- 4 LB/T | 0 | 5.26 | 5.26 | 42.11 |
| PCT. 4- 6 LB/T | 36.84 | 15.79 | 21.05 | 42.11 |
| PCT. 6- 8 LB/T | 57.89 | 47.37 | 68.42 | 10.53 |
| PCT. 8-10 LB/T | 5.26 | 31.58 | 5.26 | 0 |
| PCT. 10-12 LB/T | 0 | 0 | 0 | 5.26 |
| PCT. 12-14 LB/T | 0 | 0 | 0 | 0 |
| PCT. 14-16 LB/T | 0 | 0 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | 0 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Table 6-1 (continued)

Part 5

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 16-20<br>WEIGHT: LIGHT | | | | |
| SAMPLE SIZE | 44 | 44 | 43 | 44 |
| MEAN RESIS. LB/T | 9.3522 | 11.5745 | 10.5174 | 7.5379 |
| STD. DEV. LB/T | 2.7282 | 3.6195 | 2.9465 | 4.9130 |
| MIN. VAL. LB/T | 3.74 | 4.53 | 4.49 | -.73 |
| MAX. VAL. LB/T | 14.28 | 18.69 | 21.10 | 28.81 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 2.27 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 4.55 |
| PCT. 2- 4 LB/T | 2.27 | 0 | 0 | 6.82 |
| PCT. 4- 6 LB/T | 6.82 | 6.82 | 2.33 | 15.91 |
| PCT. 6- 8 LB/T | 25.00 | 11.36 | 11.63 | 43.18 |
| PCT. 8-10 LB/T | 29.55 | 13.64 | 27.91 | 18.18 |
| PCT. 10-12 LB/T | 18.18 | 20.45 | 32.56 | 0 |
| PCT. 12-14 LB/T | 15.91 | 25.00 | 18.60 | 0 |
| PCT. 14-16 LB/T | 2.27 | 11.36 | 2.33 | 0 |
| PCT. 16-18 LB/T | 0 | 9.09 | 2.33 | 4.55 |
| PCT. 18-20 LB/T | 0 | 2.27 | 0 | 2.27 |
| PCT. 20-22 LB/T | 0 | 0 | 2.33 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 2.27 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Part 6

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 16-20<br>WEIGHT: MEDIUM | | | | |
| SAMPLE SIZE | 10 | 10 | 10 | 9 |
| MEAN RESIS. LB/T | 7.9586 | 9.4033 | 9.5808 | 6.5406 |
| STD. DEV. LB/T | 1.7547 | 3.1972 | 4.8152 | 3.4452 |
| MIN. VAL. LB/T | 5.48 | 5.76 | 4.44 | 2.86 |
| MAX. VAL. LB/T | 10.10 | 16.01 | 22.26 | 14.88 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 0 |
| PCT. 2- 4 LB/T | 0 | 0 | 0 | 11.11 |
| PCT. 4- 6 LB/T | 20.00 | 10.00 | 10.00 | 44.44 |
| PCT. 6- 8 LB/T | 30.00 | 30.00 | 20.00 | 33.33 |
| PCT. 8-10 LB/T | 30.00 | 30.00 | 50.00 | 0 |
| PCT. 10-12 LB/T | 20.00 | 10.00 | 10.00 | 0 |
| PCT. 12-14 LB/T | 0 | 10.00 | 0 | 0 |
| PCT. 14-16 LB/T | 0 | 0 | 0 | 11.11 |
| PCT. 16-18 LB/T | 0 | 10.00 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 10.00 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

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Table 6-1 (continued)

Part 7

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 16-20 WEIGHT: HEAVY | | | | |
| SAMPLE SIZE | 24 | 24 | 24 | 24 |
| MEAN RESIS LB/T | 5.9237 | 7.8116 | 7.7849 | 5.0923 |
| STD. DEV. LB/T | 1.1731 | 2.4149 | 2.2399 | 1.5922 |
| MIN. VAL. LB/T | 4.16 | 1.25 | 4.39 | 3.18 |
| MAX. VAL. LB/T | 8.44 | 10.97 | 12.40 | 9.57 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | 4.17 | 0 | 0 |
| PCT. 2- 4 LB/T | 0 | 4.17 | 0 | 29.17 |
| PCT. 4- 6 LB/T | 54.17 | 12.50 | 25.00 | 45.83 |
| PCT. 6- 8 LB/T | 37.50 | 29.17 | 29.17 | 20.83 |
| PCT. 8-10 LB/T | 8.33 | 33.33 | 29.17 | 4.17 |
| PCT. 10-12 LB/T | 0 | 16.67 | 8.33 | 0 |
| PCT. 12-14 LB/T | 0 | 0 | 8.33 | 0 |
| PCT. 14-16 LB/T | 0 | 0 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | 0 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT >30 LB/T | 0 | 0 | 0 | 0 |

Part 8

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 16-20 WEIGHT: XHEAVY | | | | |
| SAMPLE SIZE | 20 | 20 | 19 | 20 |
| MEAN RESIS. LB/T | 6.0876 | 7.2093 | 7.5881 | 5.9276 |
| STD. DEV. LB/T | 2.0494 | 2.1904 | 1.7673 | 7.2545 |
| MIN. VAL. LB/T | 4.07 | 2.47 | 4.23 | 2.23 |
| MAX VAL. LB/T | 13.46 | 10.20 | 10.93 | 36.19 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 0 |
| PCT. 2- 4 LB/T | 0 | 10.00 | 0 | 45.00 |
| PCT. 4- 6 LB/T | 60.00 | 15.00 | 21.05 | 40.00 |
| PCT. 6- 8 LB/T | 35.00 | 45.00 | 36.84 | 10.00 |
| PCT. 8-10 LB/T | 0 | 20.00 | 31.58 | 0 |
| PCT. 10-12 LB/T | 0 | 10.00 | 10.53 | 0 |
| PCT. 12-14 LB/T | 5.00 | 0 | 0 | 0 |
| PCT. 14-16 LB/T | 0 | 0 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | 0 | 0 | 0 |
| PCT 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 5.00 |

Table 6-1 (continued)

Part 9

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 21-25 | | | | |
| WEIGHT: LIGHT | | | | |
| SAMPLE SIZE | 81 | 80 | 80 | 78 |
| MEAN RESIS. LB/T | 8.7356 | 12.1995 | 9.5451 | 6.1254 |
| STD. DEV. LB/T | 2.4190 | 3.8435 | 2.0446 | 2.2027 |
| MIN. VAL. LB/T | 4.62 | 2.96 | 5.40 | 1.38 |
| MAX. VAL. LB/T | 15.04 | 22.20 | 15.11 | 11.57 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 1.28 |
| PCT. 2- 4 LB/T | 0 | 3.75 | 0 | 15.38 |
| PCT. 4- 6 LB/T | 16.05 | 2.50 | 2.50 | 38.46 |
| PCT. 6- 8 LB/T | 27.16 | 5.00 | 18.75 | 23.08 |
| PCT. 8-10 LB/T | 28.40 | 13.75 | 40.00 | 16.67 |
| PCT. 10-12 LB/T | 14.81 | 23.75 | 27.50 | 5.13 |
| PCT. 12-14 LB/T | 11.11 | 20.00 | 8.75 | 0 |
| PCT. 14-16 LB/T | 2.47 | 15.00 | 2.50 | 0 |
| PCT. 16-18 LB/T | 0 | 11.25 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 3.75 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 1.25 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Part 10

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 21-25 | | | | |
| WEIGHT: MEDIUM | | | | |
| SAMPLE SIZE | 31 | 31 | 31 | 31 |
| MEAN RESIS. LB/T | 8.2990 | 11.3063 | 8.6556 | 5.6786 |
| STD. DEV. LB/T | 2.0307 | 3.0225 | 1.9365 | 2.9812 |
| MIN. VAL. LB/T | 5.04 | 4.32 | 5.52 | .83 |
| MAX. VAL. LB/T | 12.54 | 15.90 | 12.70 | 17.46 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 3.23 |
| PCT. 2- 4 LB/T | 0 | 0 | 0 | 19.35 |
| PCT. 4- 6 LB/T | 12.90 | 3.23 | 6.45 | 48.39 |
| PCT. 6- 8 LB/T | 48.39 | 9.68 | 35.48 | 12.90 |
| PCT. 8-10 LB/T | 9.68 | 22.58 | 29.03 | 9.68 |
| PCT. 10-12 LB/T | 22.58 | 16.13 | 22.58 | 3.23 |
| PCT. 12-14 LB/T | 6.45 | 25.81 | 6.45 | 0 |
| PCT. 14-16 LB/T | 0 | 22.58 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | 0 | 0 | 3.23 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

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Table 6-1 (continued)

Part 11

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 21-25<br>WEIGHT: HEAVY | | | | |
| SAMPLE SIZE | 45 | 45 | 45 | 45 |
| MEAN RESIS. LB/T | 6.0468 | 8.3152 | 6.9329 | 4.1945 |
| STD. DEV. LB/T | 1.8969 | 3.9709 | 2.0636 | 1.1014 |
| MIN. VAL. LB/T | 3.79 | 2.74 | 5.23 | 1.79 |
| MAX. VAL. LB/T | 12.37 | 27.66 | 16.04 | 6.69 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 2.22 |
| PCT. 2- 4 LB/T | 4.44 | 6.67 | 0 | 46.67 |
| PCT. 4- 6 LB/T | 62.22 | 17.78 | 33.33 | 42.22 |
| PCT. 6- 8 LB/T | 17.78 | 35.56 | 55.56 | 8.89 |
| PCT. 8-10 LB/T | 11.11 | 13.33 | 4.44 | 0 |
| PCT. 10-12 LB/T | 2.22 | 15.56 | 2.22 | 0 |
| PCT. 12-14 LB/T | 2.22 | 6.67 | 0 | 0 |
| PCT. 14-16 LB/T | 0 | 2.22 | 2.22 | 0 |
| PCT. 16-18 LB/T | 0 | 0 | 2.22 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 2.22 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Part 12

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 21-25<br>WEIGHT: XHEAVY | | | | |
| SAMPLE SIZE | 43 | 43 | 43 | 43 |
| MEAN RESIS. LB/T | 5.6744 | 6.8805 | 6.4743 | 3.8677 |
| STD. DEV. LB/T | 1.4798 | 2.2313 | 1.9799 | 1.7244 |
| MIN. VAL. LB/T | 2.80 | 3.54 | 3.91 | .05 |
| MAX. VAL. LB/T | 11.46 | 13.93 | 13.32 | 9.89 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 6.98 |
| PCT. 2- 4 LB/T | 9.30 | 6.98 | 2.33 | 48.84 |
| PCT. 4- 6 LB/T | 55.81 | 32.56 | 51.16 | 37.21 |
| PCT. 6- 8 LB/T | 27.91 | 34.88 | 30.23 | 2.33 |
| PCT. 8-10 LB/T | 4.65 | 16.28 | 9.30 | 4.65 |
| PCT. 10-12 LB/T | 2.33 | 6.98 | 4.65 | 0 |
| PCT. 12-14 LB/T | 0 | 2.33 | 2.33 | 0 |
| PCT. 14-16 LB/T | 0 | 0 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | 0 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Table 6-1 (continued)

Part 13

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 26-30<br>WEIGHT: LIGHT | | | | |
| SAMPLE SIZE | 318 | 316 | 316 | 313 |
| MEAN RESIS. LB/T | 8.6257 | 11.3444 | 9.2468 | 5.8047 |
| STD. DEV. LB/T | 2.3177 | 3.9169 | 2.4168 | 2.7005 |
| MIN. VAL. LB/T | 3.23 | -.04 | 4.11 | -1.82 |
| MAX. VAL. LB/T | 28.96 | 23.73 | 20.62 | 20.63 |
| PCT. < 0 LB/T | 0 | .32 | 0 | .64 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 2.24 |
| PCT. 2- 4 LB/T | .94 | .32 | 0 | 17.89 |
| PCT. 4- 6 LB/T | 14.78 | 9.18 | 6.01 | 41.85 |
| PCT. 6- 8 LB/T | 32.39 | 11.08 | 25.00 | 24.60 |
| PCT. 8-10 LB/T | 26.10 | 16.46 | 35.44 | 7.03 |
| PCT. 10-12 LB/T | 16.98 | 21.52 | 21.20 | 2.88 |
| PCT. 12-14 LB/T | 5.35 | 15.82 | 9.18 | .96 |
| PCT. 14-16 LB/T | 1.89 | 13.61 | 2.53 | 0 |
| PCT. 16-18 LB/T | .63 | 6.65 | 0 | 1.28 |
| PCT. 18-20 LB/T | .63 | 3.80 | 0 | .32 |
| PCT. 20-22 LB/T | 0 | .32 | .63 | .32 |
| PCT. 22-24 LB/T | 0 | .95 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | .31 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Part 14

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 26-30<br>WEIGHT: MEDIUM | | | | |
| SAMPLE SIZE | 128 | 129 | 129 | 129 |
| MEAN RESIS. LB/T | 7.1349 | 9.9268 | 7.9957 | 5.0530 |
| STD. DEV. LB/T | 1.8013 | 3.6814 | 1.8545 | 2.4319 |
| MIN. VAL. LB/T | 3.53 | 2.68 | 4.17 | -.34 |
| MAX. VAL. LB/T | 13.85 | 27.46 | 13.[illegible]8 | 20.39 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 1.55 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 2.33 |
| PCT. 2- 4 LB/T | 3.91 | 3.10 | 0 | 27.13 |
| PCT. 4- 6 LB/T | 23.44 | 9.30 | 13.95 | 44.96 |
| PCT. 6- 8 LB/T | 42.19 | 21.71 | 37.98 | 15.50 |
| PCT. 8-10 LB/T | 23.44 | 20.16 | 34.88 | 6.20 |
| PCT. 10-12 LB/T | 6.25 | 23.26 | 10.08 | 0 |
| PCT. 12-14 LB/T | .78 | 10.08 | 3.10 | .78 |
| PCT. 14-16 LB/T | 0 | 6.98 | 0 | .78 |
| PCT. 16-18 LB/T | 0 | 2.33 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 1.55 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | .78 | 0 | .78 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | .78 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

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Table 6-1 (continued)

Part 15

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 26-30 WEIGHT: HEAVY | | | | |
| SAMPLE SIZE | 194 | 195 | 195 | 193 |
| MEAN RESIS. LB/T | 5.7194 | 7.5479 | 6.5638 | 4.3004 |
| STD. DEV. LB/T | 1.5663 | 2.8147 | 1.6738 | 2.5059 |
| MIN. VAL. LB/T | 3.02 | 2.18 | 2.52 | -.01 |
| MAX. VAL. LB/T | 14.62 | 22.75 | 14.91 | 24.10 |
| PCT. < 0 LB/T | 0 | 0 | 0 | .52 |
| PCT. 0- 2 LB/T | 0 | 0 | 0 | 4.66 |
| PCT. 2- 4 LB/T | 4.64 | 7.69 | 2.05 | 52.33 |
| PCT. 4- 6 LB/T | 63.92 | 22.56 | 36.41 | 32.64 |
| PCT. 6- 8 LB/T | 24.74 | 34.36 | 47.69 | 4.66 |
| PCT. 8-10 LB/T | 4.12 | 19.49 | 9.74 | 1.55 |
| PCT. 10-12 LB/T | 1.03 | 10.26 | 3.59 | 2.07 |
| PCT. 12-14 LB/T | 1.03 | 3.08 | 0 | .52 |
| PCT. 14-16 LB/T | .52 | 2.05 | .51 | .52 |
| PCT. 16-18 LB/T | 0 | 0 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | .51 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | .52 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Part 16

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 26-30 WEIGHT: XHEAVY | | | | |
| SAMPLE SIZE | 119 | 119 | 119 | 117 |
| MEAN RESIS. LB/T | 5.6188 | 7.0137 | 6.1200 | 4.1941 |
| STD. DEV. LB/T | 2.2002 | 2.7561 | 1.6059 | 2.3971 |
| MIN. VAL. LB/T | 2.23 | .17 | 1.66 | .10 |
| MAX. VAL. LB/T | 24.93 | 13.58 | 11.84 | 18.22 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 0 |
| PCT. 0- 2 LB/T | 0 | .84 | .84 | 5.98 |
| PCT. 2- 4 LB/T | 5.88 | 13.45 | .84 | 57.26 |
| PCT. 4- 6 LB/T | 68.91 | 24.37 | 54.62 | 23.93 |
| PCT. 6- 8 LB/T | 19.33 | 29.41 | 35.29 | 7.69 |
| PCT. 8-10 LB/T | 4.20 | 15.13 | 5.88 | 1.71 |
| PCT. 10-12 LB/T | .84 | 10.92 | 2.52 | 1.71 |
| PCT. 12-14 LB/T | 0 | 5.88 | 0 | 0 |
| PCT. 14-16 LB/T | 0 | 0 | 0 | .85 |
| PCT. 16-18 LB/T | 0 | 0 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | .85 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | .84 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Table 6-1 (continued)

Part 17

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP : 31-40<br>WEIGHT : LIGHT | | | | |
| SAMPLE SIZE | 1366 | 1360 | 1360 | 1326 |
| MEAN RESIS. LB/T | 7.3019 | 10.6290 | 8.4129 | 5.2589 |
| STD. DEV. LB/T | 2.3923 | 3.8835 | 2.0738 | 2.4019 |
| MIN. VAL. LB/T | 1.49 | .24 | 3.15 | -3.58 |
| MAX. VAL. LB/T | 25.91 | 36.43 | 15.45 | 25.16 |
| PCT. < 0 LB/T | 0 | 0 | 0 | .38 |
| PCT. 0- 2 LB/T | .15 | .66 | 0 | 3.54 |
| PCT. 2- 4 LB/T | 2.71 | 1.99 | .37 | 20.89 |
| PCT. 4- 6 LB/T | 18.23 | 7.87 | 10.22 | 48.57 |
| PCT. 6- 8 LB/T | 36.24 | 14.34 | 35.51 | 18.33 |
| PCT. 8-10 LB/T | 26.94 | 22.12 | 33.68 | 4.22 |
| PCT. 10-12 LB/T | 11.42 | 19.34 | 14.63 | 2.19 |
| PCT. 12-14 LB/T | 3.07 | 15.81 | 4.34 | .68 |
| PCT. 14-16 LB/T | .73 | 9.71 | 1.10 | .53 |
| PCT. 16-18 LB/T | .37 | 5.07 | .07 | .23 |
| PCT. 18-20 LB/T | .07 | 1.69 | .07 | .23 |
| PCT. 20-22 LB/T | 0 | .66 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | .29 | 0 | .15 |
| PCT. 24-26 LB/T | .07 | .29 | 0 | .08 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | .15 | 0 | 0 |

Part 18

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP. : 31-40<br>WEIGHT : MEDIUM | | | | |
| SAMPLE SIZE | 563 | 564 | 563 | 555 |
| MEAN RESIS. LB/T | 7.0434 | 9.5178 | 7.6079 | 4.5233 |
| STD. DEV. LB/T | 1.9152 | 3.9069 | 2.0995 | 1.7484 |
| MIN. VAL. LB/T | 3.03 | 1.82 | 3.73 | -.37 |
| MAX. VAL. LB/T | 18.04 | 29.92 | 19.86 | 15.47 |
| PCT. < 0 LB/T | 0 | 0 | 0 | .54 |
| PCT. 0- 2 LB/T | 0 | .18 | 0 | 3.06 |
| PCT. 2- 4 LB/T | 2.66 | 3.72 | .53 | 38.74 |
| PCT. 4- 6 LB/T | 28.95 | 12.94 | 22.38 | 42.34 |
| PCT. 6- 8 LB/T | 40.14 | 21.81 | 38.19 | 12.25 |
| PCT. 8-10 LB/T | 21.49 | 20.39 | 28.60 | 1.62 |
| PCT. 10-12 LB/T | 5.86 | 18.62 | 6.57 | .90 |
| PCT. 12-14 LB/T | .53 | 11.17 | 2.49 | .36 |
| PCT. 14-16 LB/T | .18 | 6.21 | .71 | .18 |
| PCT. 16-18 LB/T | 0 | 2.84 | .18 | 0 |
| PCT. 18-20 LB/T | .18 | .53 | .36 | 0 |
| PCT. 20-22 LB/T | 0 | .53 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | .18 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | .53 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | .35 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

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Table 6-1 (continued)

Part 19

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 31-40<br>WEIGHT: HEAVY | | | | |
| SAMPLE SIZE | 838 | 835 | 834 | 821 |
| MEAN RESIS. LB/T | 5.4885 | 7.3723 | 6.3639 | 3.9898 |
| STD. DEV. LB/T | 1.8126 | 2.9718 | 1.7207 | 1.9165 |
| MIN. VAL. LB/T | 2.43 | .81 | 3.64 | -.02 |
| MAX. VAL. LB/T | 38.66 | 25.22 | 17.56 | 16.83 |
| PCT. < 0 LB/T | 0 | 0 | 0 | .12 |
| PCT. 0- 2 LB/T | 0 | .72 | 0 | 5.60 |
| PCT. 2- 4 LB/T | 9.19 | 10.30 | 2.40 | 56.03 |
| PCT. 4- 6 LB/T | 63.84 | 24.31 | 46.52 | 27.41 |
| PCT. 6- 8 LB/T | 24.11 | 27.19 | 38.13 | 7.43 |
| PCT. 8-10 LB/T | 2.03 | 20.60 | 9.95 | 1.58 |
| PCT. 10-12 LB/T | .48 | 10.66 | 1.68 | .97 |
| PCT. 12-14 LB/T | 0 | 4.19 | .60 | .37 |
| PCT. 14-16 LB/T | .12 | 1.08 | .48 | .24 |
| PCT. 16-18 LB/T | 0 | .48 | .24 | .24 |
| PCT. 18-20 LB/T | 0 | .12 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | .12 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | .12 | 0 | 0 |
| PCT. 24-26 LB/T | .12 | .12 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | .12 | 0 | 0 | 0 |

Part 20

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 31-40<br>WEIGHT: HEAVY | | | | |
| SAMPLE SIZE | 653 | 652 | 652 | 643 |
| MEAN RESIS. LB/T | 5.2118 | 6.7414 | 5.9274 | 3.7058 |
| STD. DEV. LB/T | 1.2339 | 3.1718 | 1.5491 | 1.7850 |
| MIN. VAL. LB/T | 1.50 | .22 | 1.48 | -.03 |
| MAX. VAL. LB/T | 17.85 | 22.29 | 15.15 | 29.33 |
| PCT. < 0 LB/T | 0 | 0 | 0 | .16 |
| PCT. 0- 2 LB/T | .31 | 2.45 | .15 | 4.04 |
| PCT. 2- 4 LB/T | 8.27 | 12.88 | 3.53 | 66.10 |
| PCT. 4- 6 LB/T | 75.34 | 30.67 | 57.36 | 23.95 |
| PCT. 6- 8 LB/T | 13.32 | 27.61 | 30.98 | 3.58 |
| PCT. 8-10 LB/T | 1.84 | 14.57 | 6.13 | 1.09 |
| PCT. 10-12 LB/T | .46 | 6.90 | .77 | .78 |
| PCT. 12-14 LB/T | .31 | 1.84 | .77 | 0 |
| PCT. 14-16 LB/T | 0 | 1.07 | .31 | .16 |
| PCT. 16-18 LB/T | .15 | .46 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | .77 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | .61 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | .15 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | .16 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Table 6-1 (continued)

Part 21

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 41-50 WEIGHT: LIGHT | | | | |
| SAMPLE SIZE | 645 | 647 | 647 | 625 |
| MEAN RESIS. LB/T | 7.4843 | 10.3936 | 7.9107 | 4.6568 |
| STD. DEV. LB/T | 2.0883 | 3.9117 | 2.3031 | 2.6132 |
| MIN. VAL. LB/T | 1.82 | -.73 | .82 | -4.30 |
| MAX. VAL. LB/T | 16.66 | 29.49 | 18.71 | 27.00 |
| PCT. < 0 LB/T | 0 | .15 | 0 | 2.40 |
| PCT. 0- 2 LB/T | .16 | 1.70 | .62 | 5.92 |
| PCT. 2- 4 LB/T | 3.10 | 2.32 | 2.01 | 30.56 |
| PCT. 4- 6 LB/T | 20.93 | 8.96 | 14.53 | 42.08 |
| PCT. 6- 8 LB/T | 37.36 | 14.22 | 39.10 | 13.12 |
| PCT. 8-10 LB/T | 27.60 | 19.32 | 29.98 | 2.40 |
| PCT. 10-12 LB/T | 8.06 | 18.55 | 9.27 | 1.60 |
| PCT. 12-14 LB/T | 2.33 | 17.31 | 2.94 | .96 |
| PCT. 14-16 LB/T | .31 | 10.97 | .77 | .16 |
| PCT. 16-18 LB/T | .16 | 4.02 | .46 | .48 |
| PCT. 18-20 LB/T | 0 | 1.24 | .31 | .16 |
| PCT. 20-22 LB/T | 0 | .93 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | .15 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | .16 |
| PCT. 28-30 LB/T | 0 | .15 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Part 22

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 41-50 WEIGHT: MEDIUM | | | | |
| SAMPLE SIZE | 318 | 316 | 316 | 303 |
| MEAN RESIS. LB/T | 6.9905 | 9.4416 | 7.2328 | 4.4739 |
| STD. DEV. LB/T | 1.7868 | 3.9471 | 1.9238 | 2.7483 |
| MIN. VAL. LB/T | 3.00 | -.79 | 1.79 | -.27 |
| MAX. VAL. LB/T | 17.71 | 29.51 | 13.44 | 27.74 |
| PCT. < 0 LB/T | 0 | .32 | 0 | .33 |
| PCT. 0- 2 LB/T | 0 | .95 | .32 | 10.23 |
| PCT. 2- 4 LB/T | 1.26 | 5.06 | 2.85 | 36.63 |
| PCT. 4- 6 LB/T | 30.82 | 12.66 | 23.73 | 34.98 |
| PCT. 6- 8 LB/T | 42.77 | 18.04 | 39.56 | 12.54 |
| PCT. 8-10 LB/T | 19.50 | 22.47 | 25.00 | 1.98 |
| PCT. 10-12 LB/T | 5.03 | 17.41 | 7.59 | 1.65 |
| PCT. 12-14 LB/T | .31 | 10.76 | .95 | .33 |
| PCT. 14-16 LB/T | 0 | 6.96 | 0 | .33 |
| PCT. 16-18 LB/T | .31 | 2.85 | 0 | .33 |
| PCT. 18-20 LB/T | 0 | 1.90 | 0 | .33 |
| PCT. 20-22 LB/T | 0 | .32 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | .33 |
| PCT. 28-30 LB/T | 0 | .32 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

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Table 6-1 (continued)

Part 23

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 41-50 WEIGHT: HEAVY | | | | |
| SAMPLE SIZE | 427 | 424 | 427 | 415 |
| MEAN RESIS. LB/T | 5.2761 | 7.4913 | 6.1580 | 3.8795 |
| STD. DEV. LB/T | 1.1677 | 3.0369 | 1.7735 | 2.3360 |
| MIN. VAL. LB/T | 2.71 | .15 | .18 | -.80 |
| MAX. VAL. LB/T | 10.72 | 20.13 | 12.98 | 26.96 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 1.20 |
| PCT. 0- 2 LB/T | 0 | 1.42 | .23 | 10.12 |
| PCT. 2- 4 LB/T | 9.37 | 7.78 | 6.32 | 56.39 |
| PCT. 4- 6 LB/T | 69.32 | 25.24 | 46.84 | 20.96 |
| PCT. 6- 8 LB/T | 18.50 | 27.36 | 32.55 | 7.23 |
| PCT. 8-10 LB/T | 2.11 | 19.10 | 10.30 | 1.45 |
| PCT. 10-12 LB/T | .70 | 12.03 | 2.81 | 1.93 |
| PCT. 12-14 LB/T | 0 | 4.48 | .94 | .24 |
| PCT. 14-16 LB/T | 0 | .94 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | .71 | 0 | .24 |
| PCT. 18-20 LB/T | 0 | .71 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | .24 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | .24 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Part 24

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 41-50 WEIGHT: XHEAVY | | | | |
| SAMPLE SIZE | 413 | 407 | 412 | 398 |
| MEAN RESIS. LB/T | 5.0677 | 6.4751 | 5.8149 | 3.7140 |
| STD. DEV. LB/T | 1.4928 | 3.0019 | 1.4379 | 2.0574 |
| MIN. VAL. LB/T | .62 | -.61 | 3.01 | .35 |
| MAX. VAL. LB/T | 18.64 | 22.10 | 13.20 | 22.59 |
| PCT. < 0 LB/T | 0 | .25 | 0 | 0 |
| PCT. 0- 2 LB/T | .48 | 4.42 | 0 | 10.30 |
| PCT. 2- 4 LB/T | 12.11 | 13.27 | 4.37 | 60.30 |
| PCT. 4- 6 LB/T | 74.82 | 28.99 | 58.74 | 21.11 |
| PCT. 6- 8 LB/T | 8.96 | 26.04 | 30.10 | 4.02 |
| PCT. 8-10 LB/T | 2.18 | 16.22 | 5.10 | 3.02 |
| PCT. 10-12 LB/T | .48 | 6.39 | 1.21 | .50 |
| PCT. 12-14 LB/T | .73 | 2.46 | .49 | .25 |
| PCT. 14-16 LB/T | 0 | .98 | 0 | .25 |
| PCT. 16-18 LB/T | 0 | .74 | 0 | 0 |
| PCT. 18-20 LB/T | .24 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | .25 | 0 | .25 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Table 6-1 (continued)

Part 25

| CATEGORIES | | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|---|
| TEMP.: 51-70 WEIGHT: LIGHT | | | | | |
| SAMPLE SIZE | | 491 | 488 | 487 | 461 |
| MEAN RESIS. | LB/T | 6.0706 | 9.5256 | 6.8983 | 3.9091 |
| STD. DEV. | LB/T | 2.0929 | 3.5761 | 1.9745 | 2.2315 |
| MIN. VAL. | LB/T | 1.39 | .32 | -.13 | -1.90 |
| MAX. VAL. | LB/T | 19.54 | 23.04 | 15.12 | 23.82 |
| PCT. < 0 | LB/T | 0 | 0 | .21 | 1.30 |
| PCT. 0- 2 | LB/T | .61 | .20 | .41 | 10.20 |
| PCT. 2- 4 | LB/T | 11.41 | 4.51 | 3.49 | 49.67 |
| PCT. 4- 6 | LB/T | 43.18 | 11.27 | 28.13 | 28.63 |
| PCT. 6- 8 | LB/T | 29.33 | 20.08 | 45.17 | 6.51 |
| PCT. 8-10 | LB/T | 12.02 | 22.95 | 16.43 | 1.52 |
| PCT. 10-12 | LB/T | 1.63 | 16.19 | 4.11 | 1.08 |
| PCT. 12-14 | LB/T | 1.43 | 14.55 | 1.23 | .43 |
| PCT. 14-16 | LB/T | 0 | 5.53 | .82 | .43 |
| PCT. 16-18 | LB/T | .20 | 3.28 | 0 | 0 |
| PCT. 18-20 | LB/T | .20 | .82 | 0 | 0 |
| PCT. 20-22 | LB/T | 0 | .20 | 0 | 0 |
| PCT. 22-24 | LB/T | 0 | .41 | 0 | .22 |
| PCT. 24-26 | LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 | LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 | LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 | LB/T | 0 | 0 | 0 | 0 |

Part 26

| CATEGORIES | | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|---|
| TEMP.: 51-70 WEIGHT: MEDIUM | | | | | |
| SAMPLE SIZE | | 274 | 274 | 274 | 252 |
| MEAN RESIS. | LB/T | 5.5376 | 7.9382 | 6.3627 | 3.6601 |
| STD. DEV. | LB/T | 1.6725 | 3.1976 | 1.7757 | 2.5465 |
| MIN. VAL. | LB/T | 2.41 | 1.29 | 2.71 | -.21 |
| MAX. VAL. | LB/T | 10.49 | 17.72 | 16.95 | 31.63 |
| PCT. < 0 | LB/T | 0 | 0 | 0 | .79 |
| PCT. 0- 2 | LB/T | 0 | 1.09 | 0 | 13.49 |
| PCT. 2- 4 | LB/T | 16.06 | 8.39 | 4.74 | 57.54 |
| PCT. 4- 6 | LB/T | 49.64 | 19.71 | 41.61 | 18.65 |
| PCT. 6- 8 | LB/T | 26.28 | 20.80 | 38.69 | 6.75 |
| PCT. 8-10 | LB/T | 6.57 | 25.16 | 10.95 | 1.19 |
| PCT. 10-12 | LB/T | 1.46 | 14.23 | 3.28 | .79 |
| PCT. 12-14 | LB/T | 0 | 6.57 | .36 | .40 |
| PCT. 14-16 | LB/T | 0 | 2.92 | 0 | 0 |
| PCT. 16-18 | LB/T | 0 | 1.09 | .36 | 0 |
| PCT. 18-20 | LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 | LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 | LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 | LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 | LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 | LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 | LB/T | 0 | 0 | 0 | .40 |

Table 6-1 (continued)

Part 27

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 51-70 WEIGHT: HEAVY | | | | |
| SAMPLE SIZE | 349 | 349 | 350 | 332 |
| MEAN RESIS. LB/T | 4.4464 | 6.5796 | 5.7630 | 3.4838 |
| STD. DEV. LB/T | 1.0389 | 2.7376 | 1.4168 | 2.2319 |
| MIN. VAL. LB/T | 1.34 | .49 | 2.77 | -.30 |
| MAX. VAL. LB/T | 8.92 | 15.30 | 12.43 | 23.63 |
| PCT. < 0 LB/T | 0 | 0 | 0 | .30 |
| PCT. 0- 2 LB/T | .29 | 1.72 | 0 | 14.16 |
| PCT. 2- 4 LB/T | 34.38 | 15.19 | 6.00 | 60.54 |
| PCT. 4- 6 LB/T | 58.17 | 29.23 | 59.71 | 18.37 |
| PCT. 6- 8 LB/T | 6.30 | 24.36 | 26.57 | 3.31 |
| PCT. 8-10 LB/T | .86 | 19.48 | 6.57 | 1.81 |
| PCT. 10-12 LB/T | 0 | 5.73 | .57 | 0 |
| PCT. 12-14 LB/T | 0 | 2.87 | .57 | .30 |
| PCT. 14-16 LB/T | 0 | 1.43 | 0 | .90 |
| PCT. 16-18 LB/T | 0 | 0 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | .30 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Part 28

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: 51-70 WEIGHT: XHEAVY | | | | |
| SAMPLE SIZE | 377 | 374 | 378 | 353 |
| MEAN RESIS. LB/T | 4.2570 | 6.2515 | 5.4640 | 3.1710 |
| STD. DEV. LB/T | 1.0309 | 2.7071 | 1.1871 | 1.6715 |
| MIN. VAL. LB/T | .56 | .95 | 3.20 | -.13 |
| MAX. VAL. LB/T | 11.93 | 17.26 | 13.17 | 15.08 |
| PCT. < 0 LB/T | 0 | 0 | 0 | .28 |
| PCT. 0- 2 LB/T | .80 | 2.74 | 0 | 16.71 |
| PCT. 2- 4 LB/T | 41.11 | 19.25 | 7.94 | 65.44 |
| PCT. 4- 6 LB/T | 53.65 | 24.33 | 64.55 | 13.03 |
| PCT. 6- 8 LB/T | 3.71 | 28.61 | 24.34 | 2.83 |
| PCT. 8-10 LB/T | .27 | 17.38 | 2.91 | .57 |
| PCT. 10-12 LB/T | .27 | 4.01 | 0 | .28 |
| PCT. 12-14 LB/T | 0 | .80 | .26 | .57 |
| PCT. 14-16 LB/T | 0 | 1.07 | 0 | .28 |
| PCT. 16-18 LB/T | 0 | .80 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | 0 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Table 6-1 (continued)

## Part 29

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: >70 | | | | |
| WEIGHT: LIGHT | | | | |
| SAMPLE SIZE | 471 | 468 | 465 | 433 |
| MEAN RESIS. LB/T | 4.6828 | 8.5103 | 5.6654 | 3.1388 |
| STD. DEV. LB/T | 1.7970 | 3.2108 | 1.7612 | 2.2701 |
| MIN. VAL. LB/T | .79 | .98 | -1.01 | -4.99 |
| MAX. VAL. LB/T | 19.00 | 27.23 | 17.36 | 22.43 |
| PCT < 0 LB/T | 0 | 0 | .22 | 3.70 |
| PCT. 0- 2 LB/T | 3.18 | 1.28 | 1.51 | 19.40 |
| PCT. 2- 4 LB/T | 35.03 | 5.34 | 11.18 | 56.81 |
| PCT. 4- 6 LB/T | 41.40 | 13.39 | 50.32 | 14.55 |
| PCT. 6- 8 LB/T | 16.99 | 22.86 | 23.60 | 3.23 |
| PCT. 8-10 LB/T | 2.76 | 23.29 | 6.88 | .46 |
| PCT. 10-12 LB/T | .42 | 21.37 | .86 | .23 |
| PCT. 12-14 LB/T | 0 | 8.12 | .22 | .69 |
| PCT. 14-16 LB/T | 0 | 2.56 | 0 | .69 |
| PCT. 16-18 LB/T | 0 | .64 | .22 | 0 |
| PCT. 18-20 LB/T | .21 | .21 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | .21 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | .23 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | .21 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

## Part 30

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: >70 | | | | |
| WEIGHT: MEDIUM | | | | |
| SAMPLE SIZE | 322 | 322 | 322 | 295 |
| MEAN RESIS. LB/T | 4.5053 | 7.5987 | 5.5934 | 2.9613 |
| STD. DEV. LB/T | 1.5109 | 3.6105 | 1.4392 | 1.7730 |
| MIN. VAL. LB/T | 1.64 | -.03 | 1.97 | -2.24 |
| MAX. VAL. LB/T | 11.83 | 31.85 | 11.38 | 10.09 |
| PCT. < 0 LB/T | 0 | .31 | 0 | 2.37 |
| PCT. 0- 2 LB/T | 1.86 | 2.17 | .31 | 23.05 |
| PCT. 2- 4 LB/T | 40.99 | 15.84 | 12.42 | 57.63 |
| PCT. 4- 6 LB/T | 42.24 | 18.32 | 52.80 | 9.15 |
| PCT. 6- 8 LB/T | 12.73 | 15.53 | 28.57 | 5.08 |
| PCT. 8-10 LB/T | 1.24 | 22.98 | 4.97 | 2.37 |
| PCT. 10-12 LB/T | .93 | 16.46 | .93 | .34 |
| PCT. 12-14 LB/T | 0 | 5.90 | 0 | 0 |
| PCT. 14-16 LB/T | 0 | 1.55 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | .31 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | .31 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | 0 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | .31 | 0 | 0 |

Table 6-1 (continued)

Part 31

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: >70 | | | | |
| WEIGHT: HEAVY | | | | |
| SAMPLE SIZE | 304 | 302 | 302 | 269 |
| MEAN RESIS. LB/T | 3.5404 | 6.0893 | 5.0710 | 3.2708 |
| STD. DEV. LB/T | .9026 | 2.8569 | 1.2174 | 2.4229 |
| MIN. VAL. LB/T | 1.21 | 1.13 | 1.86 | -.30 |
| MAX. VAL. LB/T | 9.95 | 21.54 | 11.00 | 20.08 |
| PCT. < 0 LB/T | 0 | 0 | 0 | 1.12 |
| PCT. 0- 2 LB/T | 2.30 | 4.64 | .33 | 21.93 |
| PCT. 2- 4 LB/T | 73.68 | 19.87 | 15.89 | 56.13 |
| PCT. 4- 6 LB/T | 22.70 | 30.46 | 64.24 | 13.38 |
| PCT. 6- 8 LB/T | .99 | 19.54 | 17.55 | 3.72 |
| PCT. 8-10 LB/T | .33 | 19.21 | 1.32 | .74 |
| PCT. 10-12 LB/T | 0 | 4.97 | .66 | 1.49 |
| PCT. 12-14 LB/T | 0 | .33 | 0 | .74 |
| PCT. 14-16 LB/T | 0 | 0 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | .33 | 0 | 0 |
| PCT. 18-20 LB/T | 0 | .33 | 0 | .37 |
| PCT. 20-22 LB/T | 0 | .33 | 0 | .37 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | 0 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Part 32

| CATEGORIES | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| TEMP.: >70 | | | | |
| WEIGHT: XHEAVY | | | | |
| SAMPLE SIZE | 385 | 384 | 386 | 352 |
| MEAN RESIS. LB/T | 3.6553 | 5.8811 | 5.0203 | 3.1016 |
| STD. DEV. LB/T | 1.0722 | 3.1284 | 1.0749 | 2.1770 |
| MIN. VAL. LB/T | -.07 | -.02 | 2.89 | -.01 |
| MAX. VAL. LB/T | 11.43 | 25.69 | 13.03 | 21.98 |
| PCT. < 0 LB/T | .26 | .26 | 0 | .28 |
| PCT. 0- 2 LB/T | 4.42 | 6.25 | 0 | 18.18 |
| PCT. 2- 4 LB/T | 70.13 | 24.74 | 13.73 | 64.20 |
| PCT. 4- 6 LB/T | 22.34 | 21.61 | 72.28 | 12.78 |
| PCT. 6- 8 LB/T | 1.82 | 25.00 | 12.95 | 2.27 |
| PCT. 8-10 LB/T | .78 | 17.71 | .52 | .57 |
| PCT. 10-12 LB/T | .26 | 2.08 | .26 | .57 |
| PCT. 12-14 LB/T | 0 | .78 | .26 | .28 |
| PCT. 14-16 LB/T | 0 | .52 | 0 | 0 |
| PCT. 16-18 LB/T | 0 | 0 | 0 | .28 |
| PCT. 18-20 LB/T | 0 | .52 | 0 | 0 |
| PCT. 20-22 LB/T | 0 | 0 | 0 | .57 |
| PCT. 22-24 LB/T | 0 | 0 | 0 | 0 |
| PCT. 24-26 LB/T | 0 | .52 | 0 | 0 |
| PCT. 26-28 LB/T | 0 | 0 | 0 | 0 |
| PCT. 28-30 LB/T | 0 | 0 | 0 | 0 |
| PCT. >30 LB/T | 0 | 0 | 0 | 0 |

Equation B.22 gives the regression variable for headwind resistance as:

$$AHEADC2W = A(V-V_w)^2 \text{ sign } (V-V_w)/W \quad (6.1)$$

where

AHEADC2W = regression variable name for headwind effect

A = the cross-sectional area of the car

V = the speed (ft/sec) of the car

$V_w$ = speed of the wind component parallel to the direction of car movement--positive if moving in the same direction as the car, negative if moving in the opposite direction (ft/sec)

sign (·) = +1 if its argument is positive
0 if its argument is zero
-1 if its argument is negative

W = weight (tons) of the car.

In computing an estimated rolling resistance, the headwind term is entered into the regression equation in the form:

$$\hat{RR} = C + \alpha_w \cdot AHEADC2W + \sum_i \alpha_i \cdot X_i \quad , (6.2)$$

where

$\hat{RR}$ = estimated rolling resistance

C = regression constant

$\alpha_w$ = regression coefficient for wind

$X_i$ = the other regression variables, expressed collectively

$\alpha_i$ = the corresponding coefficients for the other regression variables, expressed collectively.

For one particular observation, the discrepancy between raw rolling resistance and estimated rolling resistance may be taken up by a slack variable, ε , expressed as:

$$RR = RR + \varepsilon \quad . \quad (6.3)$$

This process may be repeated for all the sampled RRs available, in which case equation 6.3 could be repeated with subscripts corresponding to observation numbers. Putting equation 6.2 into 6.3 yields:

$$RR = C + \alpha_w \cdot AHEADC2W + \sum_i \alpha_i \cdot X_i + \varepsilon \quad (6.4)$$

or

$$RR_c = RR - \alpha_w \cdot AHEADC2W = C + \sum_i \alpha_i \cdot X_i + \varepsilon \quad (6.5)$$

Thus, the distributional characteristics of the corrected rolling resistance, $RR_c$, as defined in equation 6.5, are studied. This has the effect of removing that part of the raw rolling resistance that is due to the impeding effect of headwind.*

Therefore, $RR_c$ is simply computed as:

$$RR_c = RR - .00103 \cdot AHEADC2W \quad , \quad (6.6)$$

where the coefficient has been obtained from Table B-3.

Each observation for which $RR_c$ is computed can also be categorized by temperature class and the car's weight class. The categorizations used in the Hinkle Yard PC system were the following:

- Temperature:
  - <0°F
  - 1-5
  - 6-10
  - 11-15
  - 16-20
  - 21-25
  - 26-30
  - 31-40
  - 41-50
  - 51-70
  - > 70.
- Weight
  - Light, 0 to 35 tons
  - Medium, 36 to 65 tons
  - Heavy, 66 to 100 tons
  - Extra heavy, more than 100 tons.

With 11 categories for temperature and 4 for weight, a total of 44 (11 x 4) possible combined categories of weight and temperature exist. Thus, a single value of $RR_c$ might fit into any one of these 44 categories. Because the complete data base for Hinkle Yard comprised 9,600 observations, data are sufficient to construct a histogram of observed $RR_c$ values within most of the 44 categories.

However, because of Hinkle Yard's relatively mild winter climate, only four cars were observed in the lowest three temperature categories. These three temperature levels were thus deleted,

*$RR_c$ can be interpreted as the rolling resistance in the absence of air (i.e., in a vacuum) or as the rolling resistance if the wind were blowing in the same direction as the car's motion, exactly at the speed of the car. This approach also ignores any portion of the regression constant, C, attributable to headwind.

leaving 32 (8 x 4) categories. Table 6-2 presents the approximate* breakdown of observations into these 32 categories.

Table 6-2

APPROXIMATE FREQUENCIES BY WEIGHT AND TEMPERATURE CLASS

| Temperature (°F) | Weight Class | | | | |
|---|---|---|---|---|---|
| | Light | Medium | Heavy | Extra Heavy | Total |
| 11-15 | 18 | 12 | 17 | 19 | 66 |
| 16-20 | 44 | 10 | 24 | 20 | 98 |
| 21-25 | 81 | 31 | 45 | 43 | 200 |
| 26-30 | 318 | 129 | 195 | 119 | 761 |
| 31-40 | 1,366 | 564 | 838 | 653 | 3,421 |
| 41-50 | 647 | 318 | 427 | 413 | 1,805 |
| 51-70 | 491 | 274 | 350 | 378 | 1,493 |
| 70 | 471 | 322 | 304 | 386 | 1,483 |
| Total | 3,436 | 1,660 | 2,200 | 2,031 | 9,327 |

Within each of these categories, a histogram was constructed from the available data. For the purpose of this chapter, presenting these histograms in the form of relative percentages within each category, rather than as frequencies, was more convenient (see Table 6-1). Arbitrary rolling resistance distributions at each of the four measurement sections can be constructed using the information in Table 6-2. The desired distributions are merely the weighted sum of the distributions in each part of Table 6-1. For example, Table 6-3 presents the frequencies of Table 6-2 converted to percentages. If each of these percentages is divided by 100, they add to 1.0. Doing this to the first cell of Table 6-3 yields, for example, .00193. This, then, is a multiplier that is applied to the distribution in the first part of Table 6-1. When this process is repeated for all the cells of Table 6-3, applying each cell to the corresponding part of Table 6-1, and the resulting products added across each part, the results in Table 6-4 are obtained. Table 6-4 in fact, presents the overall, essentially complete sample as obtained from Hinkle Yard. This table is presented in a format similar to Table 6-1, and includes

*The frequencies are approximate because the sample size varied slightly among the four measurement sections. This was due to invalid or missing data. The frequencies in Table 6-2 represent the maximum frequency, among the four measurement sections, within each of the 32 categories.

Table 6-3

PERCENTAGE DISTRIBUTION BY WEIGHT AND TEMPERATURE CLASS AS OBTAINED FROM HINKLE YARD

| TEMP | WEIGHT CLASS | | | |
|---|---|---|---|---|
| | LIGHT | MEDIUM | HEAVY | XHEAVY |
| 11-15 | .193 | .129 | .182 | .204 |
| 16-20 | .472 | .107 | .257 | .214 |
| 21-25 | .868 | .332 | .482 | .461 |
| 26-30 | 3.409 | 1.383 | 2.091 | 1.276 |
| 31-40 | 14.646 | 6.047 | 8.985 | 7.001 |
| 41-50 | 6.937 | 3.409 | 4.578 | 4.428 |
| 51-70 | 5.264 | 2.938 | 3,753 | 4.053 |
| >70 | 5.050 | 3.452 | 3.259 | 4,139 |

mean* and standard deviation* as well as the combined weighted distributions,

## 6.2 EXAMPLES FOR ARBITRARY WEIGHT-TEMPERATURE DISTRIBUTIONS

The procedure discussed in the previous sections may be extended to any user-supplied weight-times-temperature percentage distribution. For example, if the user weights the overall corrected rolling resistance distributions toward a lower temperature, the weight-times-temperature percentage distribution shown in Table 6-5 might result. Applying this methodology would produce the overall corrected rolling resistance distributions shown in Table 6-6.

Basing a yard's rolling resistance distribution on the assumption of widely varying temperatures is not realistic. The designer usually bases the design of the hump profile on extreme** hard and easy rolling cars, which are assumed to follow one another successively. Under such circumstances, it is not possible that one car would crest the hump at 70 °F and the next car would crest at 10 °F. Basing the design on a widely varying temperature assumption, however, would yield a rolling resistance distribution with a higher variance and therefore a more conservative design.+

*These are approximate values, computed using the midpoint rolling resistance for each histogram cell. A rolling resistance of -1 lb/ton is used for the < 0 cell, and 31 lb/ton is used for the > 30 cell.

**For example, the extreme points of the 95% or 99% range.

+The illustrated examples actually do not show a strong variance trend, probably because the dependence of rolling resistance on temperature is so weak relative to the inherent variability of rolling resistance at any temperature.

Table 6-4

OVERALL DISTRIBUTIONS OF CORRECTED ROLLING RESISTANCE FOR HINKLE YARD

| | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| MEAN RESIS. LB/T | 6.00 | 8.46 | 6.82 | 4.18 |
| STD. DEV. LB/T | 2.38 | 3.86 | 2.27 | 2.47 |
| PCT. < 0 LB/T | .01 | .06 | .02 | .84 |
| PCT. 0- 2 LB/T | .63 | 1.58 | .20 | 8.92 |
| PCT. 2- 4 LB/T | 16.04 | 8.49 | 4.30 | 46.10 |
| PCT. 4- 6 LB/T | 42.02 | 17.93 | 37.16 | 29.59 |
| PCT. 6- 8 LB/T | 23.92 | 21.50 | 33.03 | 9.56 |
| PCT. 8-10 LB/T | 11.45 | 19.91 | 16.67 | 2.48 |
| PCT. 10-12 LB/T | 4.16 | 13.75 | 5.94 | 1.22 |
| PCT. 12-14 LB/T | 1.26 | 8.47 | 1.94 | .47 |
| PCT. 14-16 LB/T | .27 | 4.62 | .51 | .30 |
| PCT. 16-18 LB/T | .12 | 2.15 | .12 | .20 |
| PCT. 18-20 LB/T | .07 | .82 | .05 | .10 |
| PCT. 20-22 LB/T | 0.00 | .32 | .03 | .06 |
| PCT. 22-24 LB/T | 0.00 | .17 | .01 | .07 |
| PCT. 24-26 LB/T | .03 | .07 | 0.00 | .02 |
| PCT. 26-28 LB/T | 0.00 | .06 | 0.00 | .03 |
| PCT. 28-30 LB/T | .01 | .04 | 0.00 | .02 |
| PCT. >30 LB/T | .01 | .03 | 0.00 | .02 |

Table 6-5

PERCENTAGE DISTRIBUTION BY WEIGHT AND TEMPERATURE CLASS: HYPOTHETICAL WEIGHT-TEMPERATURE DISTRIBUTION 1

| | WEIGHT CLASS | | | |
|---|---|---|---|---|
| TEMP | LIGHT | MEDIUM | HEAVY | XHEAVY |
| 11-15 | 3.000 | 3.000 | 3.000 | 3.000 |
| 16-20 | 5.000 | 5.000 | 5.000 | 5.000 |
| 21-25 | 6.000 | 6.000 | 6.000 | 6.000 |
| 26-30 | 4.000 | 4.000 | 4.000 | 4.000 |
| 31-40 | 2.000 | 2.000 | 2.000 | 2.000 |
| 41-50 | 2.000 | 2.000 | 2.000 | 2.000 |
| 51-70 | 1.500 | 1.500 | 1.500 | 1.500 |
| >70 | 1.500 | 1.500 | 1.500 | 1.500 |

Tables 6-7 and 6-8 illustrate an example of basing the overall rolling resistance distribution on a more restricted temperature range. Table 6-7 was prepared under the assumption that the temperature when two successive cars were humped would be about 40 °F; therefore, only the two temperature ranges bracketing 40 °F are given any weight.* This assumption results in the overall corrected rolling resistance distribution in Table 6-8.

*The two temperature ranges are weighted equally.

## 6.3 COMPUTATIONAL EXAMPLE

This section presents an abridged set of computations demonstrating how the data in Table 6-1 can be used to obtain overall corrected rolling resistance distributions. This example corresponds to Hypothetical Distribution 1 of the preceding section, given in Tables 6-5 and 6-6. Only the calculations for the measurement section 1 corrected rolling resistance distribution are shown.

Computation of the overall corrected rolling resistance distribution begins with the cell percentage in the upper left hand corner of Table 6-5. This value is 3%, or 0.03. This multiplies the measurement section 1 resistance distribution in Part 1 of Table 6-1, giving:

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 5.56 \\ 27.78 \\ 27.78 \\ 11.11 \\ 22.22 \\ 5.56 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \times 0.03 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ .1668 \\ .8334 \\ .8334 \\ .3333 \\ .6666 \\ .1668 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (6.7)$$

This process continues, working across the row 1 of Table 6-5 (which is the order in which the parts of Table 6-1 are presented). For example, the calculations for the extra heavy category of row 1 of Table 6-5 would be:

Table 6-6

OVERALL DISTRIBUTIONS OF CORRECTED ROLLING RESISTANCE FOR HYPOTHETICAL WEIGHT-TEMPERATURE DISTRIBUTION 1

| | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| MEAN RESIS. LB/T | 6.75 | 8.86 | 7.68 | 5.00 |
| STD. DEV. LB/T | 2.50 | 3.72 | 2.72 | 3.05 |
| PCT. < 0 LB/T | .00 | .04 | .01 | .48 |
| PCT. 0- 2 LB/T | .22 | .81 | .10 | 4.77 |
| PCT. 2- 4 LB/T | 7.37 | 6.08 | 2.16 | 35.61 |
| PCT. 4- 6 LB/T | 38.22 | 15.29 | 27.01 | 34.35 |
| PCT. 6- 8 LB/T | 29.35 | 23.63 | 32.11 | 15.53 |
| PCT. 8-10 LB/T | 13.80 | 19.58 | 21.26 | 5.37 |
| PCT. 10-12 LB/T | 6.99 | 15.49 | 11.87 | 1.37 |
| PCT. 12-14 LB/T | 3.35 | 9.98 | 3.95 | .62 |
| PCT. 14-16 LB/T | .55 | 5.02 | .60 | .71 |
| PCT. 16-18 LB/T | .05 | 2.76 | .28 | .51 |
| PCT. 18-20 LB/T | .04 | .72 | .01 | .18 |
| PCT. 20-22 LB/T | 0.00 | .12 | .14 | .06 |
| PCT. 22-24 LB/T | 0.00 | .16 | .50 | .02 |
| PCT. 24-26 LB/T | .04 | .02 | 0.00 | .02 |
| PCT. 26-28 LB/T | 0.00 | .18 | 0.00 | .01 |
| PCT. 28-30 LB/T | .01 | .02 | 0.00 | .12 |
| PCT. >30 LB/T | .00 | .01 | 0.00 | .26 |

Table 6-7

PERCENTAGE DISTRIBUTION BY WEIGHT AND TEMPERATURE CLASS: HYPOTHETICAL WEIGHT-TEMPERATURE DISTRIBUTION 2

| | ------------ WEIGHT CLASS ------------ | | | |
|---|---|---|---|---|
| TEMP | LIGHT | MEDIUM | HEAVY | XHEAVY |
| 11-15 | 0.000 | 0.000 | 0.000 | 0.000 |
| 16-20 | 0.000 | 0.000 | 0.000 | 0.000 |
| 21-25 | 0.000 | 0.000 | 0.000 | 0.000 |
| 26-30 | 0.000 | 0.000 | 0.000 | 0.000 |
| 31-40 | 12.500 | 12.500 | 12.500 | 12.500 |
| 41-50 | 12.500 | 12.500 | 12.500 | 12.500 |
| 51-70 | 0.000 | 0.000 | 0.000 | 0.000 |
| >70 | 0.000 | 0.000 | 0.000 | 0.000 |

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 36.84 \\ 57.89 \\ 5.26 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \times 0.03 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1.1052 \\ 1.7367 \\ .1578 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (6.8)$$

The process then repeats across all subsequent rows. For example, the calculations immediately following equation 6.8 above would be:

$$\begin{bmatrix} 0 \\ 0 \\ 2.27 \\ 6.82 \\ 25.00 \\ 29.55 \\ 18.18 \\ 15.91 \\ 2.27 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \times 0.05 = \begin{bmatrix} 0 \\ 0 \\ .1135 \\ .3410 \\ 1.2500 \\ 1.4775 \\ .9090 \\ .7955 \\ .1135 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (6.9)$$

Finally, the right-hand sides of all the computations such as in equations 6-7 through 6-9 are summed to yield:

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ .1668 \\ .8334 \\ .8334 \\ .3333 \\ .6666 \\ .1668 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \ldots + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1.1052 \\ 1.7367 \\ .1578 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ .1135 \\ .3410 \\ 1.2500 \\ 1.4775 \\ .9090 \\ .7955 \\ .1135 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \ldots = \begin{bmatrix} .00 \\ .22 \\ 7.37 \\ 38.22 \\ 29.35 \\ 13.80 \\ 6.99 \\ 3.35 \\ .55 \\ .05 \\ .04 \\ 0.00 \\ 0.00 \\ .04 \\ 0.00 \\ .01 \\ .00 \end{bmatrix} \qquad (6.10)$$

This is the result that was given in Table 6-6.

## 6.4 EFFECT OF HEADWIND

The preceding rolling resistance distributions have been corrected for wind. In design and

Table 6-8

OVERALL DISTRIBUTION OF CORRECTED ROLLING RESISTANCE FOR HYPOTHETICAL WEIGHT-TEMPERATURE DISTRIBUTION 2

| | ROLL. RESIS. M.S. 1 | ROLL. RESIS. M.S. 2 | ROLL. RESIS. M.S. 3 | ROLL. RESIS. M.S. 4 |
|---|---|---|---|---|
| MEAN RESIS, LB/T | 6.31 | 8.51 | 6.93 | 4.27 |
| STD. DEV. LB/T | 2.11 | 3.87 | 2.16 | 2.34 |
| PCT. < 0 LB/T | 0.00 | .09 | 0.00 | .64 |
| PCT. 0- 2 LB/T | .14 | 1.56 | .17 | 6.60 |
| PCT. 2- 4 LB/T | 6.08 | 7.16 | 2 80 | 45.70 |
| PCT. 4- 6 LB/T | 47.78 | 18.95 | 35.04 | 32.67 |
| PCT. 6- 8 LB/T | 27.67 | 22.08 | 35.51 | 9.81 |
| PCT. 8-10 LB/T | 12.96 | 19.35 | 18.59 | 2.17 |
| PCT. 10-12 LB/T | 4.06 | 13.74 | 5.57 | 1.31 |
| PCT. 12-14 LB/T | .91 | 8.50 | 1.69 | .40 |
| PCT. 14-16 LB/T | .17 | 4.74 | .42 | .23 |
| PCT. 16-18 LB/T | .12 | 2.15 | .12 | .19 |
| PCT. 18-20 LB/T | .06 | .87 | .09 | .09 |
| PCT. 20-22 LB/T | 0.00 | .43 | 0.00 | 0.00 |
| PCT. 22-24 LB/T | 0.00 | .14 | 0.00 | .05 |
| PCT. 24-26 LB/T | .02 | .05 | 0.00 | .01 |
| PCT. 26-28 LB/T | 0.00 | .07 | 0.00 | .09 |
| PCT. 28-30 LB/T | 0.00 | .10 | 0.00 | .02 |
| PCT. >30 LB/T | .02 | .02 | 0.00 | 0.00 |

analysis, the additional resistances due to headwind must be taken into account to obtain correct results. The best way of handling headwind is during the analysis itself. Because the headwind effect at every point changes as a function of car speed (see equation 6.1), it is most properly handled by a differential equation formulation taking this dependence into account. However, such an approach would complicate the analysis more than many designers would wish.

Another complication arises from the fact that the parameters A and W in equation 6.1 are also subject to random variability from car to car. Thus, the additional resistance due to headwind, when added into the overall corrected resistance distributions, as shown in Tables 6-4, 6-6, and 6-8, will generally cause the variance of the total resistance distribution to increase over that which would apply if A and W were constants. Addressing this problem mathematically is possible, but the approach is cumbersome. The following paragraphs treat this problem from the standpoint of the extreme cases.

The approach described here is intended to be simple to use. It is aimed toward the special situation where the rolling resistance distribution is desired only for the selection of hard and easy rolling cars for design. It is assumed that the designer has constructed a table similar to Tables 6-4, 6-6, and 6-8 and has selected design hard and easy rolling cars from it.

Combining equations 6.1 and 6.6 yields a conversion from the corrected rolling resistances, RR (the distribution of which was obtained in the previous section), to the effective rolling resistances, $RR_f$, which includes the impeding effect of headwind:

$$RR_f = RR_c + .00103 \cdot A(V-V_w)^2 \cdot \text{sign}(V-V_w)/W \qquad (6.11)$$

Equation 6.11 contains the following variables:

- A , car cross-sectional area ($ft^2$)
- W , car weight (tons)
- V , car speed (ft/sec)
- $V_w$ , wind speed (ft/sec).

Nominal values are selected for V and $V_w$. (This concept of nominal values for these two variables is analogous to that used in Chapter 5 to display the regression results.) For example, typical values might be:

- V = 16 ft/sec
- $V_w$ = 0 ft/sec (zero ambient wind).

Parameters A and W are treated from the standpoint of the easy and hard rolling cars. For the easy rolling car, $RR_f$ will be increased the least when A is small and W is large.

Similarly, for the hard rolling car, $RR_f$ will be increased the most when A is large and W is small.

The user selects "large" and "small" values of these parameters for the particular application. Tables 6-9 and 6-10 are presented as an aid in making this selection. Using the tenth and ninetieth percentile levels in the Tables 6-9 and 6-10 results in the approximate values:

- Easy roller

  A = 80 $ft^2$
  W = 120 tons

Table 6-9

DISTRIBUTION OF "A," CAR BULKHEAD AREA (SQUARE FEET) FOR 10% OF HINKLE YARD SAMPLE

| CODE | ABSOLUTE FREQ | RELATIVE FREQ (PCT) | ADJUSTED FREQ (PCT) | CUM FREQ (PCT) |
|---|---|---|---|---|
| 30.00 | 4 | .4 | .4 | .4 |
| 40.00 | 6 | .6 | .6 | 1.0 |
| 50.00 | 23 | 2.2 | 2.3 | 3.3 |
| 60.00 | 10 | 1.0 | 1.0 | 4.3 |
| 70.00 | 19 | 1.8 | 1.9 | 6.2 |
| 80.00 | 41 | 3.9 | 4.1 | 10.3 |
| 90.00 | 8 | .8 | .8 | 11.1 |
| 100.00 | 17 | 1.6 | 1.7 | 12.8 |
| 110.00 | 10 | 1.0 | 1.0 | 13.8 |
| 120.00 | 15 | 1.4 | 1.5 | 15.3 |
| 130.00 | 22 | 2.1 | 2.2 | 17.5 |
| 140.00 | 33 | 3.2 | 3.3 | 20.8 |
| 150.00 | 72 | 6.9 | 7.2 | 28.0 |
| 160.00 | 667 | 64.1 | 66.7 | 94.7 |
| 170.00 | 19 | 1.8 | 1.9 | 96.6 |
| 180.00 | 31 | 3.0 | 3.1 | 99.7 |
| 190.00 | 3 | .3 | .3 | 100.0 |
| 0 | 40 | 3.8 | MISSING | |
| TOTAL | 1040 | 100.0 | 100.0 | |

- Hard roller

$A = 158\ ft^2$
$W = 28$ tons.

Using the above values in equation 6.11 results in:

- Easy-rolling car

$$RR_{f,e} = RR_{c,e} + .00103 \cdot 80 \cdot (16-0)^2/120$$
$$= RR_{c,e} + 0.18 \qquad (6.12)$$

- Hard-rolling car

$$RR_{f,h} = RR_{c,h} + .00103 \cdot 158 \cdot (16-0)^2/28$$
$$= RR_{c,h} + 1.49 \qquad (6.13)$$

Table 6-10

DISTRIBUTION OF "W," CAR LOADED WEIGHT (TONS) FOR 10% OF HINKLE YARD SAMPLE

| CODE | ABSOLUTE FREQ | RELATIVE FREQ (PCT) | ADJUSTED FREQ (PCT) | CUM FREQ (PCT) |
|---|---|---|---|---|
| 20.00 | 16 | 1.5 | 1.5 | 1.5 |
| 30.00 | 263 | 25.3 | 25.3 | 26.8 |
| 40.00 | 198 | 19.0 | 19.0 | 45.9 |
| 50.00 | 65 | 6.3 | 6.3 | 52.1 |
| 60.00 | 57 | 5.5 | 5.5 | 57.6 |
| 70.00 | 50 | 4.8 | 4.8 | 62.4 |
| 80.00 | 69 | 6.6 | 6.6 | 69.0 |
| 90.00 | 68 | 6.5 | 6.5 | 75.6 |
| 100.00 | 43 | 4.1 | 4.1 | 79.7 |
| 110.00 | 48 | 4.6 | 4.6 | 84.3 |
| 120.00 | 36 | 3.5 | 3.5 | 87.8 |
| 130.00 | 114 | 11.0 | 11.0 | 98.7 |
| 140.00 | 8 | .8 | .8 | 99.5 |
| 150.00 | 1 | .1 | .1 | 99.6 |
| 160.00 | 1 | .1 | .1 | 99.7 |
| 180.00 | 1 | .1 | .1 | 99.8 |
| 190.00 | 2 | .2 | .2 | 100.0 |
| TOTAL | 1040 | 100.0 | 100.0 | |

where

$RR_{c,e}$ = effective rolling resistance of easy rolling car (lb/ton)

$RR_{r,e}$ = rolling resistance (lb/ton) of easy rolling car as selected by user from distributions constructed as discussed in Sections 6.2 through 6.4

$RR_{f,h}$ = effective rolling resistance of hard rolling car (lb/ton)

$RR_{c,h}$ = rolling resistance in (lb/ton) of hard rolling car as selected by user from distributions constructed as discussed in Sections 6.2 through 6.4.

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## APPENDIX A: STATISTICAL ANALYSIS OF ENGLEWOOD YARD EXPERIMENTAL DATA

### A.1 METHODS USED TO COLLECT THE DATA

SRI collected these data on Englewood Yard during a study conducted in 1970 for Southern Pacific (Gardiner et al., 1970).

To collect the Englewood Yard data, SRI used special electronic switches* taped to the rail at 32 locations on one track route from the hump to the classification tracks. These electronic switches gave the passage times of selected cars at each location by timing the passage of the first wheel; which caused each electronic switch in turn to close.

Paired with each passage time at an electronic switch was the known location of that switch, measured as the distance from an arbitrary origin (essentially the hump crest). Distance control was maintained by surveying the location of each electronic switch. Thus, the data consisted of paired distance-time points [(X,t) points]. Table A-1 presents data on the rolling of one of the cars in the Englewood Yard data set (selected arbitrarily as a typical case). Such data were obtained for 56 cars in the data base. The number of data points for individual cars varied fairly uniformly from 8 to 16; to have sufficient points for the analysis, any cars for which there were fewer than 8 points were excluded.

The electronic switches were also paired at about 10-foot intervals to create a speed trap for estimating the car's speed (V). (These estimated speeds are indicated in Table A-1.) In this analysis, however, these estimated speeds were not required (with one exception), so the pairing of successive electronic switches was ignored.

In this analysis, only that portion of each car's roll that occurs on the "constant-grade" section of the classification track was considered; this restriction eliminated additional complexity in the analysis. A "constant" grade is a theoretical concept because irregularities arise during construction and from settling. Therefore, SRI made precise survey measurements of the elevation of the top of the rail near each electronic switch and used in the analysis an average effective grade: the drop from the first to last electronic switch divided by the distance between these electronic switches.**

*Not to be confused with rail switches; to avoid this confusion, the special instrumentation is referred to as "electronic switches."

**The first and last switches were those actually used and varied from car to car.

Table A-1

TYPICAL ENGLEWOOD YARD DATA SET FOR ONE CAR; RUN 91

| t (sec) | X (ft) | V (ft/s) |
|---|---|---|
| $t_o$= 63.000 | $X_o$= 2123.02 | $V_o$= 10.89 |
| 63.994 | 2133.84 | |
| 81.782 | 2322.50 | 10.43 |
| 82.874 | 2333.89 | |
| 101.061 | 2521.54 | 9.83 |
| 102.206 | 2532.79 | |
| 121.251 | 2720.64 | 9.67 |
| 122.609 | 2733.77 | |
| 142.427 | 2923.25 | 9.03 |
| 143.649 | 2934.29 | |
| 164.390 | 3121.33 | 8.85 |
| 165.878 | 3134.50 | |
| 187.648 | 3321.95 | 8.45 |
| 189.000 | 3333.37 | |
| 211.314 | 3521.79 | 8.45 |
| 212.644 | 3533.03 | |

### A.2 ROLLABILITY MODEL USED FOR ANALYSIS

In this analysis, one of the most common rollability models (Wong et al., 1981) was used, that is, that each car's rolling resistance varies linearly as a function of its speed. Each car was treated for the purpose of its dynamics as a point mass, the motion of which is governed by the following differential equations:

$$\frac{d^2X}{dt^2} = \frac{dV}{dt} = \alpha + \beta V \quad , \tag{A.1}$$

$$\alpha = g_e\left(G - \mu - C - W - \frac{S}{L} - \frac{R}{L}\right) \quad , \tag{A.2}$$

$$\beta = g_e(-\mu_V - W_V) \quad , \tag{A.3}$$

$$g_e = \left[\frac{T}{T + I}\right] g \quad , \tag{A.4}$$

where

- X = distance from an arbitrary origin (ft)
- V = velocity of the car (ft/sec)
- t = time (sec)
- $\alpha$ = the sum of all static terms contributing to the acceleration of the car ($ft/sec^2$)
- $\beta$ = the sum of all velocity-dependent terms contributing to the acceleration of the car ($sec^{-1}$)
- $g_e$ = the effective acceleration of gravity used to account for energy stored in the rotating wheels of the car ($ft/sec^2$)
- g = acceleration of gravity ($ft/sec^2$)
- G = grade (downgrades taken positive) (ft/ft)
- $\mu$ = static rolling resistance (lb/lb)
- C = curve resistance, if applicable (lb/lb)
- W = wind resistance (lb/lb)
- S = velocity head lost in switch if applicable (ft)
- R = velocity head extracted by retarder if applicable (ft)
- L = length of the section of track (ft)
- $\mu_V$ = velocity-dependent resistance coefficient (lb/lb per ft/sec)
- $W_V$ = velocity-dependent wind resistance coefficient (lb/lb per ft/sec)
- T = weight of the car (lb)
- I = additional weight of the car to account for the rotation of the wheels (lb).

The solutions of the differential equation for $\beta \neq 0$ and taking $V = V_o$ and $X = X_o$ at $t = 0$ are:

$$V = -\frac{\alpha}{\beta} + \left(\frac{\alpha}{\beta} + V_o\right) \exp(\beta t) \qquad (A.5)$$

and

$$X = X_o - \frac{\alpha}{\beta} t - \frac{1}{\beta}\left(\frac{\alpha}{\beta} + V_o\right) [1 - \exp(\beta t)] \qquad (A.6)$$

For $\beta = 0$ (i.e., only static rolling resistance), the solutions reduce to the well-known case of uniformly accelerated motion (for the above boundary conditions), as follows:

$$V = V_o + \alpha t \qquad (A.7)$$

and

$$X = X_o + V_o t + \frac{1}{2}\alpha t^2 \quad . \qquad (A.8)$$

The $\beta = 0$ case is the usual static rolling resistance formulation and is the one used in most other analyses in this report. Equation A.8 is indeed mathematically the limit of equation A.6 as $\beta \to 0$.

Equations A.1 through A.4 were simplified considerably for this analysis. A track section that has essentially a constant grade (except for settling) and that has no switches, retarders or curvature was deliberately selected; thus C, S, and R in equation A.2 were all zero. Further, the wind effect was not considered as a separate term (no matching wind data were available), so W in equation A.2 and $W_V$ in equation A.3 were zero.* In addition, the inertia effect of the rotating wheels was ignored, making I zero in equation A.4. With these simplifications, equations A.2 and A.3 can be rewritten as, respectively:

$$\alpha = g(G - \mu) \qquad (A.9)$$

$$\beta = g(-\mu_V) \quad . \qquad (A.10)$$

For convenience, one further change was made. In equations A.9 and A.10 the resistances are expressed in the unitless form appropriate for analysis. However, expressing the resistance in pounds per ton is more convenient for reporting purposes. Therefore, equations A.9 and A.10 were rewritten as:

$$\alpha = g\left(G - \frac{R_s}{2000}\right) \qquad (A.11)$$

$$\beta = g\left(-\frac{R_v}{2000}\right) \quad , \qquad (A.12)$$

where

- $R_s$ = static component of car resistance (lb/ton)
- $R_V$ = velocity-dependent component of car resistance (lb/ton per ft/sec).

## A.3 STATISTICAL ANALYSIS

The solutions of the differential equations, specifically equations A.6 and A.8, provide an analytical relationship between a car's distance and time that precisely matches the empirical data obtained in the Englewood Yard study (Table A-1). The general solution of differential equation A.6 is in a nonlinear form, but nonlinear regression statistical techniques can be used calibrate the parameters $\alpha$ and $\beta$ or alternatively $R_s$ and $R_V$. Further, because the origins used for t and X in the data (Table A-1) are entirely arbitrary, the first (X,t) data point for each car can be treated as the origin for that analysis with no loss of generality; this is done by subtracting $t_o$ from all the other t values and subtracting $X_o$ from all the other X values.**

This simple transformation ensures compliance with the boundary conditions used to derive equations A.5 through A.8, and further eliminates the parameter $X_o$.

---

*This effectively includes the wind resistance into the $\mu$ and $\mu_V$ terms.

**In Table A-1, subtract 63.000 from all the values in the t column and subtract 2123.02 from all the values in the X column.

The parameter $V_0$ is required in equation A.6 or A.8; it could be estimated as a part of the regression or it could be estimated using the first two (X,t) points in the data for each car, as shown in Table A-1. The latter approach was used in this analysis.

SRI used a procedure in SPSS (Nie et al., 1975; Robinson, 1977) to perform a separate nonlinear regression for each car in the Englewood Yard data base. The procedure progresses iteratively. It must be supplied with an initial starting point; on the basis of past experience, SRI used $R_s$ = 2.1 lb/ton and $R_v$ = 0.55 lb/ton per ft/sec for all cars. The procedure then modifies the parameters $R_s$ and $R_v$ so as to improve the fit* of the theoretical relation (equation A.6 or A.8) to the empirical data (as in Table A-1). The iterations proceed until a local, global minimum is attained. As with many iterative procedures, convergence is not guaranteed.

Equations A.6 and A.8 treat X as the dependent variable with t being the independent variable; but in the Englewood Yard data these roles were actually reversed. Although the strict statistical approach would have been to solve equation A.6 (A.8) for t as a function of X, the transcendental nature of equation A.6 prevented that approach. Consequently, for each car t was treated as if it were the independent variable and equation A.6 (or A.8) was used to estimate X. This approach was most likely to produce practical, pragmatic results.

"Reasonable"** results were obtained from the regression for 39 of the 56 cars in the data base. In most cases, the fitted relationship (equation A.6) gave an excellent representation of the car's rolling behavior on the classification track. Figure A-1 is a histogram of the standard deviations of the empirical points about the fitted relationships (for each car in the data base for which reasonable results were obtained, one standard deviation value was obtained). For one car, the standard deviation can be considered as representing the average error in using the theoretical relationship to estimate the car's position in place of the actual empirical data. These standard deviations are generally quite small, mostly on the order of 2 feet or less over a total distance of more than 1,000 feet. Even considering that the accumulative nature of a distance-time trace tends to make errors in a regression small, the quality of the fitted curves to the data is

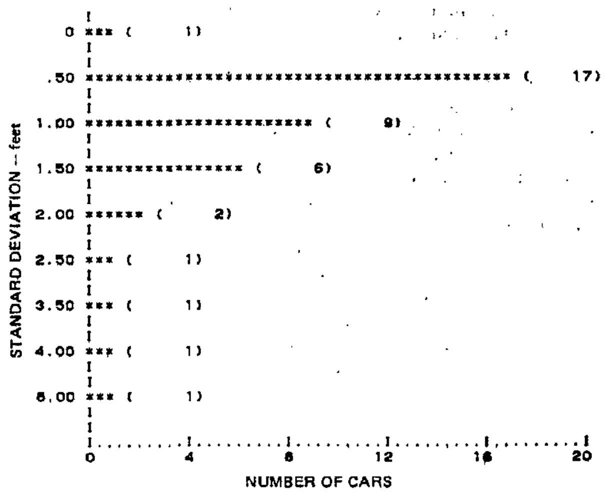



FIGURE A-1 HISTOGRAM OF STANDARD DEVIATIONS BETWEEN FITTED THEORETICAL RELATIONSHIPS AND EMPIRICAL DATA

generally excellent. Figure A-2 is an example of the fidelity of the fitted relationship to the empirical data points. This plot of the data and fitted relationship for Run 91, shown earlier in Table A-1, reveals that the difference between the empirical data and the fitted curve is barely discernible.

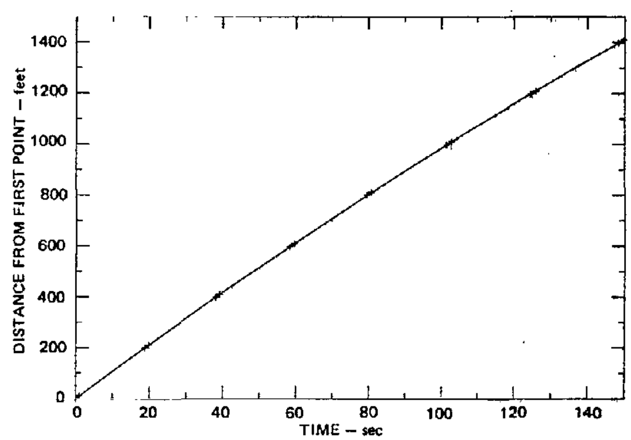



FIGURE A-2 DATA POINTS AND FITTED RELATIONSHIPS FOR RUN 91

As mentioned, reasonable results for 17 of the cars in the data base were not obtained because:

- Eight cases failed to converge to a solution.
- Seven converged to a solution that was unreasonable.

---

*The fit is measured as the sum of the squared differences between the empirical data points and the theoretical relation, using the latest estimate of the desired parameter values.

**In this context, "reasonable" means that the nonlinear iterative regression process converged and that the resulting parameter values roughly agreed with our own experience and with the literature.

- Two converged to a reasonable solution but had minor data errors and so were discarded.

Table A-2 presents the (X,t) points for Run 213, which converged but to unreasonable parameter values. As the table indicates, the speeds of the car were highly inconsistent. The actual data collected were times, not speeds, and the inconsistent nature of the time is best represented graphically in Figure A-3, where the data problems are revealed as a "wavy" X-t plot. These problems may be due to erroneous times given by the electronic switches or to conditions not accounted for in the rollability model, such as gusty, variable winds, wheels badly out-of-round, curve memory, or sloshing of liquid in tank car.

Table A-2

DATA SET FOR RUN 213

| t (sec) | X (ft) | V (ft/sec) |
|---|---|---|
| $t_o$ = 89.932 | $X_o$ = 2123.02 | $V_o$ = 6.606 |
| 91.570 | 2133.84 | |
| | | 3.791 |
| 141.340 | 2322.50 | |
| | | 6.163 |
| 143.188 | 2333.89 | |
| | | 6,057 |
| 174.167 | 2521.54 | |
| | | 5.838 |
| 176.094 | 2532.79 | |
| | | 3.486 |
| 229.982 | 2720.64 | |
| | | 5.466 |
| 232.384 | 2733.77 | |
| | | 5.310 |
| 268.068 | 2923.25 | |
| | | 4.730 |
| 270.402 | 2934.29 | |
| | | 3.045 |
| 331,836 | 3121.33 | |
| | | 4.422 |
| 334.814 | 3134.50 | |
| | | 4.159 |
| 379.880 | 3321.95 | |
| | | 4.120 |
| 382.652 | 3333.37 | |
| | | 2.958 |
| 446.349 | 3521.79 | |
| | | 4.577 |
| 448.805 | 3533.03 | |

In every case that failed to converge to a solution, or that converged to unreasonable results, problems existed in the data that were similar to those shown in Table A-2 and Figure A-3. Further, in the 39 cases that yielded reasonable results, the data invariably appeared to be fairly valid and were usually totally valid. Thus, the nonlinear regression technique may be a good indicator of the validity of the data on each car. Deciding whether data are "reasonable" or "unreasonable" is a subjective decision; therefore, among the 39 cases for which reasonable results were obtained are a few for which reasonableness is marginal.

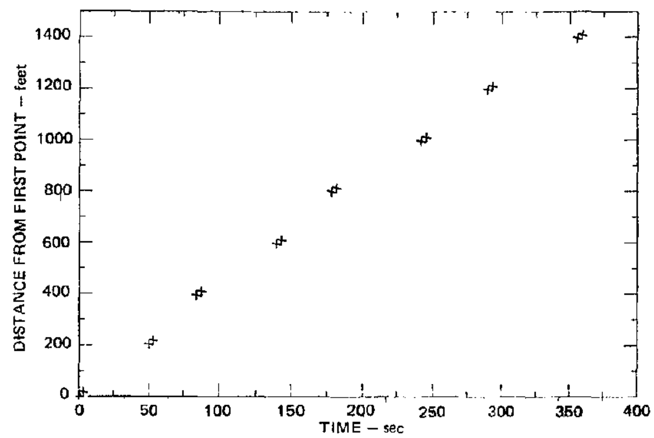



FIGURE A-3 DATA POINTS FOR RUN 213

Figure A-4 is a histogram of the distribution of the parameter $R_S$, the static portion of the rolling resistance. Similarly, Figure A-5 is a histogram of $R_V$, the velocity-dependent portion of the rolling resistance. The range of values for both parameters appears to be consistent with values reported in the literature. The empirical distributions of both parameters include zero within their range. Thus, at least some of these parameters might be expected not to differ significantly from zero in the statistical sense. However, only an approximate statistical test is available to test such an hypotheses—namely,

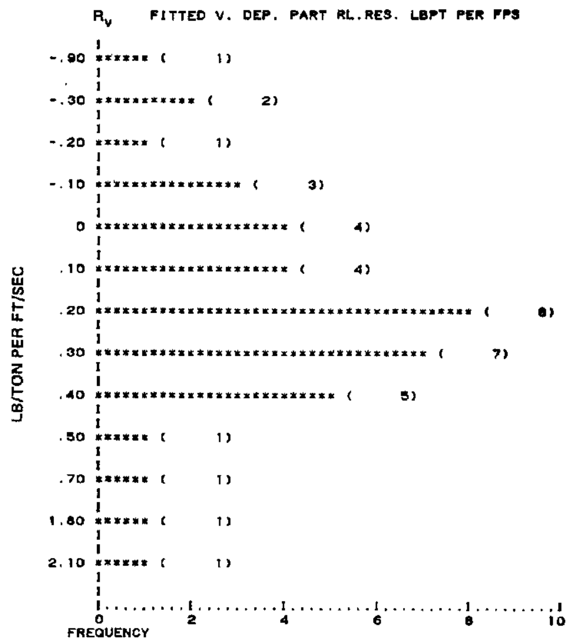
```
STATISTICAL ANALYSES ON FITTED RESIS. PARAM. FOR ENGLWD. DATA
FILE   NONLPAR  (CREATION DATE =  81/05/07.)

      RS      FITTED STATIC PART OF ROLL. RES., LB P T
             I
      -12.  ****** (      1)
             I
       -5.  ****** (      1)
             I
       -2.  *************** (      3)
             I
        0   *************** (      3)
             I
        1.  **************************************** (      8)
 LB/TON      I
        2.  ********************************************* (      9)
             I
        3.  ****************************** (      6)
             I
        4.  ************************* (      5)
             I
        6.  *************** (      3)
             I
             I.........I.........I.........I.........I.........I
             0         2         4         6         8        10
             FREQUENCY

MEAN        1.513     STD ERR       .505     MEDIAN      1.889
MODE        2.000     STD DEV      3.153     VARIANCE    9.941
KURTOSIS    8.304     SKEWNESS    -2.227     RANGE      18.000
MINIMUM   -12.000     MAXIMUM      6.000     SUM        59.000
C.V. PCT  208.410     .95 C.I.      .491          TO     2.535

VALID CASES      39     MISSING CASES      0
```

FIGURE A-4 DISTRIBUTION OF $R_S$ PARAMETER




STATISTICAL ANALYSES ON FITTED RESIS. PARAM. FOR ENGLWD. DATA

FILE NONLPAR (CREATION DATE = 80/03/19.)

| | | | | | |
|---|---|---|---|---|---|
| MEAN | .236 | STD ERR | .078 | MEDIAN | .206 |
| MODE | .200 | STD DEV | .489 | VARIANCE | .239 |
| KURTOSIS | 7.566 | SKEWNESS | 2.001 | RANGE | 3.000 |
| MINIMUM | -.900 | MAXIMUM | 2.100 | SUM | 9.200 |
| C.V. PCT | 207.101 | .95 C.I. | .078 | TO | .394 |

VALID CASES 39 MISSING CASES 0

FIGURE A-5 DISTRIBUTION OF $R_V$ PARAMETER

that based on the assumption of a linear estimator. Using this test, SRI found that 11 of the 39 estimated values of $R_s$ and 10 of the 39 estimated values for $R_v$ did not differ significantly from zero.

Note that the total, or gross, resistance for any one car at any given speed is computed by

$$RR = R_s + R_v * V \qquad (A.13)$$

where

RR = total, or gross, resistance of the car at speed V (lb/ton)
V = instantaneous speed of the car (ft/sec).

Equation A.13 defines a straight line in the RR-V plane; to better represent the nature of these data, in Figure A-6 the 39 resulting straight lines are plotted for the cars for which reasonable results were obtained. The curves in the range of 5 to 15 ft/sec are drawn with bolder lines. Most of the speeds in the Englewood data set were in this range; the lighter portions of these lines are essentially

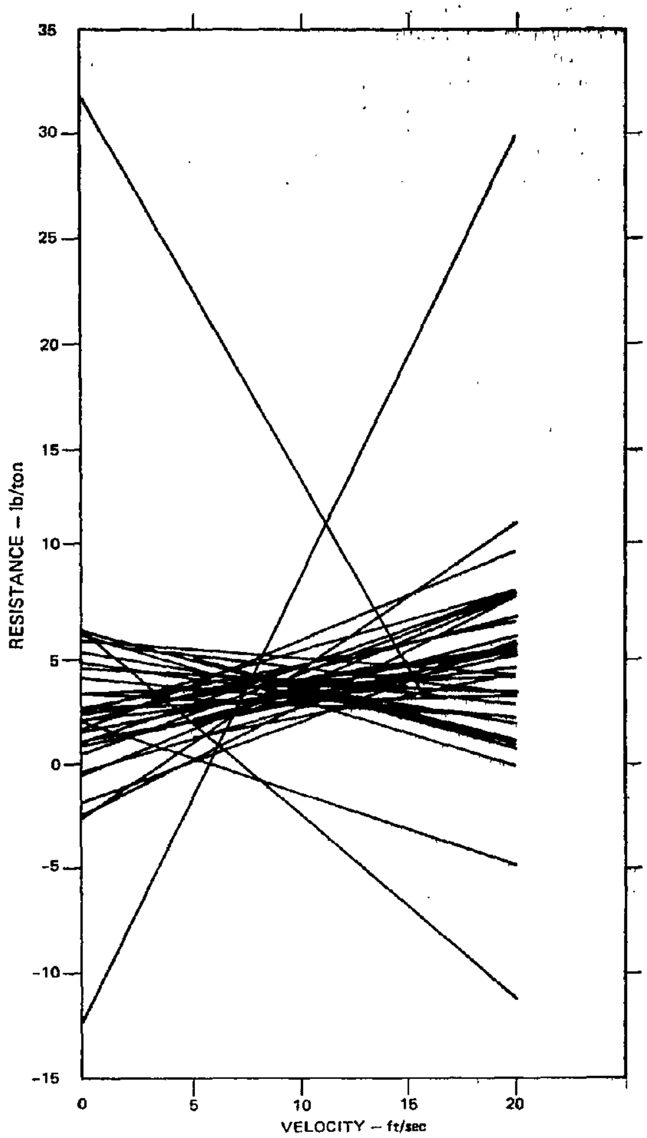



FIGURE A-6 TOTAL RESISTANCE AS AN INSTANTANEOUS FUNCTION OF VELOCITY FOR FITTED RELATIONSHIPS FOR ENGLEWOOD YARD DATA

extrapolations. The four lines noticeable as outliers represent the most questionable cases of the 39 that were accepted as being reasonable. The general trend indicated in Figure A-6 is for resistance to increase with increasing speed; however, a number of exceptions are evident. Nevertheless, the general tendency to increase noted in this illustration agrees with the literature.

To investigate whether any relationship exists between the parameters $R_s$ and $R_v$ for a car, SRI performed a correlation analysis (or bivariate regression), treating the fitted values of

$R_s$ as observations of an independent variable and $R_v$ as observations of a dependent variable. Figure A-7, a scatterplot of the $R_v$ data points as a function of the $R_s$ points, presents the results of this analysis. A strong relationship between these parameters appears to exist. Indeed, the statistics printed in Figure A-7 indicate that $R_v$ can be estimated from $R_s$ by the relationship

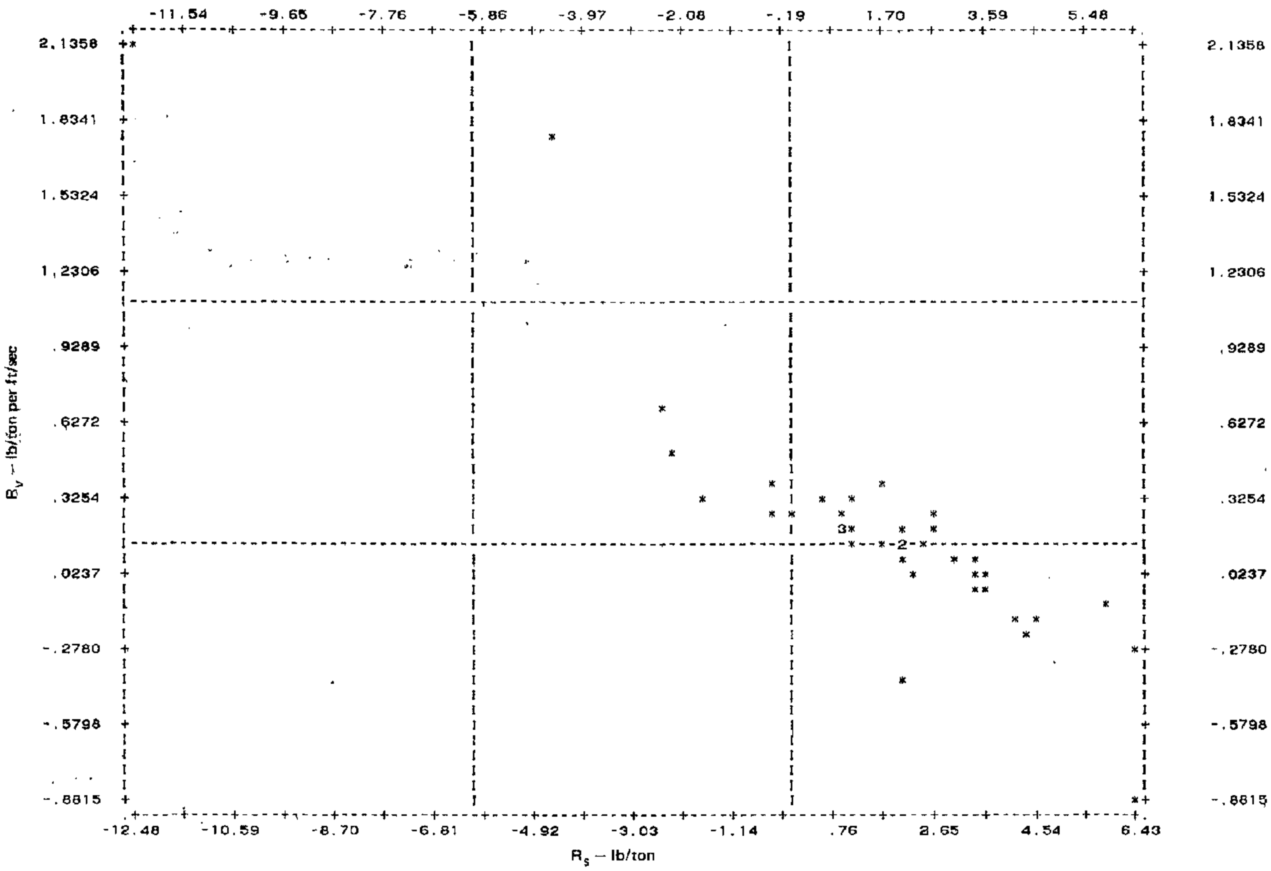
$$R_v = .44 - .138 * R_s \quad . \qquad (A.14)$$

The standard deviation about this regression equation is 0.202 lb/ton per ft/sec, a reduction by more than a factor of 2 from the standard deviation of $R_v$ by itself (reported in Figure A-5): 0.489 lb/ton per ft/sec.

However, whether the trend evident in Figure A-7 represents an actual physical relationship is not clear. To a considerable extent, a significant trade-off is possible between the parameters $R_s$ and $R_v$ for a single car. This is most easily

STATISTICAL ANALYSES ON FITTED RESIS. PARAM. FOR ENGLWD. DATA 81/05/07. 15.3 PAGE 3

FILE NONLPAR (CREATION DATE = 81/05/07.)
SCATTERGRAM OF (DOWN) VELRES FITTED V. DEP. PART RL.RES, LBPT PER FPS (ACROSS) STRES FITTED STATIC PART OF ROLL. RES., LB P




STATISTICAL ANALYSES ON FITTED RESIS. PARAM. FOR ENGLWD. DATA 81/05/07. 15.3 PAGE 4

STATISTICS..

| | | | | | |
|---|---|---|---|---|---|
| CORRELATION (R)- | -.91421 | R SQUARED - | .83577 | SIGNIFICANCE R - | .00001 |
| STD ERR OF EST - | .20182 | INTERCEPT (A) - | .44377 | STD ERROR OF A - | .03576 |
| SIGNIFICANCE A - | .00001 | SLOPE (B) - | -.13767 | STD ERROR OF B - | .01003 |
| SIGNIFICANCE B - | .00001 | | | | |
| PLOTTED VALUES - | 39 | EXCLUDED VALUES- | 0 | MISSING VALUES - | 0 |

******** IS PRINTED IF A COEFFICIENT CANNOT BE COMPUTED.

FIGURE A-7 REGRESSION AND SCATTER DIAGRAM BETWEEN FITTED $R_v$ AND FITTED $R_s$

explained qualitatively in terms of the lines in Figure A-6. Consider the region roughly outlined by the largest mass of heavy lines--the region that supplied most of the data for the analysis. A line can be drawn passing through this region by--

- Making $R_s$ small (e.g., ∿ zero), but compensating for this by increasing $R_v$ (e.g., ∿ .333 lb/ton per ft/sec).
- Making $R_v$ small (e.g., ∿ zero), but compensating by increasing $R_s$ (e.g., ∿ 4 lb/ton).

This trade-off could yield precisely the type of relationship indicated in Figure A-7. Without more data covering a wider range of speeds and conditions, it is not possible to determine to what extent this trade-off has brought about the relationship shown in Figure A-7. Statistical estimation theory, however, would indicate that a portion of the trend of Figure A-7 is due to this trade-off, rather than to an underlying physical relationship.

## A.4 CONCLUSIONS

This appendix presents a methodology for estimating speed-dependent rolling resistance relationships on a car-by-car basis. It is distinct from approaches used in most other rollability investigations, in which only the relationships for a mass of many cars are studied. Thus, those investigations do not isolate the relationships applying to particular individual cars. This analysis has shown that the linear speed dependence parameter is usually significant. However, the question arises of whether this speed-dependent relationship truly adds a statistically significant amount of information over that which would be obtained if the regression were to be repeated using a model having only a static resistance term (i.e., delete the β term from equation A.1). This additional analysis is one avenue for future work. The model of equation A.1 could also be expanded to include a squared speed dependence term (e.g., a $\gamma V^2$ term could be added). This would bring this model into conformance with the most commonly mentioned model in the literature, allowing investigation of the $V^2$ dependence.

Also, $V_o$ could be added as a parameter to the least-squares estimation process using equation A.6. This would permit additional flexibility in fitting the model to the data and would probably reduce the sensitivity of the model to errors in the data--especially in situations where errors occurred in the first two (X,t) points, which were used to estimate $V_o$.

Another avenue for further work would be to estimate the parameters using the (V,t) points rather than the (X,t) points (e.g., using equations A.5 or A.7). The empirical (V,t) relationship would usually be less smooth than the (X,t) relationship and so might yield a poorer fit to the model; at least this would be an interesting alternate to study.

Obtaining data from a wider range of conditions would also be worthwhile. Not only would this wider data base shed more light on the validity (or lack thereof) of the relationship shown in Figure A-7, but it could allow extension of the analysis to include situations involving switches and track curvature, perhaps also permitting calibration of these effects.

Finally, further work could be conducted within the limited context of the analysis reported here. For example, when data points are obviously erroneous, those points could be eliminated and the analysis repeated. Because this was a preliminary analysis, SRI did not attempt such "massaging" of the data. Rather, only a preliminary investigation was attempted of the workability of the nonlinear regression approach to the study of the individual car's behavior. In future rollability studies, the approach documented in this appendix would be perhaps the strongest for obtaining useful, valid results.

# APPENDIX B: DETAILED DISCUSSION OF REGRESSION ANALYSES

## B.1 GENERAL

This appendix describes the regression analyses that were performed to investigate and calibrate the effects of several variables on freight car rolling resistance. Certain problems in the data due to the way in which they were collected are discussed, as are the actions taken to address them. The specific quantitative results obtained are discussed at the end of this appendix.

The data available from Hinkle and DeWitt yards are detailed in Chapter 4 and briefly reviewed below. The analyses described in this appendix are based solely on these two yards.

The rolling resistance observations were made in four measurement sections between the crest and the classification tracks. The first two measurement sections were short, and the third and fourth were generally long. Coupled with each rolling resistance observation in each measurement section was a "vector" of independent variables. The set of observed variable values (both dependent and independent) corresponding to one observation at one point along the track is called a case. This is the terminology used in SPSS (Nie et al., 1975), the commercial software package that was used to perform these analyses. The four observations on a single car were treated as separate cases. Thus, the independent variables varied in different ways--some were constant within the cases for a single car (e.g., truck center length), some were constant within the cases for a single measurement section and track (e.g., curve variables), and some varied for every case regardless of car and/or measurement section (e.g., car speed).

One important variable is the car's speed within the measurement section. Measurement sections 1 and 2 were short, so for these sections an estimate of the measurement section midpoint speed was also used as the average speed within the measurement section. Measurement sections 3 and 4 were long and had varying geometry within them on a single route. Therefore, in these measurement sections the average speed was computed as:

$$V_{av} = \frac{V_1 + V_2 + V_3}{4} \quad (B.1)$$

where

$V_{av}$ = estimated average speed within the measurement section

$V_1$ = entry speed to the measurement section

$V_2$ = midpoint speed of the measurement section

$V_3$ = exit speed from the measurement section.

Depending on the measurement section, various $V_1$, $V_2$, and $V_3$ values may themselves have been estimates.

## B.2 SOME MATHEMATICAL DETAILS OF THE REGRESSION

The analyses discussed here are stepwise, multiple linear regressions, using rolling resistance or resistance force as the dependent variable against a host of independent variables. The approach used was largely exploratory, several regressions being performed in an iterative manner to obtain a qualitative as well as quantitative grasp of the nature of the dependencies in the data.

In addition to revealing dependencies between the dependent variable and the independent variables, regression analysis calibrates an actual relationship that can be used to estimate the dependent variable from the independent variables. This relationship is of the form:

$$\hat{y} = a_o + a_1x_1 + a_2x_2 + a_3x_3 + \ldots \quad (B.2)$$

where

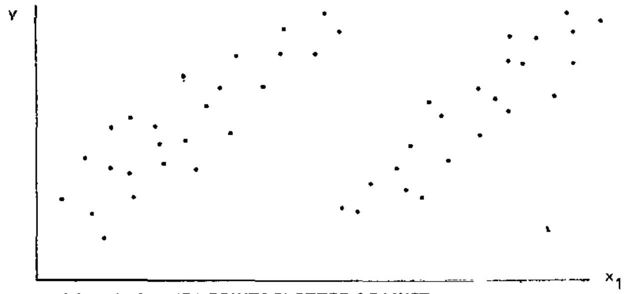
$\hat{y}$ = estimated value of the dependent variable y

$x_1$, $x_2$, = the independent variables

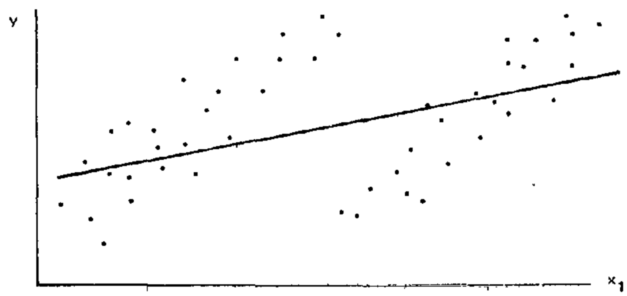
$a_o$, $a_1$, $a_2$, = calibration coefficients estimated by the regression analysis.

The individual $x_i$ variables can be directly available variables or transformations of directly available variables. (Various classes of $x_i$ are discussed later.)

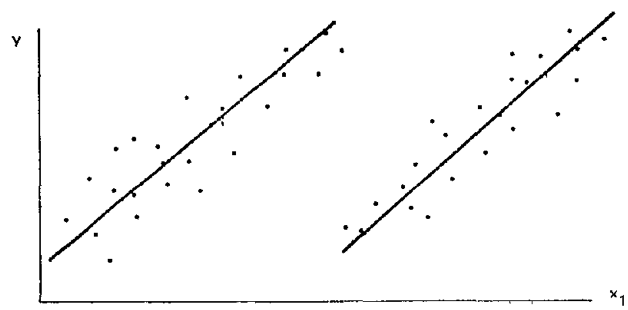
A strength of regression analysis is its ability to assess the effect of each independent variable in conjunction with the effects of all other independent variables, thereby unmasking effects hidden when only bivariate relationships are examined. For example, Figure B-1(a) is a plot of hypothetical y values against an $x_1$ independent variable. A bivariate relationship between y and $x_1$ would yield the relationship shown in Figure B-1(b). However, the points fall into two distinct groups. Supposing that these groups represent two distinct values of a third variable, $x_2$, including both independent variables $x_1$ and $x_2$ in the equation results in a much more significant explanation of the relationship between y, $x_1$, and $x_2$, as shown in Figure B-1(c).* In Figure B-1(c), the two curves can be thought of as the $x_2$ contours of the regression surface in the y, $x_1$ plane.




(a) OBSERVED POINTS PLOTTED AGAINST $x_1$




(b) REGRESSION CURVE FOR BIVARIATE RELATIONSHIP $y = a_o + a_1 x_1$




(c) REGRESSION SURFACE FOR MULTIVARIATE RELATIONSHIP $y = a_o + a_1 x_1 + a_2 x_2$

FIGURE B-1 HYPOTHETICAL REGRESSION

One problem often encountered in regression analyses is that when two or more independent variables tend to vary in much the same way (i.e., are highly correlated), discerning among the effects of these variables may be difficult or impossible. This problem, called multicolinearity, occurred with some of the independent variables reported here and are discussed in Section B.3.1.

The rest of this section discusses the nature of the $x_i$ used in the regression.

### B.2.1 Simple Nonlinear Transformations

It is often customary to take a transformation of some directly observed independent variable to account for nonlinearities, which by engineering judgment are believed to exist. For example, such a transformation might be:

$$x_3 = \ln (x_3') \qquad \text{(B.3)}$$

where

- $x_3$ = "variable" as entered in the regression analysis
- $x_3'$ = some variable that would be actually measured or available (such as distance from the hump crest to the measurement section).

This logarithmic transformation was actually made for one of the variables used in this analysis, distance from hump crest. This variable was a surrogate for the warm-up of the journal bearings as the car rolled farther and farther. However, this warm-up was not expected to continue indefinitely; eventually, the journal bearings should tend toward some steady-state temperature. The logarithmic transformation is useful because it enabled SRI to create an independent variable that conformed approximately to this behavior.

Another transformation used was of the form:

$$x_3 = 1/x_3' \quad . \qquad \text{(B.4)}$$

This reciprocal transformation was used for the car weight independent variable, because the rolling resistance is theoretically the inverse of the car's weight.** A reciprocal transformation for the distance from the most recently traversed oiler was also used. Not only was the oiler's effect expected to taper off in some "decay" manner, but also the cars initially humped were expected not to have passed an oiler for some time.* Therefore, this distance was set as "infinity" for the measurement sections preceding the master and group retarders. Whereas "infinity" cannot be handled in a regression, the reciprocal of "infinity," zero, can be.

### B.2.2 Polynomial Power Terms

The individual $x_i$ can be powers of other $x_i$, for example,

$$x_4 = x_3^2 \quad . \qquad \text{(B.5)}$$

However, a transformation such as in equation B.5 would generally result in the entrance into the equation of two highly correlated independent variables, which is undesirable. To avoid this problem, squared terms were entered into the equation in the alternative form:

$$x_4' = (x_3 - \overline{x}_3) \qquad \text{(B.6)}$$

Where $\overline{x}_3$ is the mean value of all the observed values for the variable $x_3$. The $x_4'$ term primarily picks up only that part of the dependence of y on $x_3$ that is of a squared nature, allowing testing of such squared dependence, and drives down the correlation between $x_3$ and $x_4'$. The regression using the $x_4$ term can be transformed after the analysis into the form that would have existed had equation B.4 been used, by noting

$$\begin{aligned}\hat{y} &= a_0' + a_3' x_3 + a_4' x_4' + \ldots \\ &= a_0' + a_3' x_3 + a_4'(x_3 - \overline{x}_3)^2 + \ldots \\ &= (a_0' + a_4' \overline{x}_3^2) + (a_3' - 2a_4' \overline{x}_3)\, x_3 + a_4' x_3^2 + \ldots \\ &= a_0 + a_3 x_3 + a_4 x_4 + \ldots \qquad \text{(B.7)}\end{aligned}$$

where

$$a_0 = a_0' + a_4' x_3^2$$
$$a_3 = a_3' - 2a_4' \overline{x}_3$$
$$a_4 = a_4' \quad .$$

Squared terms were used as in equation B.6 for the average measurement section speed and for temperature. The squared term for speed enabled SRI to check for the $V^2$ dependence often reported in the literature; the squared term for

---

*Note also that the bivariate relationship between y and $x_2$, in the absense of $x_1$, would also explain very little.

**Weight was used directly as the independent variable in the case where resistance force was the dependent variable.

*Oiled or greased wheels tend to defeat the effect of the retarders. Therefore, a common design practice is to attempt to route cars so as to avoid oilers before humping.

temperature enabled SRI to check for first order nonlinearities with temperature, as might be expected because the freezing point of water (32 °F) was well within the range of data collected.

Higher power ($x_i^3$, $x_i^4$, etc.) terms were not included in the analysis.

### B.2.3 Dummy Variables

"Dummy" variables were also included in the regression. A dummy variable indicates an individual observation's membership in a group: If the observation is a member of the group, the dummy variable is 1; otherwise, the dummy variable is 0. In this study, two dummy variables that were immediately apparent were--

- Moisture conditions*: 1 if wet, 0 if otherwise.
- A car's bearings: 1 if friction, 0 if otherwise (i.e., roller bearings).

When there were several mutually distinct groups (such as type of car--boxcar, flatcar, tank car, and the like), one of the groups was selected as a "reference group" and had no dummy variable associated with it (e.g., boxcar). Dummy variables were then created to indicate membership in the remaining groups (tank, flat, and so on). In this example, if the car is a tank car, the tank dummy variable for the car is set to 1, and the other car type dummy variables are set to 0.

### B.2.4 Interaction Terms

Sometimes the effect of one independent variable on the dependent variable varies depending on the level of another independent variable, in which case the effect of the second independent variable depends on the level of the first independent variable. Such behavior is customarily handled by including a first-order interaction term, usually of the form:

$$x_4 = x_2 x_3 \quad . \qquad (B.8)$$

However, with this form $x_4$ usually has an undesirably high correlation with one or both of $x_2$ and $x_3$. This correlation can be reduced by using the alternate form:

$$x_4' = (x_2 - \overline{x}_2)(x_3 - \overline{x}_3) \quad . \qquad (B.9)$$

Equation B.9 was used in the analysis. Note the similarity of equation B.9 to the squared term, equation B.6. In both equations B.6 and B.9, an interaction term is primarily sensitive to the interaction effect of the variables. Also as is the case with equation B.6, equation B.9 can be converted to the form of equation B.8 by some simple algebra, resulting in modified coefficients.

With 22 independent variables being considered, the number of interaction terms could have become quite large.* Therefore, the number of first-order interactions was kept to the minimum. Typical interaction terms considered were car type with the headwind term** (to take into account varying car cross-sectional shapes) and bearing type with weight (differing bearing frictions).

Higher level interaction terms (e.g., the products of three, four, and more variables) could also be defined. However, because of the quality of available data and to keep the problem to manageable size, such terms were not considered in this analysis.

### B.2.5 Special Transformations for Switches and Curves

Rollability measurement section 3 contained switches and curves, and section 4 usually had some curves. If switch and curvature variables had been put directly into the regression equation, erroneous results could have been obtained because the rolling resistance as measured across these measurement sections was an average value that included curvature and switches, as well as varying amounts of straight track. The same velocity head loss could be measured across a long tangent section, owing to its length, or across a short curved section, owing to the (presumed) additional curve resistance.

In deriving a correct set of independent switch and curve variables to be used in the regression analysis, the assumption was that:

- The tangent track rolling resistance, R, applies everywhere. R is assumed to include all resistance terms except those pertaining to switches and curves. On curves, an additional rolling resistance, $R_c$, applies. $R_c$ may be assumed to be a function of certain curvature variables. Thus, the total resistance on the curve is $R + R_c$.
- Each switch traversed extracts a velocity head loss of $H_s$ from the car, regardless of the switch type or of the orientation of the switch relative to the car. Therefore, if $N_s$ switches are traversed in a measurement section, the total velocity head loss due to the switches is $N_sH_s$.

*The data collected did not distinguish between rain and snow.

*If there are n independent variables, the number of potential first-order interactions is n(n-1)/2.

**Defined in Section B.2.6.

Using these assumptions, the velocity head relationship applicable to a measurement section can be depicted as in Figure B-2.

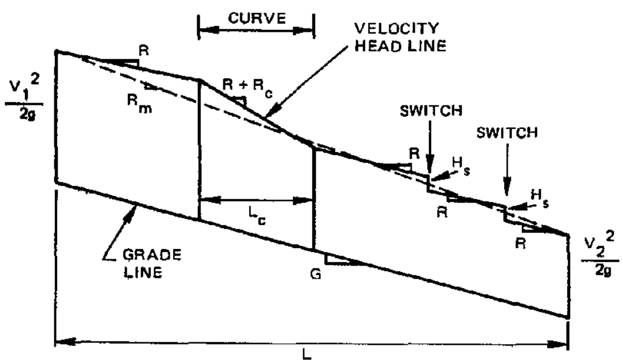



FIGURE B-2 VELOCITY HEAD/RESISTANCE RELATIONSHIPS IN ROLLABILITY MEASUREMENT SECTION WITH SWITCHES AND CURVES

The raw rolling resistance, $R_m$, as measured in this section is:

$$R_m = G - \frac{V_2^2 - V_1^2}{2gL} \qquad (B.10)$$

where

$R_m$ = measured rolling resistance (lb/lb)
$G$ = grade (ft/ft)
$V_1$ = speed at start of measurement section (ft/sec)
$V_2$ = speed at end of measurement section (ft/sec)
$L$ = length of measurement section (ft)
$g$ = acceleration of gravity (32.2 ft/sec$^2$).

However, using the velocity head relationships from Figure B-2, the measurement section exit velocity head can be computed as:

$$\frac{V_2^2}{2g} = \frac{V_1^2}{2g} - N_sH_s - L_cR_c + L(G - R) \qquad (B.11)$$

or, rearranging terms:

$$G - \frac{V_2^2 - V_1^2}{2gL} = \frac{N_sH_s}{L} + \frac{L_cR_c}{L} + R \quad . \qquad (B.12)$$

Comparing equation B.12 with equation B.10 results in

$$R_m = \frac{N_sH_s}{L} + \frac{L_cR_c}{L} + R \quad . \qquad (B.13)$$

The numerator in the middle term on the right-hand side is the total head loss, $H_c$, due to the curve resistance, that is,

$$H_c = L_cR_c \quad . \qquad (B.14)$$

However, head loss on a curve is usually expressed in terms of loss per degree of central angle, Δ:

$$H_c = h_c\Delta \quad , \qquad (B.15)$$

where

$h_c$ = velocity head loss per degree central angle
Δ = total central angle (degrees).

Furthermore, $h_c$ has often been expressed as a function of degree of curve; for example, Southern Pacific* recommends the curve compensation shown in Table B-1.

Table B-1

CURVE COMPENSATION

| Degree of Curve | Compensation* (feet per degree of central angle) |
|---|---|
| 0°00'-3°00' | .035 |
| 3°01'-6°00' | .040 |
| 6°01'-8°30' | .045 |
| 8°31'-10°00' | .050 |

*For unlubricated curves. For lubricated curves, values are approximately half those tabulated.

The relationship shown in Table B-1 can be closely approximated by a linear equation of the form:

$$h_c = \alpha + \beta D \quad , \qquad (B.16)$$

where

α β = coefficients to be fitted
D = degree of curve.

Putting equation B.16 in B.15 results in

$$H_c = \alpha\,\Delta + \beta\,D\,\Delta \quad . \qquad (B.17)$$

*Source: Barney Gallacher.

The $D\Delta$ in equation B.17 with coefficient $\beta$ is in the form of an interaction term. Therefore, for consistency with the interaction term approach discussed earlier, we replaced $D\Delta$ with $(D-\bar{D})(\Delta-\bar{\Delta})$. Further, for completeness, a D term was included alone in the equation, resulting in an expression for $H_c$ of

$$H_c = \alpha\Delta + \beta\ (D-\bar{D})(\Delta-\bar{\Delta}) + \gamma D \quad . \qquad (B.18)$$

Comparing equation B.18 with equation B.14, and making the implied substitution into equation B.13, results in

$$R_m = \frac{N_s H_s}{L} + \frac{\alpha\Delta + \beta(D-\bar{D})(\Delta-\bar{\Delta}) + \gamma D}{L} + R \quad . \qquad (B.19)$$

Because all rolling resistances used in the analysis were in pounds per ton, equation B.19 can be written as:

$$\begin{aligned} R_m(\text{lb/ton}) = H_s &\left(\frac{2000\ N_s}{L}\right) + \alpha\left(\frac{2000\ D}{L}\right) \\ &+ \beta\left[\frac{2000(D-\bar{D})(\Delta-\bar{\Delta})}{L}\right] \qquad (B.20) \\ &+ \gamma\left(\frac{2000\ D}{L}\right) + R(\text{lb/ton}) \quad . \end{aligned}$$

Equation B.20 is precisely in the form amenable to inclusion in the regression. The rightmost term, R, collectively includes all regression terms except those for switches and curves. The left-hand side is precisely the dependent variable that was used in the regression. The quantities in brackets in equation B.20 became the independent variables for switches and curves used in the regression (i.e., the $x_i$ in the notation of the previous sections), and the parameters $H_s$, $\alpha$ , $\beta$, and $\gamma$ became the regression coefficients. In measurement sections 1 and 2, which had no switches or curves, the variables $N_s$, $\Delta$ , and D were set to zero.*

### B.2.6 Effect of Headwind

The headwind variable was constructed in accordance with the classic wind drag model, which is of the form:

$$D = c_d A(V - V_w)^2 \text{ sign } (V - V_w) \quad , \qquad (B.21)$$

where

D = wind drag force
$c_d$ = drag coefficient
A = cross-sectional area of car
V = speed of the car
$V_w$ = speed of the wind component parallel to the car's direction of movement--positive if moving in the same direction as the car, and negative if moving in the opposite direction
sign (x) = 1 if x is positive,
-1 if x is negative.

Therefore, the regression variable constructed for this term was**

$$A(V - V_w)^2 \text{ sign } (V - V_w)/W \quad , \qquad (B.22)$$

where

W = weight of the car (tons).

The quantity A was obtained from the UMLER file as the product of extreme width times extreme height.

An average value of $c_d$ over all cars was included as part of the regression coefficient, as was a "shape" factor arising from the fact that, in most cases, the extreme width times extreme height yields a rectangular pseudo-cross-section larger than the actual cross-section of the car (e.g., compare the circular cross-section of a tank car with the rectangle in which it is inscribed). The interaction term analysis does provide the capability to differentiate between the headwind effects of different car types.

## B.3 DIFFICULTIES IN THE DATA

Several difficulties were encountered in the regression analyses because of the nature of the data available from the process control computer systems. Because these systems were designed to control humped cars, the provision of data for statistical studies was a secondary consideration. In particular, the experimental design imposed by the process control computer system was somewhat inadequate to support an analysis as extensive as that reported here. The next sections discuss the problems in detail.

### B.3.1 Multicolinearity

The switch variable as defined in equation B.20, the three curve variables also defined in equation B.20, and the reciprocal distance-from-oiler variable discussed in Section B.2.1 all were highly multicolinear. This was due to the way the yard and process control system were designed: Only measurement section 3 had

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*Note that the "interaction" term for D and $\Delta$ is not zero for tangent measurement sections. $\bar{D}$ and $\bar{\Delta}$ were taken over all observations, including the zero values for tangent sections.

**No division by W was used when resistance force was the dependent variable; thus, the term in that case was $A\ (V-V_w)^2$ sign $(V-V_w)$.

switches,* plus the bulk of the curvature. Furthermore, the only oilers encountered were at the beginning of measurement section 3. The correlations among these variables were sometimes in excess of .90, so it was very difficult for the regression procedure to separate the individual effects of these variables.

Nonetheless, these variables collectivly had an important effect on rolling resistance. Therefore, they had to be included in the analysis in some manner so that their effects would not affect the calibration of the other independent variables. Because of this multicolinearity problem, the interaction term (i.e., the term with coefficient B in equation B.20) between degree of curve D and central angle $\Delta$ had to be eliminated. This had no detrimental effect because in view of its high correlation with the D and $\Delta$ terms, the interaction term added little information. SRI then proceeded with the remaining multicolinear terms--$\Delta$, D, $N_s$, and the oiler variable. Although this problem prevented the accurate calibration of the effects of these variables, separate analyses indicated that, at least in the case of the noninteraction term regressions, the calibration of the other variables was not adversely affected. (This problem is discussed in more detail in Section B.4.)

### B.3.2 Relationship Between Rolling Resistance and Speed

The rolling resistance of a car is an important variable determining its speed, and the speed may also affect the rolling resistance. SRI wished to examine the latter effect through the analyses. The nature of the data from the process control systesm, and the manner in which these data were collected created two problems:

- The speed in certain measurement sections--especially section 1--caused the speed to be an almost linear function of resistance in those sections. This relationship did not represent the underlying physical relationship, but instead was an artifact of the way the data were collected.

- Assuming that an underlying dependence of rolling resistance on speed exists, the motion of each car would be governed by an appropriate differential equation taking this relationship into account. However, the way the process control system measures rolling resistance ignores the possibility of such a relationship.

These problems are discussed more fully in Appendix C. Nonetheless, neither of these problems should have an adverse effect on the regression analysis, provided the underlying data base represents a diverse set of conditions.

*We had no data that would permit inclusion of the switches between the master and group retarders.

## B.4 RESULTS OF THE ANALYSES

### B.4.1 General

The results of three regression analyses are reported in this section:

- Rolling resistance as a dependent variable without interaction terms.

- Rolling resistance as a dependent variable with selected interaction terms.

- Resistance force as a dependent variable without interaction terms.

A total of 17 independent variables were considered, excluding the interaction terms. These variables are listed in Table B-2. Of these 17 terms, not all were logically distinct. Two (AVTSV2 and TEMP2) were simply second-power terms as described in Section B.2.2. Others, such as AHEADC2W, were a logical composite of several other variables.

The actual quantitative results of these analyses are presented in Tables B-3 through B-5. A common format is used in all these tables to indicate the presence or absence of interaction terms. These tables present sufficient information to develop actual computing formulas for predicting mean rolling resistance, given values for the independent variables. For example, the prediction equation implied by Table B-3 reads in part:

$$\hat{RR} = 89.19*\left(\frac{1}{\text{WTTONS}}\right) + .2546*\text{AVTSV} + .003775*(\text{AVTSV}-16.72)^2 + \ldots \ldots - .8629 \quad . \qquad \text{(B.23)}$$

Here, the "hat" on RR denotes that it is an estimated rather than observed value. The interaction term equation in Table B-4 would yield similar terms but would be much longer. For example, the term due to the interaction between RWTTONS and AVTSV would be computed as

$$\ldots + 6.211*\left(\frac{1}{\text{WTTONS}} - .02110\right)*(\text{AVTSV} - 16.72) + \ldots \quad . \qquad \text{(B.24)}$$

### B.4.2 Rolling Resistance as Dependent Variable; No Interaction Terms

The results presented in Table B-3--the first-order noninteraction term equation with RR as the dependent variable--are discussed in Chapter 5. This equation has an $R^2$ value of 0.478, meaning that the regression "explains" 47.8% of the squared variation about the "grand" mean

Table B-2

VARIABLES USED IN REGRESSION ANALYSES

| Variable | Description |
|---|---|
| Dependent variables | |
| RR | Rolling resistance in lb/ton |
| RFORCE | Resistance force in lb (RR*WTTONS). |
| RWTTONS [or WTTONS] | Reciprocal of car weight in tons, i.e., RWTTONS = 1/WTTONS, where WTTONS is car weight in tons. RWTTONS was used with RR as dependent variable, and WTTONS was used with RFORCE as dependent variable. |
| AVTSV | Average measurement section velocity, in ft/sec (see equation B.1). |
| AVTSV2 | AVTSV squared term: [AVTSV - mean (AVTSV)] (see section B.2.2.). |
| HCURVT | Term for total central angle of curve. Its coefficient can be read directly as feet of velocity head lost per degree of central angle.* |
| HDEGCURV | Term for average degree of curvature in measurement section (D term in equation B.20). Its coefficient can be read directly as feet of velocity head lost per degree of central angle. |
| Independent variables | |
| HSWTLOSS | Term for switch loss ($N_S$ term in equation B.20). Its coefficient can be read directly as velocity head lost per switch.* |
| RDFOMTS | Reciprocal of distance from oiler (in feet) to middle of measurement section. |
| LDFCMTS | Natural logarithm of distance from crest (in feet) to middle of measurement section. |
| MOIST | Dummy variable: 0 dry, 1 wet. |
| TEMP | Temperature in °F. |
| TEMP2 | Temperature squared term: [TEMP - mean(TEMP)] (see section B.2.2). |
| SIDEC | Sidewind component in ft/sec. |
| AHEADC2W [or AHEADC2] | Headwind term (see section B.2.5). AHEADC2W - AHEADC2/WTTONS AHEADC2W was used with RR as dependent variable, and AHEADC2 was used with RFORCE as dependent variable. |
| TRCNTL | Truck center-to-center length in feet. |
| BEARDUM | Dummy variable: 0 if roller bearings, 1 if friction bearings. |
| Car type | |
| GONDUM | Dummy variable: 1 if gondola car, 0 if otherwise. |
| FLATDUM | Dummy variable: 1 if flatcar, 0 if otherwise. |
| HOPDUM | Dummy variable: 1 if hopper, 0 if otherwise. |
| REFDUM | Dummy variable, 1 if refrigerator car, 0 if otherwise. |
| TANKDUM | Dummy variable: 1 if tank car, 0 if otherwise. |
| VEHDUM | Dummy variable: 1 if vehicular car, 0 if otherwise. |
| DEWITDUM | Dummy variable: 0 for case from Hinkle Yard, 1 for case from DeWitt Yard. |

*Ft-tons of energy lost with force as dependent variable.

Table B-3

REGRESSION RESULTS WITH RR (ROLLING RESISTANCE) AS DEPENDENT VARIABLE, NO INTERACTION TERMS CONSIDERED

| VARIABLE | MEAN | COEF. | COEFFICIENTS – INTERACTION TERMS | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | RWTTONS | AVTSV | AVTSV2 | HCURVT | HDEGCURV | HSWTLOSS | RDFOMTS | LDFCMTS | MOIST | TEMP | TEMP2 | SIDEC | AHEADC2W | TRCNTL | BEARDUM | GONDUM | FLATDUM | HOPDUM | REFDUM | TANKDUM | VEHDUM | DEWITDUM |
| RWTTONS | | 89.19 | | | | | | | | | | | | | | | | | | | | | | |
| AVTSV | 16.72 | .2546 | | | | | | | | | | | | | | | | | | | | | | |
| AVTSV2 | | .003775 | | | | | | | | | | | | | | | | | | | | | | |
| HCURVT | | .006904 | | | | | | | | | | | | | | | | | | | | | | |
| HDEGCURV | | NS | | | | | | | | | | | | | | | | | | | | | | |
| HSWTLOSS | | NS | | | | | | | | | | | | | | | | | | | | | | |
| RDFOMTS | | NS | | | | | | | | | | | | | | | | | | | | | | |
| LDFCMTS | | .3457 | | | | | | | | | | | | | | | | | | | | | | |
| MOIST | | NS | | | | | | | | | | | | | | | | | | | | | | |
| TEMP | 44.11 | -.03788 | | | | | | | | | | | | | | | | | | | | | | |
| TEMP2 | | .0001948 | | | | | | | | | | | | | | | | | | | | | | |
| SIDEC | | NS | | | | | | | | | | | | | | | | | | | | | | |
| AHEADC2W | | .001031 | | | | | | | | | | | | | | | | | | | | | | |
| TRCNTL | | NS | | | | | | | | | | | | | | | | | | | | | | |
| BEARDUM | | NS | | | | | | | | | | | | | | | | | | | | | | |
| GONDUM | | 1.174 | | | | | | | | | | | | | | | | | | | | | | |
| FLATDUM | | .5543 | | | | | | | | | | | | | | | | | | | | | | |
| HOPDUM | | NS | | | | | | | | | | | | | | | | | | | | | | |
| REFDUM | | NS | | | | | | | | | | | | | | | | | | | | | | |
| TANKDUM | | .6585 | | | | | | | | | | | | | | | | | | | | | | |
| VEHDUM | | NS | | | | | | | | | | | | | | | | | | | | | | |
| DEWITDUM | | -.5475 | | | | | | | | | | | | | | | | | | | | | | |
| CONST. | | -.8629 | | | | | | | | | | | | | | | | | | | | | | |

N = 4465 $R^2$ = .478 $\sigma_R$ = 2.81 lb/ton Coef. of Var. = 35.1% F = 340.5
Blank cells indicate variables not analyzed.
All variables significant at 5%

Variable mean values are given only where needed for prediction equation.

Table B-4

REGRESSION RESULTS WITH RR (ROLLING RESISTANCE) AS DEPENDENT VARIABLE, INTERACTION TERMS INCLUDED

| VARIABLE | MEAN | COEF. | COEFFICIENTS – INTERACTION TERMS | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | RWTTONS | AVTSV | AVTSV2 | HCURVT | HDEGCURV | HSWTLOSS | RDFOMTS | LDFCMTS | MOIST | TEMP | TEMP2 | SIDEC | AHEADC2W | TRCNTL | BEARDUM | GONDUM | FLATDUM | HOPDUM | REFDUM | TANKDUM | VEHDUM | DEWITDUM |
| RWTTONS | .02110 | 95.62 | | | | | | | | | | | | | | | | | | | | | | |
| AVTSV | 16.72 | .2162 | 6.211 | | | | | | | | | | | | | | | | | | | | | |
| AVTSV2 | | -.01537 | | | | | | | | | | | | | | | | | | | | | | |
| HCURVT | 62.84 | .01141 | NS | .001191 | | | | | | | | | | | | | | | | | | | | |
| HDEGCURV | 25.82 | .01275 | NS | NS | | | | | | | | | | | | | | | | | | | | |
| HSWTLOSS | | | | | | | | | | | | | | | | | | | | | | | | |
| RDFOMTS | .000841 | -1400 | NS | -268.2 | | | | | | | | | | | | | | | | | | | | |
| LDFCMTS | 6.614 | .8368 | -13.63 | | | | | | | | | | | | | | | | | | | | | |
| MOIST | .03404 | NS | | NS | | NS | NS | | NS | -.5167 | | | | | | | | | | | | | | |
| TEMP | 44.11 | -.04232 | -1.613 | NS | | | | | NS | .008099 | NS | | | | | | | | | | | | | |
| TEMP2 | | .0002052 | | | | | | | | | | | | | | | | | | | | | | |
| SIDEC | 3.756 | NS | NS | | | | | | | | NS | -.001095 | | | | | | | | | | | | |
| AHEADC2W | 765.6 | 001113 | NS | | | | | | | | -.0005747 | NS | | NS | | | | | | | | | | |
| TRCNTL | 43.04 | NS | -1.712 | -.004448 | | NS | NS | | NS | | | | | NS | .00003734 | | | | | | | | | |
| BEARDUM | .17156 | NS | -36.00 | -.05712 | | NS | NS | | | NS | NS | NS | | | | | | | | | | | | |
| GONDUM | .1147 | 1.348 | | | | | | | | | | | | .04509* | 0009056 | | | | | | | | | |
| FLATDUM | .1557 | .7704 | | | | | | | | | | | | NS | .0004668 | | | | | | | | | |
| HOPDUM | .0410 | NS | | | | | | | | | | | | -.1355 | NS | | | | | | | | | |
| REFDUM | 1525 | NS | | | | | | | | | | | | NS | NS | | | | | | | | | |
| TANKDUM | .0950 | .6234 | -23.62† | NS | | NS | -.009608 | | | | | | | -.06361 | NS | | | | | | | | | |
| VEHDUM | .0354 | .5055 | | | | | | | | | | | | NS | NS | | | | | | | | | |
| DEWITDUM | | -.8261 | | | | | | | | | | | | | | | | | | | | | | |
| CONST. | | -2.981 | | | | | | | | | | | | | | | | | | | | | | |

N = 4465 $R^2$ = .538 $\sigma_R$ = 2.47 lb/ton Coef. of Var = 33.1% F = 143.4
Blank cells indicate variables not analyzed.
All variables significant at 5% except as indicated

Variable mean values are given only where needed for prediction equation.

*Significant at .062
†Significant at .051

Table B-5

REGRESSION RESULTS WITH RFORCE (RESISTANCE FORCE) AS DEPENDENT VARIABLE, NO INTERACTION TERMS CONSIDERED

| VARIABLE | MEAN | COEF | COEFFICIENTS – INTERACTION TERMS | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | RWTTONS | AVTSV | AVTSV2 | HCURVT | HDEGCURV | HSWTLOSS | RDFOMTS | LDFCMTS | MOIST | TEMP | TEMP2 | SIDEC | AHEADC2W | TRCNTL | BEARDUM | GONDUM | FLATDUM | HOPDUM | REFDUM | TANKDUM | VEHDUM | DEWITDUM |
| RWTTONS | | 4.814 | | | | | | | | | | | | | | | | | | | | | | |
| AVTSV | | 13.64 | | | | | | | | | | | | | | | | | | | | | | |
| AVTSV2 | | NS | | | | | | | | | | | | | | | | | | | | | | |
| HCURVT | | .3578 | | | | | | | | | | | | | | | | | | | | | | |
| HDEGCURV | | NS | | | | | | | | | | | | | | | | | | | | | | |
| HSWTLOSS | | NS | | | | | | | | | | | | | | | | | | | | | | |
| RDFOMTS | | NS | | | | | | | | | | | | | | | | | | | | | | |
| LDFCMTS | | 27.48 | | | | | | | | | | | | | | | | | | | | | | |
| MOIST | | NS | | | | | | | | | | | | | | | | | | | | | | |
| TEMP | | -1.722 | | | | | | | | | | | | | | | | | | | | | | |
| TEMP2 | | NS | | | | | | | | | | | | | | | | | | | | | | |
| SIDEC | | NS | | | | | | | | | | | | | | | | | | | | | | |
| AHEADC2W | | .0009991 | | | | | | | | | | | | | | | | | | | | | | |
| TRCNTL | | NS | | | | | | | | | | | | | | | | | | | | | | |
| BEARDUM | | NS | | | | | | | | | | | | | | | | | | | | | | |
| GONDUM | | 70.91 | | | | | | | | | | | | | | | | | | | | | | |
| FLATDUM | | 31.40 | | | | | | | | | | | | | | | | | | | | | | |
| HOPDUM | | NS | | | | | | | | | | | | | | | | | | | | | | |
| REFDUM | | NS | | | | | | | | | | | | | | | | | | | | | | |
| TANKDUM | | 40.24 | | | | | | | | | | | | | | | | | | | | | | |
| VEHDUM | | NS | | | | | | | | | | | | | | | | | | | | | | |
| DEWITDUM | | -19.27 | | | | | | | | | | | | | | | | | | | | | | |
| CONST. | | -282.3 | | | | | | | | | | | | | | | | | | | | | | |

N = 4465 $R^2$ = .524 $\sigma_R$ = 165.9 lb Coef. of Var. 40.5% F = 491.1
Blank cells indicate variables not analyzed.
All variables significant at 5%
Variable means are not given since they are not required for prediction equation.

rolling resistance. The standard deviation of the observed values of RR about the predicted $\hat{RR}$ is 2.61 lb/ton; this can be interpreted roughly as being the average error value in using the prediction equation as a substitute for the observed values of RR.

These results indicate that, while RR does vary signficiantly as a function of the independent variables, much unexplained variation remains. This could be indicative of the omission of some important explanatory variable, but all important independent variables that have been reported in the literature were included. Consequently, considerable random variation most likely inherently exists in the rolling resistance data analyzed. This could be because each car's rolling behavior is in great part random in nature or because random errors arose from the way each car's rolling resistance was measured. (The error analysis, presented in Appendix C, indicates that the manner in which most yard process control systems estimate a car's rolling resistance can be subject to much error.)

### B.4.3 Rolling Resistance as Dependent Variable with Interaction Terms

Table B-4 presents the results of a regression with RR as dependent variable, including selected interaction terms among the independent variables. Attempting to include all first-order interaction terms in the analysis would have exceeded the capacity of SRI's computer; thus, engineering judgment was used to select only those terms that were believed likely to have a significant effect.*

The interaction term regression offered only a slight improvement in the prediction of RR compared with the noninteraction results. The $R^2$ increased to 0.538; the standard deviation about the predicted RR decreased only slightly, to 2.47 lb/ton. Further, some aspects of the behavior of the prediction equation as a function of certain independent variables are unexplainable and may reflect biases in the data. Consequently, the use of this equation is not recommended. Results from the interaction term regression analysis are presented below, however.

The statistical difficulties reported with multicolinearity in the noninteraction regression were magnified in the interaction term regression. In both Hinkle and DeWitt yards, the measurement sections where most of the curve data and all the switch data were obtained were the same (section 3). Further, this section was just after the oilers, so the four variables HCURVT, HDEGCURV, HSWTLOSS, and RDFOMTS were all highly multicolinear. Because the switch variable was particularly troublesome, it was eliminated and any switch losses were combined into the curve losses.*

The interaction terms involving each of these variables were also highly multicolinear within the category of a single additional interacting variable. That is, the multicolinearity problems occurred within the sets consisting of:

[HCURVT, HDEGCURV, RDFOMTS]

[HCURVT x AVTSV, HDEGCURV x AVTSV, RDFOMTS x AVTSV]

[HCURVT x LDFCMTS, HDEGCURV x LDFCMTS, RDFOMTS x LDFCMTS]

etc.

However, no severe multicolinearity problems occurred between these different sets.

A strong negative interaction was found between the car speed and oiler (AVTSV and RDFOMTS) terms. The effect of this term was to invert the usual relationship between speed and rolling resistance, after the car had recently passed an oiler, as shown in Figure B-3. This illustration was drawn using a reference car, in the same manner as the illustrations in Chapter 5. As can be seen, the rolling resistance actually decreased with increasing speed at car speeds greater than about 14 to 15 ft/sec; the effect applies only when an oiler has recently been traversed (see the "oiler 500 ft upstream" curves). The curves for "no oiler" are somewhat more reasonable, although the concavity of the curves is counterintuitive. However, most important, the effect of the oiler is greatly exaggerated, as can be seen by comparing the "no oiler" and the "oiler 500 ft upstream" curves. The behavior diagramed in Figure B-3 does not really reflect the effect of oilers at all, but rather reflects:

- A general depression of resistance values with speed in measurement section 3. The oiler variable, most of the variation of which occurred in this section (due to proximity), was merely a convenient variable for the regression procedure to implicate in this behavior.

- The multicolinearity among the variables, most of whose variation (from non-zero values) occurred in measurement section 3. The positive association between the curve variables and resistance, presented below, would tend to cause a negative association between other multicolinear variables, such as oilers, and resistance.

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*Based on SRI's judgment, as well as the literature. Certain statistical difficulties forced the exclusion of certain variables and some interaction terms.

*Thus, the interpretation of the curve loss terms should be regarded as an average value including both curve and some switch loss.

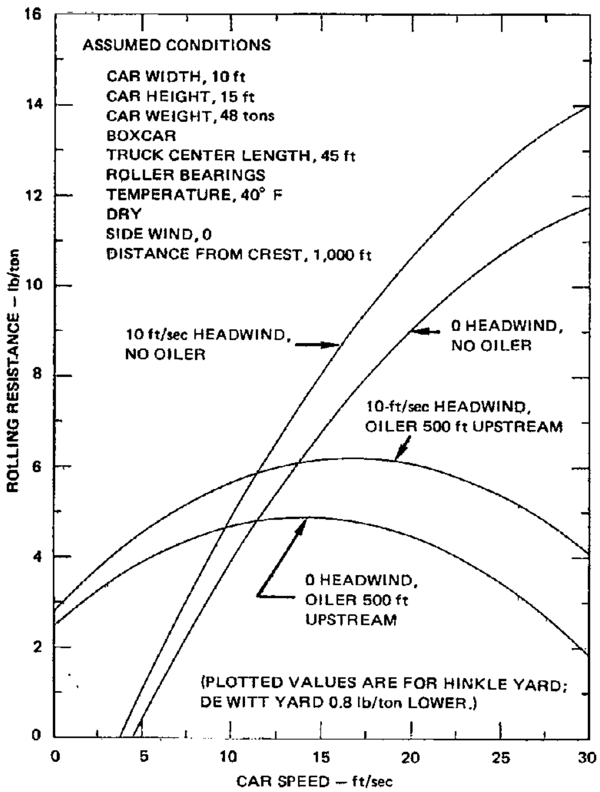



FIGURE B-3 ROLLING RESISTANCE AS A FUNCTION OF CAR VELOCITY, HEADWIND, AND OILER LOCATION FOR INTERACTION TERM REGRESSION

The preceeding discussion was a prelude to the discussion of the effects of curves, presented below, and is intended to indicate some of the problems inherent in the same analysis from which the curve effects were derived. Thus, although the magnitude of these curve effects seems reasonable, we cannot recommend their use due to the closely related counterintuitive behavior as discussed above.

The interaction term analysis indicates that the additional velocity head loss over the length of a curve, over and above the losses due to a car's baseline tangent track resistance, can be computed from the relationships:

$$H_L = .001191V\Delta - .008500\Delta + .01366D \quad \text{(non-tank car)}$$

$$H_L = .001191V\Delta - .008500 + .004055D \quad \text{(tank car)}, \qquad (B.25)$$

where

$H_L$ = velocity head loss (ft) (over and above tangent track rolling resistance losses)

V = car speed (ft/sec)

Δ = central angle of the curve (degrees)

D = degree of curvature (degrees).

Note that this relationship expresses the curve loss in terms of the total head loss along the entire length of the curve. Because expressing curve losses per degree of central angle is often customary, the relationships in equation B.25 can be divided through by Δ to yield:

$$\frac{H_L}{\Delta} = .001191V - .008500 + .01366\frac{D}{\Delta} \quad \text{(non-tank cars}$$

$$\frac{H_L}{\Delta} = .001191V - .008500 + .004055\frac{D}{\Delta} \quad \text{(tank cars)} \quad . \qquad (B.26)$$

These relationships are presented graphically in Figure B-4.

That a tank car would lose less head on a curve is in agreement with conventional wisdom, which is that the inertia of the liquid cargo "sloshing" has the tendency to propel these cars through such loss areas.*

Note also that the contribution of Δ to $H_L$ is negative (i.e., implying energy gain) up to a speed of about 7 ft/sec. However, the overall effect of the curve is a net loss for virtually all conditions likely to occur in a real design.

### B.4.4 Resistance Force as Dependent Variable, No Interaction Terms

In this analysis, a car's resistance force was used in each measurement section as the dependent variable. This approach is more in conformance with theory, where it is force components that are linearly additive. The results of this analysis were presented in Table B-5. Statistically, the analysis offered certain moderate improvements over the noninteraction regression with rolling resistance ase dependent variable. The $R^2$ was 0.524, roughly the same as for the interaction term analysis, but without the undesirable behavior exhibited by the latter. The significant variables and the signs of their coefficients (Table B-5) are in rough agreement with those provided by the noninteraction rolling resistance analysis (Table B-3). Further, most of the coefficients in Table B-5, when divided by the average car weight (or roughly equivalently, multipled by the average reciprocal car weight given in Table B-4), give a coefficient fairly close to that in Table B-3, as would be expected. Neither of the second power terms--AVTSV2 and TEMP2--was significant with force as the dependent variable; these are not, however, among the more heavily weighted terms when rolling resistance is the dependent variable. One interesting result is that by removing the

*Such wisdom neglects the effect of the liquid's rebound, which would subsequently slow the car.

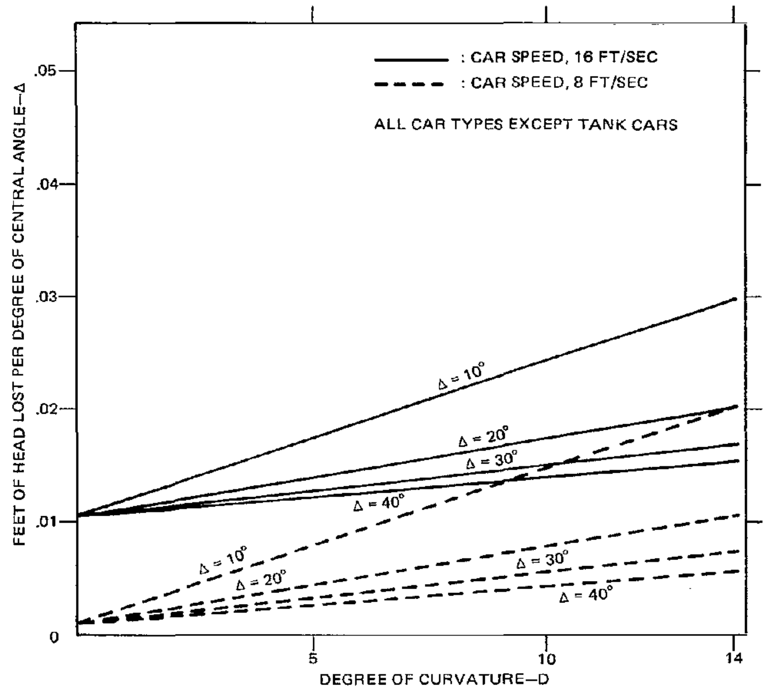



FIGURE B-4 CURVE LOSS AS A FUNCTION OF DEGREE OF CURVE, CENTRAL ANGLE, AND CAR SPEED

reciprocal relationship between a car's rolling resistance and its weight, the resistance force analysis indicates that resistance force increases as a car's weight increases, whereas rolling resistance decreases, in general, as the weight of a car increases. This is to be expected, since the frictional resistance forces are directly proportional to the car's weight.

An interaction term regression analysis was not performed with resistance force as dependent variable, because--

- Rolling resistance, not force, was the variable commonly used in design.
- Undesirable behavior occurred when the interaction term regression used rolling resistance as dependent variable.

# APPENDIX C: ERROR ANALYSIS OF ROLLING RESISTANCE

## C.1 INTRODUCTION

This appendix reports on two error analyses that SRI performed to assess the magnitude of uncertainties in the rolling resistances of cars arising from inconsistencies in the method used to compute them. The first analysis was based on the assumption that the most commonly used rolling resistance model (static resistance, i.e., no velocity dependence) was applicable, and the uncertainties in measured rolling resistances arising from measurement errors were computed. Error expressions were derived for the two most commonly used methods for computing static rolling resistance, which are based on (1) the speed of a car at two points and (2) the travel time of a car through two track sections. The error characteristics for the first method were within the range of acceptability but the error characteristics of the second method were not.

In the second analysis, the the assumption was that the underlying rolling resistances were speed dependent. The objective was to answer the question of whether valid results can be obtained when (1) independent observations of rolling resistance and speed are unavailable and (2) relationships derived from the assumption of an underlying static resistance model are used to compute resistances while in fact the underlying model is speed dependent. The conclusion was that valid results could be obtained, provided the data were collected from a wide variety of speeds and conditions; that is, analyses should be based on data combined from many resistance measurement sections.

## C.2 ERRORS IN MEASURING THE INDEPENDENT VARIABLES FOR STATIC ROLLING RESISTANCE MODELS

By far the most common model of car dynamics used in the rail industry is based on the assumption that each car's rolling resistance is independent of its speed.* Most of the data available for this study were obtained under this assumption. Two methods are commonly used to measure static rolling resistances, and each is discussed below.

Before discussing the errors arising from these two methods, however, a description of the general relationship used to analyze errors for both methods is necessary. Suppose a dependent variable, y, is a function of a set of independent variables $x_i$, that is,

$$y = f(x_1, x_2, \ldots x_n) \quad . \qquad (C.1)$$

Further, suppose that each $x_i$ is subject to an uncertainty, $x_i$, where each of the $\Delta x_i$ have been computed under the same probability of occurrence. Then it can be shown* that the error in y, $\Delta y$, can be computed approximately** by the relationship

$$\Delta y = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial y}{\partial x_i}\,\Delta x_i\right)^2} \quad . \qquad (C.2)$$

This relationship is used in the derivation of error formulas in sections C.2.1 and C.2.2.

### C.2.1 Rollability Computation from Speeds at Two Points

In the traditional formula for computing a car's rolling resistance, the speeds of the car at two points are used; the speeds can be obtained by radar or from two successive speed trap zones. This formula actually computes the rolling resistance by computing the car's acceleration. When equation 2.9 (Chapter 2) is put into equation 2.5, the equation becomes+

$$R = G - \frac{V_2^2 - V_1^2}{2gL} \quad . \qquad (C.3)$$

where

- R = measured rolling resistance (unitless)
- G = grade (unitless)
- $V_1$ = car speed at an upstream point 1
- $V_2$ = car speed at a downstream point 2
- L = distance from point 1 to point 2
- g = acceleration of gravity.

---

*The car's resistance force does not change at different speeds. Speeds at different points (i.e., acceleration) are, however, used to compute each car's resistance.

*S. J. Kline and F. A. McClintock; "Describing the Uncertainties in Single-Sample Experiments," Mechanical Engineering, January 1953, pp. 3-8.

**The relationship is exact for a linear function of normally distributed $x_i$.

+Often this relationship is expressed in terms of elevation rather than grade, reflecting the fact that under the static formulation the car's drop really determines its terminal speed in a track section, which need not be on a constant grade (within limits, e.g., the car must not stop). However, grade is used in this analysis because it is more commonly seen and more convenient to use.

In deriving an expression for $\Delta R$, every term in equation C.3, including g,* is considered to be subject to error. Applying equation C.2 to equation C.3 yields the general error relationship for the rolling resistance measured by equation C.3:

$$\Delta R = \left[\left(\frac{V_1 \Delta V_1}{gL}\right)^2 + \left(\frac{V_2 \Delta V_2}{gL}\right)^2 + \left(\frac{V_2^2}{2gL^2} - \frac{V_1^2}{2gL^2}\right)^2 \Delta L^2 + \Delta G^2 + \left(\frac{V_2^2}{2g^2 L} - \frac{V_1^2}{2g^2 L}\right) \Delta g^2\right]^{1/2} \qquad (C.4)$$

Given typical values of parameters, and their errors, equation C.4 provides a general expression for computing an approximate error, $\Delta R$, in R.

C.2.1.1 Errors in Speeds Only

The major errors usually are believed to occur in the speed measurements. Assuming that no errors exist in the other parameters (i.e., $\Delta L = \Delta G = \Delta g = 0$), and assuming $\Delta V_1 = \Delta V_2$, equation C.4 simplifies to**

$$\Delta R = \frac{\Delta V}{gL} \sqrt{V_1^2 + V_2^2} \qquad (C.5)$$

If R is to be measured with a certain degree of accuracy, equation C.5 can be used to analyze what the nature of a specification of $\Delta V$ would be.

*The value of g—a convenient "handle"—is often modified in "tuning" a yard.

**We performed a more rigorous derivation of this relationship assuming that $\Delta V_1$ and $\Delta V_2$ were normally distributed random variables with mean zero and variance $\sigma^2$. This derivation is not given here because it is long and mathematically tedious. However, we found the expectation and variance of $\Delta R$ to be, respectively,

$$E(\Delta R) = 0$$

$$Var(\Delta R) = \left(\frac{\sigma_v}{gL}\right)^2 \left(V_1^2 + V_2^2 + \sigma_v^2\right)$$

or,

$$\sigma_R + \frac{\sigma_v}{gL} \sqrt{V_1^2 + V_2^2 + \sigma_v^2} \quad .$$

Because $V_1$ and $V_2$ are usually much greater than $\sigma_v$, the $\sigma_v^2$ term may be dropped inside the square root, yielding a result confirming equation C.5 (with $\sigma_v <=> \Delta_v$).

The following excerpts describing this specification are from an analysis by Robert L. Kiang (1980): "Some realistic values for g, L, $V_1$, and $V_2$ are:

$g = 32.2$ ft/sec$^2$
$L = 50$ ft
$V_1 = 10$ mph (13.20 ft/sec)
$V_2 = 9$ mph (14.67 ft/sec)

"The following exemplifies three different ways of specifying accuracy:

- Constant $\Delta R$ specification:

  "A reasonable $\Delta R$ is
  1.0 lb/ton or
  .05% grade, then
  $\Delta V = 0.03$ mph.
  This requirement is quite severe.

- Constant $\Delta R/R$ specification:

  "If a reasonable value of 10% is used, then
  for R = 1 lb/ton, $\Delta V = 0.003$ mph,
  for R = 2 lbs/ton, $\Delta V = 0.006$ mph,
  for R = 10 lbs/ton, $\Delta V = 0.03$ mph.

  "As can be seen, the spec on $\Delta V$ is no longer a single number.

- Constant $\Delta V/V$ specification:

  "A commercial radar unit has a accuracy of about 0.1 mph at 10 mph.

  Then
  $\Delta R = 3.6$ lbs/ton.

  This value of $\Delta R$ is too coarse."

This analysis indicates that considerable errors in measured rolling resistance can be expected to occur unless the speed measurement is highly accurate. Incorrect speed measurement will increase the variance of the measured R values for the car population over what would be obtained if R were measured with zero error. This can be corrected for, however, by increasing the sample size. Using the log-normal distribution fitted to the data of Figure 4.3 (Chapter 4), the standard deviation of the rolling resistance distribution can be computed to be 3.24 lb/ton. Using this value as if it represents the true standard deviation of an underlying population (i.e., assuming it reflects only on the expected sampling error but not on measurement error), treating the $\Delta R$ of 3.6 lb/ton derived above as the standard deviation of the measurement error, and assuming the measurement error for each car to be independent of the true underlying rolling resistance of that car, the standard deviation of the measured sample can be computed as

$$\sqrt{3.24^2 + 3.6^2} = 4.84 \text{ lb/ton} \quad .$$

Then the width of the confidence interval for a 200-car sample for the sample mean will increase from 0.90 lb/ton (based on the 3.24 lb/ton value) to 1.34 lb/ton (based on the 4.84 lb/ton value). This is still considered acceptable for the analysis because (1) for most analyses the sample was several times larger than 200 cars and (2) the analysis is conservative, since the empirical distribution cited probably already had considerable measurements error.

C.2.1.2 Errors in Other Variables

Strictly speaking, errors in such parameters as L, G, and g should be considered as fixed errors (or biases) rather than as random errors. However, if the analysis data base is combined from many measurement sections in such a way that the average error in L, G, and g is nearly zero,* equation C.4 is still approximately correct. Suppose an error of 100% exists in each of the parameters in equation C.3; substituting $V_1 = pV_1$, $V_2 = pV_2$, etc., into equation C.4 produces:

$$\Delta R = p\left[\underbrace{\left(\frac{V_1^2}{gL}\right)^2}_{\text{Contrib. of } \Delta V_1} + \underbrace{\left(\frac{V_2^2}{gL}\right)^2}_{\text{Contrib. of } \Delta V_2} + \underbrace{\left(\frac{V_2^2 - V_1^2}{2gL}\right)^2}_{\text{Contrib. of } \Delta L} + \underbrace{G^2}_{\text{Contrib. of } \Delta G} + \underbrace{\left(\frac{V_2^2 - V_1^2}{2gL}\right)^2}_{\text{Contrib. of } \Delta g}\right]^{1/2} \quad \text{(C.6)}$$

Thus, each term can be used to assess the sensitivity of rolling resistance to the same relative error in each of five parameters. It is immediately apparent from equation C.6 that the sensitivity to errors in g and L becomes negligible the closer $V_2$ is to $V_1$. It is also apparent that whatever the absolute error, $\Delta G$, in G, at least that much absolute error in R will be guaranteed. For the parameter values given in Section C.2.1.1, $V_2$ and $V_1$ are fairly close; using those values and the values for g and L enumerated and assuming that G = 3%, the following relationship is obtained for $\Delta R$ (in lb/ton) in terms of p shown in the relationship expressed in equation C.7 below.

By far the greatest sensitivity is to errors in $V_1$ and $V_2$. In fact, for the parameter values assumed above, errors of the same relative size in the other parameters can essentially be ignored. For a 1% error in each parameter (p = .01), equation C.7 gives $\Delta R$ = 3.5 lb/ton, which is in approximate agreement** with results cited earlier. The size of $\Delta R$ is directly proportional to p; therefore, if p and $\Delta R$ double (e.g., with a 2% error in each parameter), $\Delta R$ = 7.0 lb/ton. These errors can become quite large, even for a relatively modest 2% expected error in each of the five independent variables. However, in the above analysis, most of the error was contributed by the $V_1$ and $V_2$ terms. As discussed in section C.2.1.1, an error in $V_1$ and $V_2$ is more likely to be on the order of 1%, so those conclusions still hold.

Suppose, however, that $V_1$ and $V_2$ are decidedly different (as could apply in measurement section 3 of Hinkle Yard). For example, let us assume the following typical values for Hinkle Yard measurement section 3:

$V_1$ = 10 mph (14.67 ft/sec)
$V_2$ = 5 mph (7.33 ft/sec)
G = 0.001 ft/ft (0.1%)
L = 500 ft
g = 32.2 ft/sec$^2$.

Then, using equation C.6, $\Delta R$ (in lb/ton) is shown in the relationship expressed in equation C.8 below.

$$\Delta R = 2000\ p\ \sqrt{\underbrace{.01171}_{\text{Contrib. of } \Delta V_1} + \underbrace{.01785}_{\text{Contrib. of } \Delta V_2} + \underbrace{.00016}_{\text{Contrib. of } \Delta L} + \underbrace{.00090}_{\text{Contrib. of } \Delta G} + \underbrace{.00016}_{\text{Contrib. of } \Delta g}} \quad \text{(C.7)}$$

$$\Delta R = 2000\ p\ \sqrt{\underbrace{.000179}_{\text{Contrib. of } \Delta V_1} + \underbrace{.000011}_{\text{Contrib. of } \Delta V_2} + \underbrace{.000025}_{\text{Contrib. of } \Delta L} + \underbrace{.000001}_{\text{Contrib. of } \Delta G} + \underbrace{.000025}_{\text{Contrib. of } \Delta g}} \quad \text{(C.8)}$$

*For example, $L - L_t + L_e$ where $L_t$ is the true but unknown value for a specific section and $L_e$ is the error. Combining measurements from many separate measurement sections, the various $L_e$'s can be treated as separate observations of a multinominally distributed random variable, with $E(L_e) \cong 0$ and $\sigma(L_e) \cong \Delta L$. A similar argument can be made for G and g.

**The results do not agree exactly because earlier we used $V = \Delta V_1 = \Delta V_2$, whereas here we use $\Delta V_1 = \Delta V_2$.

The bulk of the sensitivity still applies to errors in the measured speeds, particularly in $V_1$. A 1% error in each parameter produces an error of only 0.3 lb/ton in R. This error is much lower than in the previous analysis and arises from each error term except G, contributing a quantity to the error inside the square root, which is inversely proportional to the measurement section length, L. Because L is large, it tends to reduce the sensitivity to relative errors in the parameters. Because greater differences between $V_1$ and $V_2$ are usually associated with larger test sections, the greater differences affecting the error contributions of $\Delta L$ and $\Delta g$ tend to be compensated by the longer test section length.

However, there is also one other case where $V_1$ and $V_2$ could be decidedly different but where the measurement section could be short: at the master retarder measurement section (measurement section 1) when that section is on a steep grade. At Hinkle Yard, this section is about 80 feet long and has about a 3.1% grade. The Hinkle data base for measurement section 1 indicates that a 2-lb/ton easy-rolling car will enter this 80-foot measurement section at about 17 ft/sec and exit at about 21 ft/sec. Putting these values into equation C.6 yields the relationship expressed by equation C.9 below.

These results are not appreciably different from those discussed earlier for equation C.7; again, the errors in the speeds themselves contribute most to the overall error. Using equation C.9, a 1% error in each of the parameters would yield a 4.22-lb/ton error in R.

## 2.2 Rollability Computation from Passage Times Through Two Track Sections

New process control systems use a revised approach to measuring rolling resistance. This method is used commonly and is the one used at Hinkle Yard. This approach computes acceleration using equation 2.10. With the parameters changed slightly, this relationship is

$$a = \frac{2(d_2 t_1 - d_1 t_2)}{(t_1 + t_2)\, t_1 t_2} \qquad \text{(C.10)}$$

where

- $a$ = acceleration of a car
- $d_1$ = distance from wheel detector 1 to wheel detector 2
- $t_1$ = passage time from wheel detector 1 to wheel detector 2
- $d_2$ = distance from wheel detector 2 to wheel detector 3
- $t_2$ = passage time from wheel detector 2 to wheel detector 3.

These parameters are diagramed in Figure C-1. If equation C.10 is put into equation 2.5, the product is

$$R = G - \frac{2(d_2 t_1 - d_1 t_2)}{g(t_2 + t_2) t_1 t_2} \qquad \text{(C.11)}$$

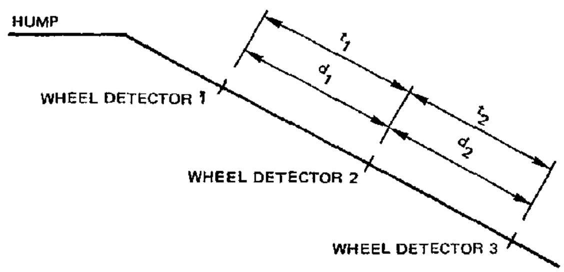



FIGURE C-1 ROLLABILITY MEASUREMENT SECTION USING PASSAGE TIMES THROUGH TWO TRACK SECTIONS

Proceeding as in the previous section, applying equation C.2 to equation C.11 produces the relationship expressed in equation C.12 below.

$$\Delta R = 2000\, p \sqrt{\underbrace{.01259}_{\substack{\text{Contrib.}\\\text{of}\\ \Delta V_1}} + \underbrace{.02931}_{\substack{\text{Contrib.}\\\text{of}\\ \Delta V_2}} + \underbrace{.00087}_{\substack{\text{Contrib.}\\\text{of}\\ \Delta L}} + \underbrace{.00096}_{\substack{\text{Contrib.}\\\text{of}\\ \Delta G}} + \underbrace{.00087}_{\substack{\text{Contrib.}\\\text{of}\\ \Delta g}}} \qquad \text{(C.9)}$$

$$\Delta R = \Bigg\{ \left(\frac{2}{g(t_1+t_2)t_1}\right)^2 \Delta d_1^2 + \left(\frac{-2}{g(t_1+t_2)t_2}\right)^2 \Delta d_2^2 + \frac{4}{g^2}\left[\frac{-d_2 t_1^2 + 2d_1 t_1 t_2 + d_1 t_2^2}{t_2(t_1^2+t_1 t_2)^2}\right]^2 \Delta t_1^2 + \frac{4}{g^2}\left[\frac{d_1 t_2^2 - 2d_2 t_1 t_2 - d_2 t_1^2}{t_1(t_1 t_2+t_2^2)^2}\right]^2 \Delta t_2^2 + \left[\frac{2(d_2 t_1 - d_1 t_2)}{g^2(t_1+t_2)t_1 t_2}\right]^2 \Delta g^2 + \Delta G^2 \Bigg\}^{1/2} \qquad \text{(C.12)}$$

Because the result is laborious, the approach of choice is that in Section C.2.1.2, assuming the same relative error p in each of the parameters. For the master retarder rollability measurement section at Hinkle Yard, a 2-lb/ton easy-rolling car should be traveling at about 19 ft/sec at the second wheel detector. Combining this speed with other data and with the geometry of this measurement section, and making some simple calculations yields the following parameter values for equation C.12:

$$G = 3.1\%$$
$$g = 32.2 \text{ ft/sec}^2$$
$$d_1 = 40 \text{ ft}$$
$$d_2 = 40 \text{ ft}$$
$$t_1 = 2.212 \text{ sec}$$
$$t_2 = 1.989 \text{ sec.}$$

Substituting these values into equation C.12 yields the relationship expressed in equation C.13 below.

Equation C.13 reveals that the measured rolling resistance is sensitive to errors in both the d and t parameters. For example, a 1% relative error (i.e., p = .01) in all six parameters yields a $\Delta R$ of 11.3 lb/ton--far in excess of the assumed 2-lb/ton actual underlying rolling resistance. Even if only one of the parameters is in error by 1%--for example, $t_1$--an error in R in excess of 5 lb/ton still arises. The error size does not diminish appreciably for harder rolling cars; for a car with an actual rolling resistance of 10 lb/ton, $t_1$ and $t_2$ must be updated. For 10 lb/ton, the mid-test section speed is about 17.5 ft/sec, yielding

$$t_1 = 2.411 \text{ sec}$$
$$t_2 = 2.162 \text{ sec.}$$

Other parameter values remain the same. The analogous error equation in terms of p becomes the relationship expressed in equation C.14 below.

The expected errors are still nearly as great: a 1% error in each parameter yields a $\Delta R$ of 9.6 lb/ton, and a 1% error in $t_1$ alone yields a $\Delta R$ of 4.2 lb/ton. That the error for a harder rolling car does not decrease much is not surprising; for this measurement section, the steep grade off the hump, much more than the rolling resistance, governs each car's speed. Therefore, virtually the entire population of cars will be moving at a relatively high speed through the measurement section, so that $t_1$ and $t_2$ become quite small and therefore must be measured very accurately if $\Delta R$ is to be small.

Thus, the rollability measurement technique that is based on the measurement of a car's passage times through two track sections is much more error prone than the technique that measures the car's speed at two points. However, this conclusion is based on the assumption that the same relative errors apply to each of the parameters directly measured for each of the two techniques. If the 1% error assumption used in the above analysis should prove to be markedly different for one technique vis-a-vis the other, a different conclusion could be reached. However, the general equations derived (equations C.4 and C.12) may be used to explore and compare the techniques for detecting errors of other sizes, if desired.

## C.3 ERROR ANALYSIS OF RELATIONSHIPS BETWEEN ROLLING RESISTANCE AND SPEED

Appendix B, Section B.3.2, discusses two problems in the rolling resistance data collection and analysis:

(1) Lack of independent observations of rolling resistance and speed.

(2) Differential equation formulation as opposed to static computational relationships.

Described here is the error analysis performed to address these two problems. The thrust was toward addressing problem 2, but information on problem 1 was also obtained. The conclusion of this analysis was that neither problem prevents the analyst from obtaining conclusions of practical utility, provided that rolling resistance data are collected for a wide variety of speeds and conditions. These problems are discussed in detail before the error analysis is described.

### C.3.1 Detailed Discussion of Rolling Resistance--Speed Problems

C.3.1.1 Lack of Independent Observations of Rolling Resistance and Speed--Equation C.3 gives a relationship between rolling resistance and speed applicable in measurement sections with uniform geometric characteristics. This equation may be used to estimate a raw measurement

$$\Delta R = 2000\, p \sqrt{\underbrace{.0715}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta d_1}} + \underbrace{.0884}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta d_2}} + \underbrace{.0633}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta t_1}} + \underbrace{.0970}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta t_2}} + \underbrace{.0009}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta g}} + \underbrace{.0010}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta G}}} \quad . \quad \text{(C.13)}$$

$$\Delta R = 2000\, p \sqrt{\underbrace{.0508}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta d_1}} + \underbrace{.0631}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta d_2}} + \underbrace{.0448}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta t_1}} + \underbrace{.0695}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta t_2}} + \underbrace{.0007}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta g}} + \underbrace{.0010}_{\substack{\text{Contrib.}\\ \text{of}\\ \Delta G}}} \quad . \quad \text{(C.14)}$$

section rolling resistance, $R_m$. Further, the relationship may be inverted to yield

$$V_2 = V_1^2 + 2gL(G-R_m) \quad . \qquad (C.15)$$

In measurement section 1, an independent measurement of speed was not available. Therefore, the measurement section 1 midpoint speed (which was used as the average test section speed) was estimated using equation C.15. The $V_1$ speed in equation C.15 was not really really random; the hump speed was treated as a constant in this study.* Therefore, most of the variation in speed at measurement section 1 was due to the term with the most widely varying randomness in equation C.15 for measurement section 1, $R_m$. This resulted in a nearly total coupling of these two important variables in measurement section 1, as shown in Figure C-2** for the Hinkle Yard data. A similar problem existed in measurement section 2 but was not as extreme because the $V_1$ term contained more variation (the master retarder let out speed). Additional randomness existed in the measurement section because the calculation was made over the varying geometries of seven or eight group retarder track sections. In Figure C-3, the effect can be seen only as a pronounced "grain" of negative slope in the data. Note that the overall correlation is slightly positive (i.e., opposite to the grain) but nonetheless significant.

Figures C-4 and C-5 show the rolling resistance versus speed relationships for measurement sections 3 and 4, respectively. In measurement section 4, a similar problem existed but to a lesser extent. Here, the process control system did provide independent estimates of speed and rolling resistance. In the computations, the rolling resistance was used in computing the average test section speed for extrapolating tangent point speed upstream to obtain test section entry speed and downstream to obtain test section exit speed. These speeds were then used to compute test section average speed, as explained in Section 5.2.5.

Finally, an analogous but opposite problem existed in measurement section 3: The raw rolling resistance itself was estimated using equation C.3.+ Using this rolling resistance, a midpoint speed was then interpolated‡ for the overall average speed. However, there were several degrees of freedom in the resulting computation because both the entry and exit speeds were independently obtained random measures, and the varied geometries of each route induced additional variation.

When the data from all four test sections were combined, as in Figure C-6, the effect of the computational relationships were reduced, although there was still a pronounced grain to the data. As with the multicolinearity problem, the undersirable side effects of this computational coupling of speed and rolling resistance were reduced still further by combining the data for more than one yard. This is demonstrated by Figures C-7 and C-8. Figure C-7 shows the four DeWitt Yard measurement sections combined; it is analogous to Figure C-6 in interpretation and behavior. Figure C-8 shows the four measurement sections of Hinkle Yard and the four measurement sections of DeWitt Yard combined into a single data base. Only a slight graininess remains; it is much less noticeable in Figure C-8 for the two combined data bases than for either of the two considered alone. Consequently, the Hinkle and DeWitt Yard data bases were combined for the regression analysis.

One casualty of the problem was the interaction term between speed and distance. Since the interaction term would have attempted allowing rolling resistance to have a separate slope with speed within each measurement section, it would obviously be unduly sensitive to the strong relation shown in measurement section 1. Thus, this interaction could not be included in the analyis.

C.3.1.2 Differential Equation Formulation

If rolling resistance really depends on speed, a differential equation formulation should be used in the car's motion and resistance computations. Neither the process control systems nor our subsequent data processing programs used such an approach, however. The relations given earlier in this appendix are based on the static (i.e., nonvelocity-dependent) formulation.

Assuming only a linear dependence of rolling resistance on speed, the basic differential equation governing each car's motion was discussed in Appendix A, and was given in equation A.1. The more general solution of the equation was given in equation A.5 and A.6.

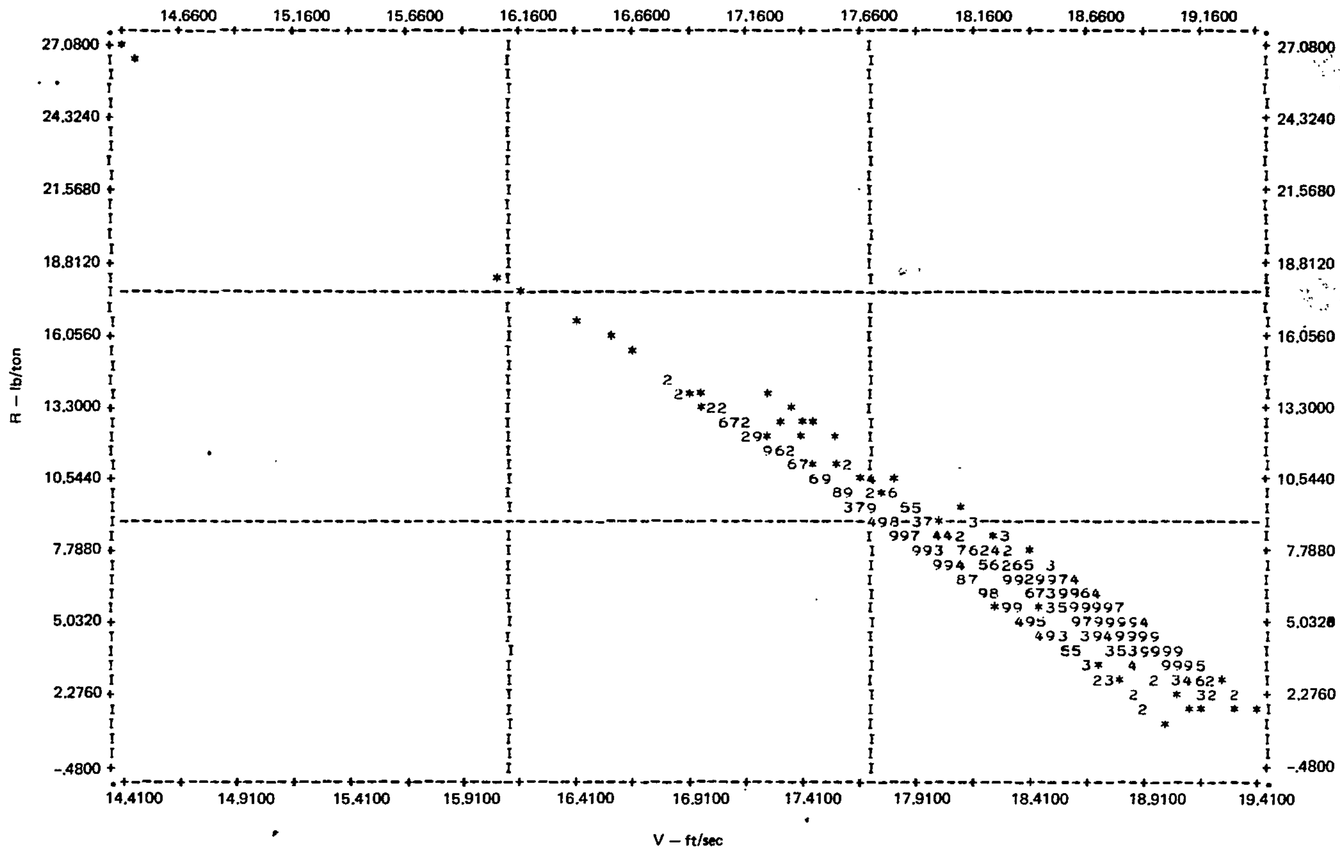
---

*This was simply a constant obtained from yard personnel.

**The remaining variation evident in Figure C-2 is due primarily to using four values of effective gravitational acceleration, ge, for the four car weight classes.

+Test section midpoint speed was computed halfway between these two points, usually after but occasionally before the system provided speed at the tangent point.

‡Using the actual grade geometry, but ignoring specific corrections for switch and curve effects, which were not known but were included in an average sense because they affected the value of $R_m$ as discussed in section B.2.5.



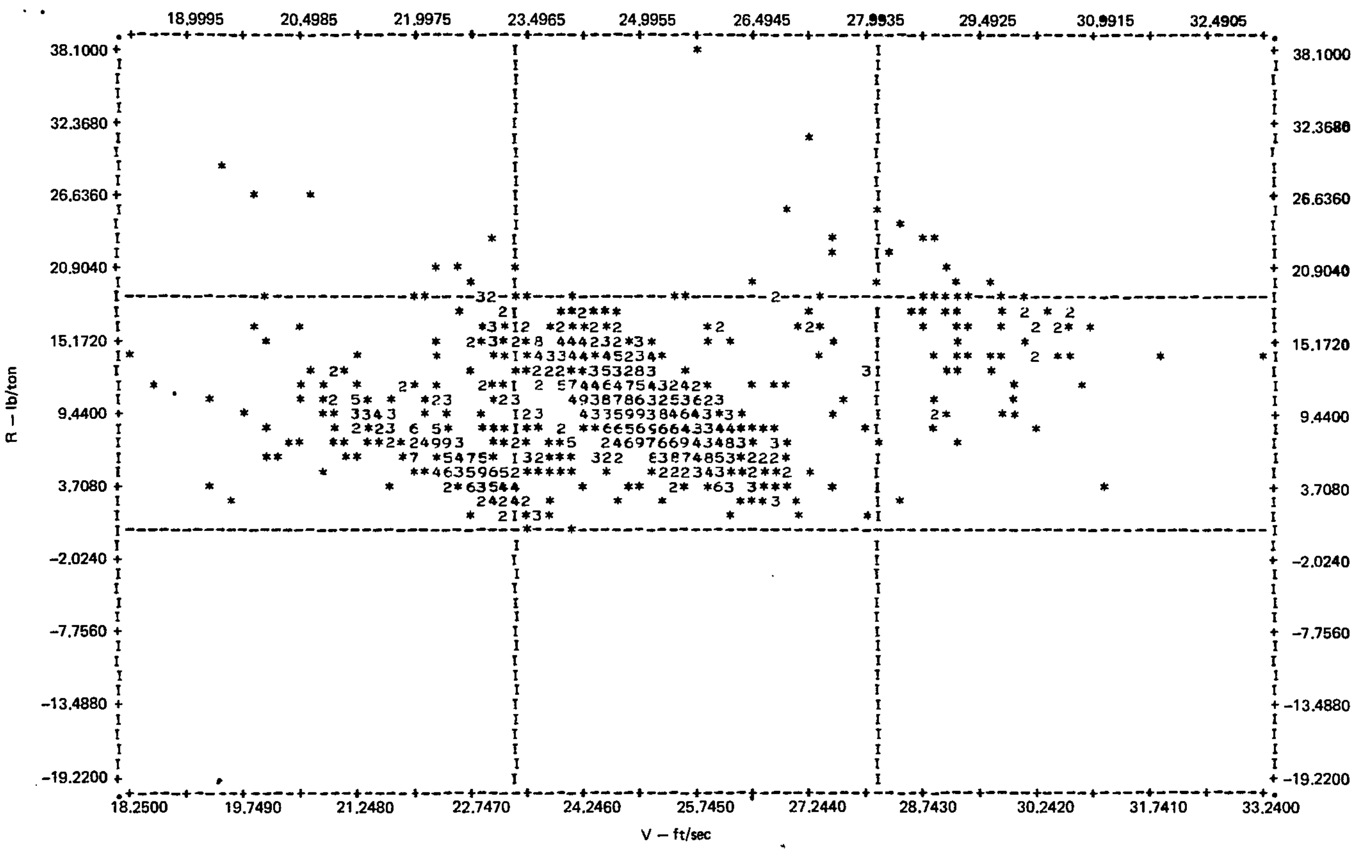

STATISTICS . .

| | | | | | |
|---|---|---|---|---|---|
| CORRELATION (R) – | -.96839 | R SQUARED – | .93778 | SIGNIFICANCE R – | .00001 |
| STD ERR OF EST – | .69322 | INTERCEPT (A) – | 90.97306 | STD ERROR OF A – | .67239 |
| SIGNIFICANCE A – | .00001 | SLOPE (B) – | -4.58193 | STD ERROR OF B – | .03665 |
| SIGNIFICANCE B – | .00001 | | | | |

PLOTTED VALUES – 1039 EXCLUDED VALUES – 0 MISSING VALUES – 1

******** IS PRINTED IF A COEFFICIENT CANNOT BE COMPUTED.

FIGURE C-2 OBSERVED ROLLING RESISTANCE AS A FUNCTION OF SPEED IN MEASUREMENT SECTION 1 (HINKLE YARD DATA)



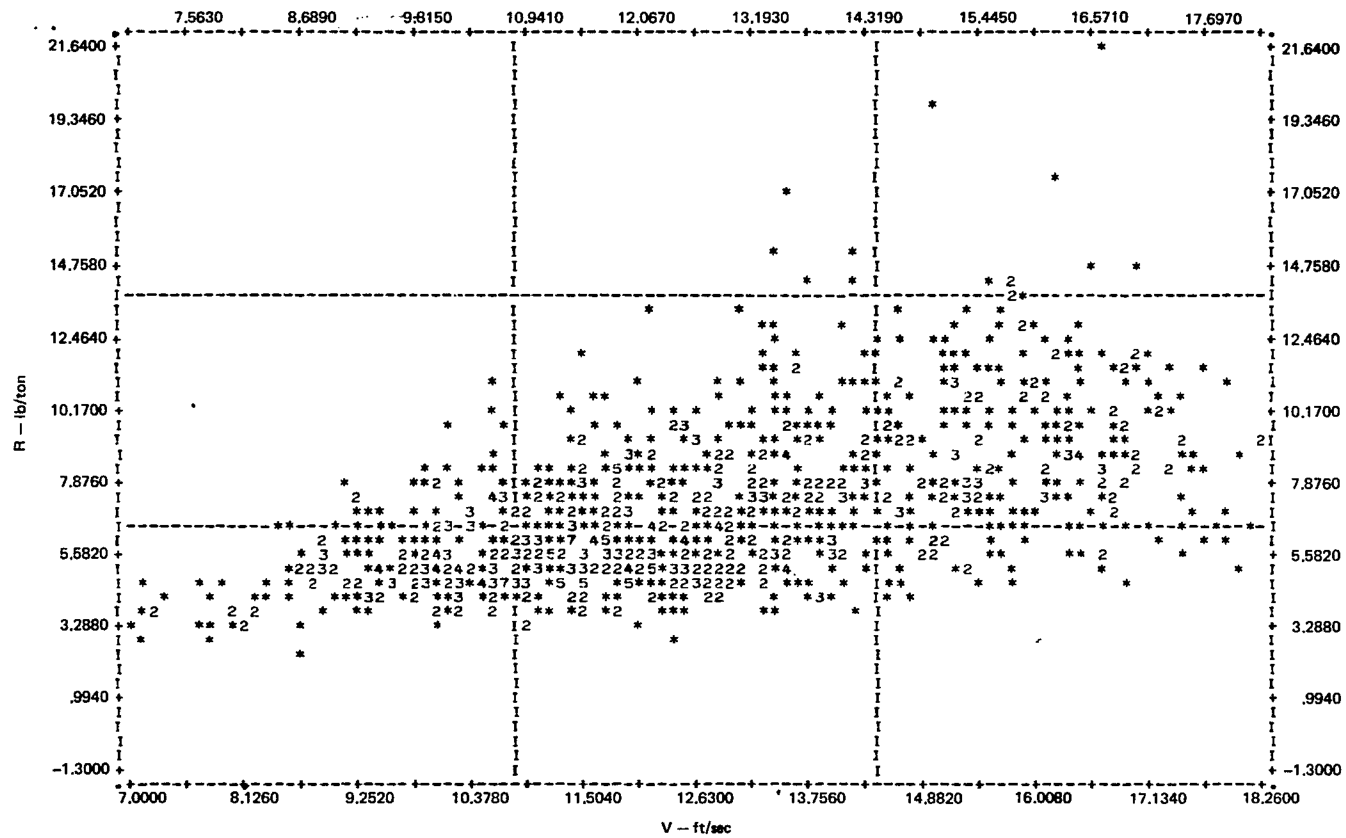

STATISTICS . .

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CORRELATION (R) | – | .18845 | R SQUARED | – | .03551 | SIGNIFICANCE R | – | .00001 |
| STD ERR OF EST | – | 4.45162 | INTERCEPT (A) | – | -.01074 | STD ERROR OF A | – | 1.66486 |
| SIGNIFICANCE A | – | .49743 | SLOPE (B) | – | .41628 | STD ERROR OF B | – | .06743 |
| SIGNIFICANCE B | – | .00001 | | | | | | |

PLOTTED VALUES – 1037 EXCLUDED VALUES – 0 MISSING VALUES – 3

******** IS PRINTED IF A COEFFICIENT CANNOT BE COMPUTED.

FIGURE C-3 OBSERVED ROLLING RESISTANCE AS A FUNCTION OF SPEED IN MEASUREMENT SECTION 2 (HINKLE YARD DATA)

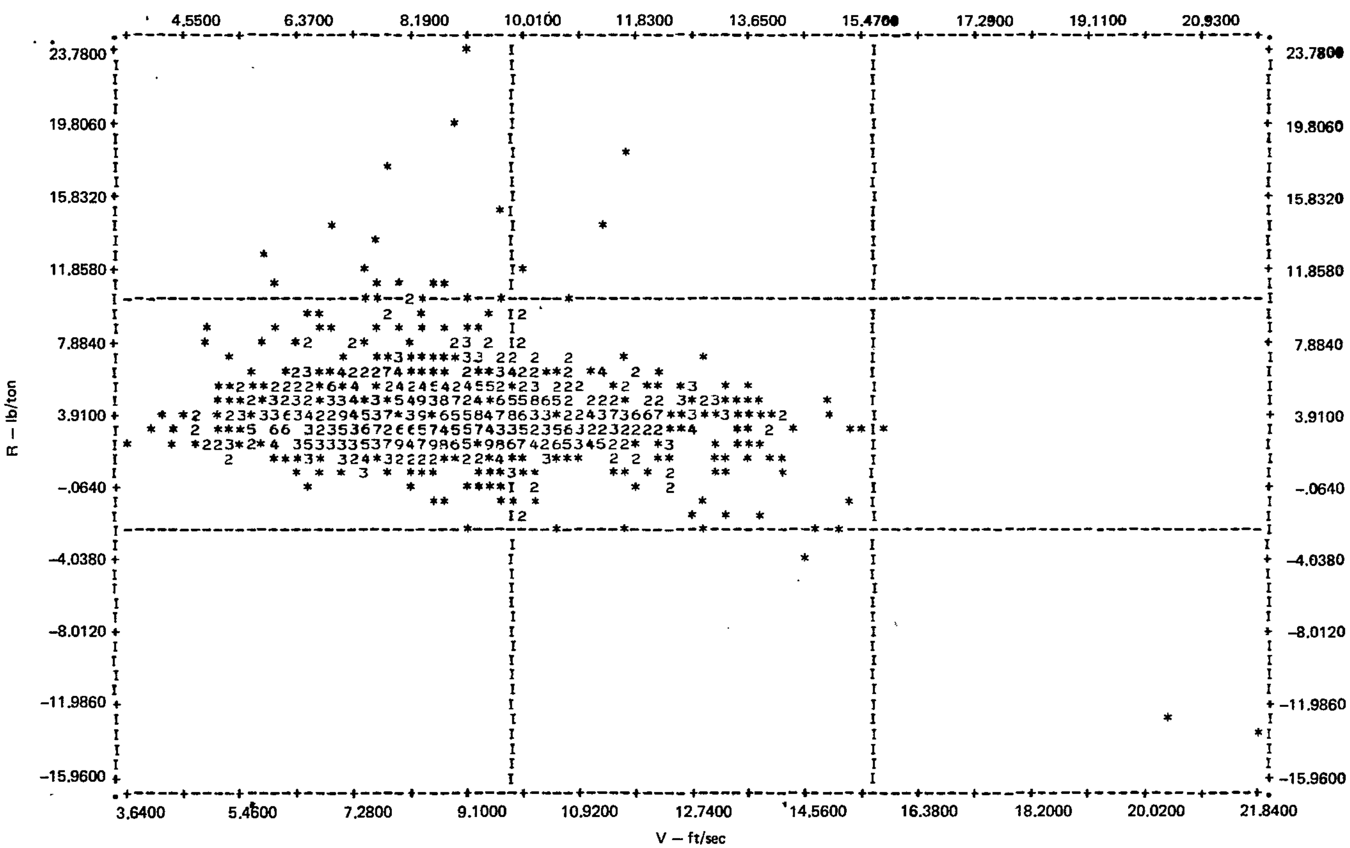



STATISTICS . .

| | | | | | |
|---|---|---|---|---|---|
| CORRELATION (R) – | .55971 | R SQUARED – | .31327 | SIGNIFICANCE R – | .00001 |
| STD ERR OF EST – | 2.06671 | INTERCEPT (A) – | -.10923 | STD ERROR OF A – | .34951 |
| SIGNIFICANCE A – | .37735 | SLOPE (B) – | .58254 | STD ERROR OF B – | .02678 |
| SIGNIFICANCE B – | .00001 | | | | |

PLOTTED VALUES – 1039 EXCLUDED VALUES – 0 MISSING VALUES – 1

FIGURE C-4 OBSERVED ROLLING RESISTANCE AS A FUNCTION OF SPEED IN MEASUREMENT SECTION 3 (HINKLE YARD DATA)

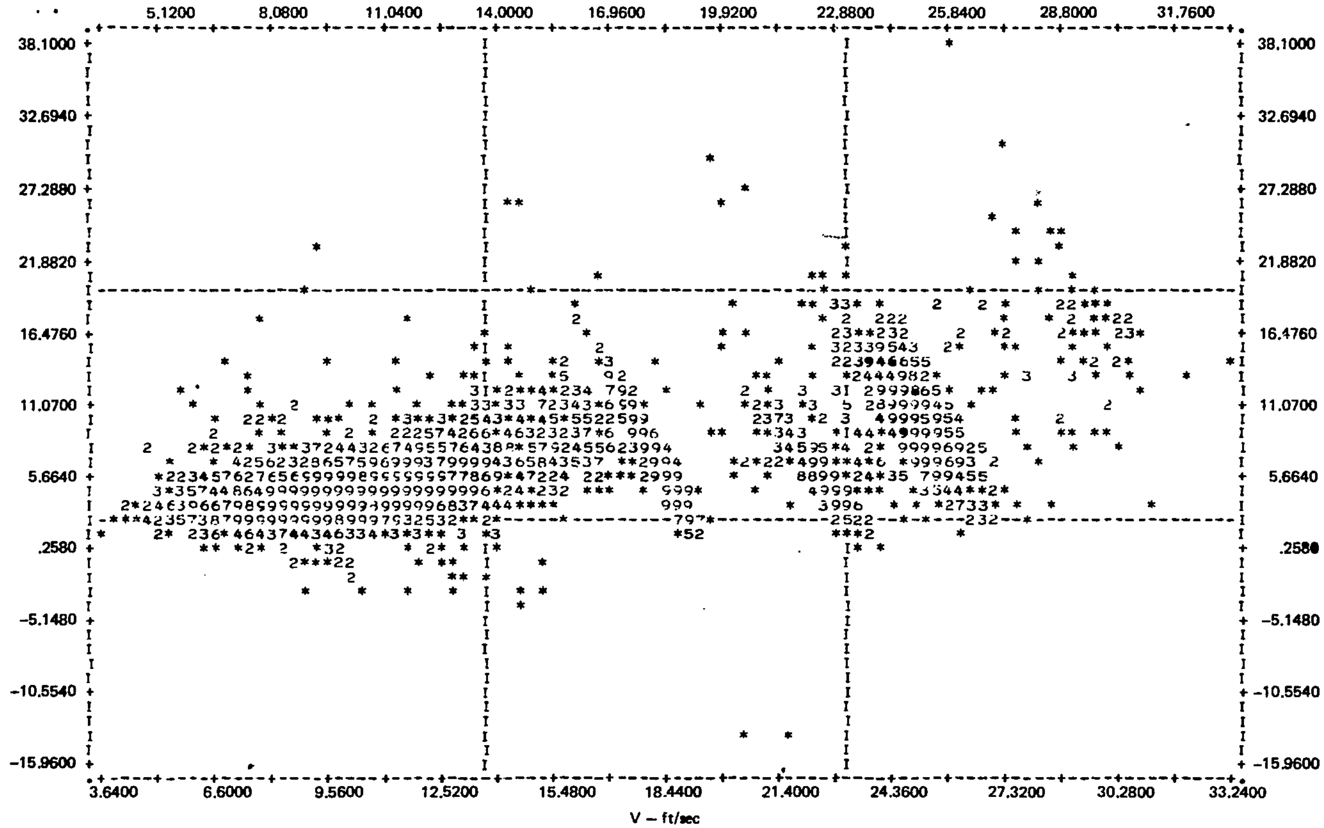



STATISTICS . .

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CORRELATION (R) | – | -.18941 | R SQUARED | – | .03588 | SIGNIFICANCE R – | .00001 |
| STD ERR OF EST | – | 2.47325 | INTERCEPT (A) | – | 6.31027 | STD ERROR OF A – | .32771 |
| SIGNIFICANCE A | – | .00001 | SLOPE (B) | – | -.21605 | STD ERROR OF B – | .03510 |
| SIGNIFICANCE B | – | .00001 | | | | | |

PLOTTED VALUES – 1020 EXCLUDED VALUES – 0 MISSING VALUES – 20

FIGURE C-5 OBSERVED ROLLING RESISTANCE AS A FUNCTION OF SPEED IN MEASUREMENT SECTION 4 (HINKLE YARD DATA)

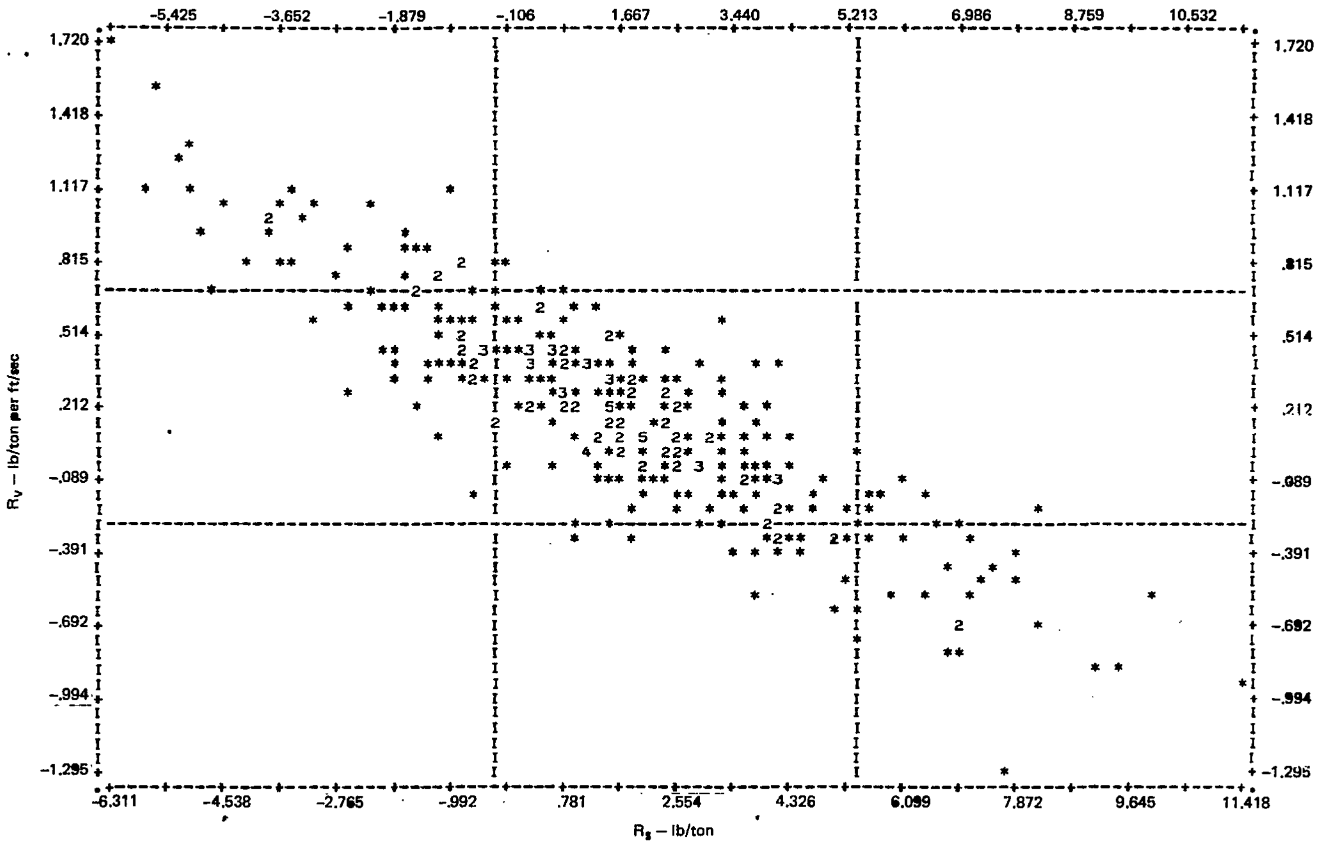



STATISTICS . .

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CORRELATION (R) – | .49992 | R SQUARED – | .24992 | SIGNIFICANCE R – | .00001 |
| STD ERR OF EST – | 3.30613 | INTERCEPT (A) – | 2.20796 | STD ERROR OF A – | .14561 |
| SIGNIFICANCE A – | .00001 | SLOPE (B) – | .30920 | STD ERROR OF B – | .00838 |
| SIGNIFICANCE B – | .00001 | | | | |

PLOTTED VALUES – 4087 EXCLUDED VALUES – 0 MISSING VALUES – 21

FIGURE C-6 OBSERVED ROLLING RESISTANCE AS A FUNCTION OF SPEED – ALL FOUR MEASUREMENT SECTIONS COMBINED (HINKLE YARD DATA)



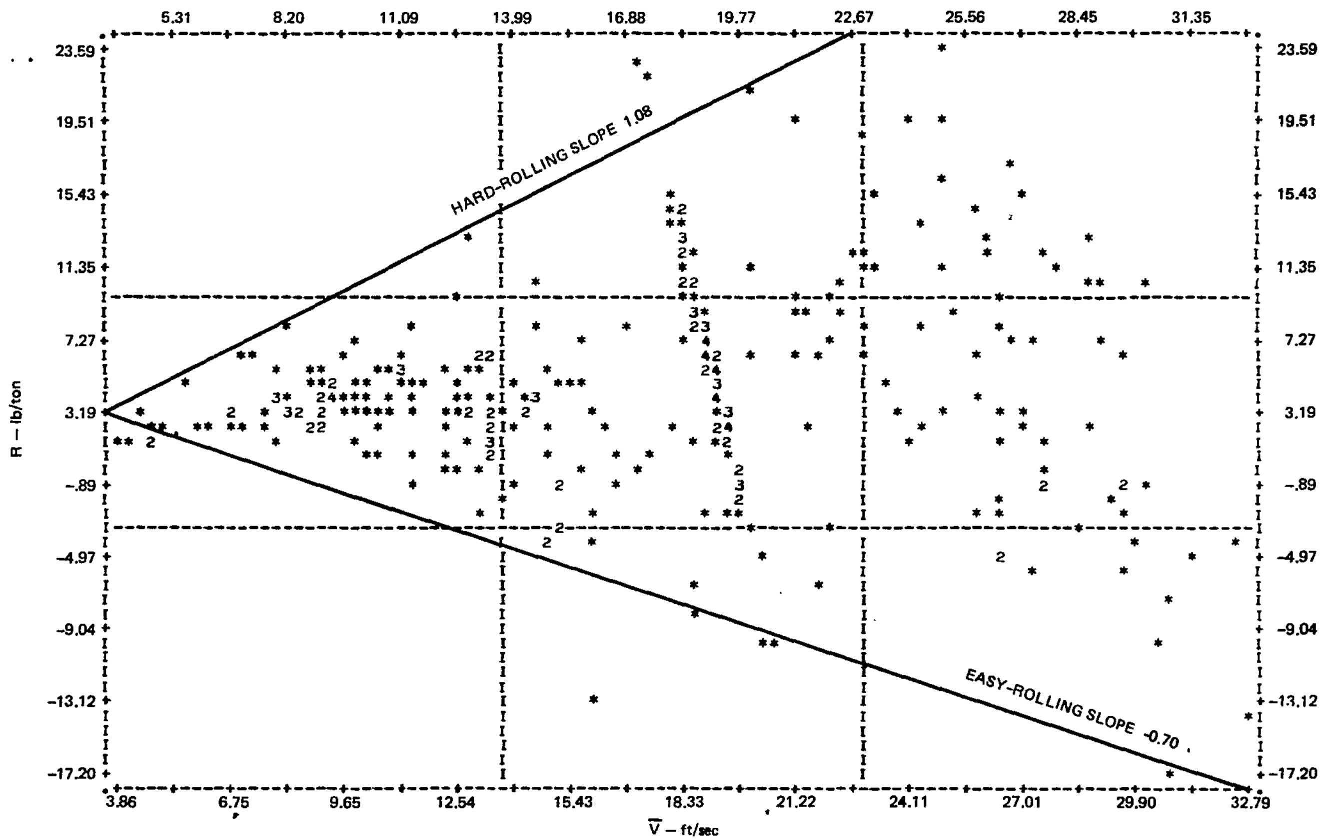

ERROR ANAL. ON STATIC RESISTANCES WHEN C.E. APPLIES

STATISTICS . .

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CORRELATION (R) – | -.87353 | R SQUARED – | .76305 | SIGNIFICANCE R – | .00001 |
| STD ERR OF EST – | .21511 | INTERCEPT (A) – | .44101 | STD ERROR OF A – | .01382 |
| SIGNIFICANCE A – | .00001 | SLOPE (B) – | -.13239 | STD ERROR OF B – | .00414 |
| SIGNIFICANCE B – | .00001 | | | | |

PLOTTED VALUES – 320 EXCLUDED VALUES – 0 MISSING VALUES – 0

FIGURE C-7 SCATTER DIAGRAM OF ERRDE SIMULATION RANDOMLY GENERATED VALUES OF $R_V$ VERSUS $R_S$, FROM RUN USING ENGLEWOOD YARD PARAMETERIZATION – 320 CASES IN FOUR MEASUREMENT SECTIONS




STATISTICS . .

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CORRELATION (R) – | .02978 | R SQUARED – | .00089 | SIGNIFICANCE R – | .29781 |
| STD ERR OF EST – | 5.80391 | INTERCEPT (A) – | 4.36132 | STD ERROR OF A – | .90265 |
| SIGNIFICANCE A – | .00001 | SLOPE (B) – | .02596 | STD ERROR OF B – | .04886 |
| SIGNIFICANCE B – | .29781 | | | | |

PLOTTED VALUES – 320 EXCLUDED VALUES – 0 MISSING VALUES – 0

FIGURE C-8 SCATTER DIAGRAM OF ERRDE SIMULATION STATISTICALLY COMPUTED RESISTANCES (R) VERSUS CAR's MEASUREMENT SECTION AVERAGE SPEED ($\overline{V}$), FROM RUN USING ENGLEWOOD YARD PARAMETERIZATION – 320 CASES IN FOUR MEASUREMENT SECTIONS

Elimination of the variable t from these equations produces

$$X - X_o = \frac{1}{\beta}(V - V_o) - \frac{\alpha}{\beta^2}\ln\frac{V + \alpha/\beta}{(\alpha/\beta + V_o)} \quad . \quad (C.16)$$

This equation is in the form that would have to be used, assuming that measured speeds had been measured at several points along the track. Further, the parameters $\alpha$ and $\beta$ would be expected to change with every change in geometry, switch, and so on, further compounding data requirements. If data were sufficient, the parameters would have to estimated by an iterative numerical technique such as nonlinear regression or the solution of simultaneous nonlinear equations.*

Therefore, in this study the above approach was not recommended. The nature of the errors involved in using a static rolling resistance formulation in this study were analyzed, however, and the results are reported in the next section.

C.3.2 Methodology

Each car's rolling resistance was assumed to be linearly dependent on its speed. Then, each car's motion was described by the differential equation A.1 (Appendix A). In the analysis of Englewood Yard data on distance versus time for a sample of 39 cars (Appendix A), the statistical distribution information presented in Table C-1 was found for the parameters $R_s$ and $R_v$ of the differential equation.** That is, each car's behavior is governed by the correlated pair of random variables ($R_s$, $R_v$).

Table C-1

DISTRIBUTION OF PARAMETERS $R_s$ AND $R_v$

| Parameter | Mean Value | Standard Deviation |
|---|---|---|
| $R_s$ | 1.513 lb/ton | 3.513 lb/ton |
| $R_v$ | 0.236 lb/ton/ ft/sec | 0.429 lb/ton/ ft/sec |

Correlation of $R_s$ and $R_v$ = −.914.
Estimation equation:

$R_v$ = .44 − .138 $R_s$ (  = .202 lb/ton per ft/sec).

*The choice of the technique would depend on the number of data points available.

**$R_x$ is assumed to be the algebraic sum of all static resistances, and $R_v$ is the sum of all velocity-dependent resistances. The above-mentioned parameterization is obtained by substituting equations A.11 and A.12 into A.1.

This information was also shown graphically in Figures A-6 and A-7. Figure A-6 is a scatter diagram of the fitted parameter $R_s$ plotted against $R_v$. Each point on this diagram represents the two parameters for one particular car. The instantaneous overall resistance R at any speed can then be computed from the relationship

$$R = R_s + R_v V. \qquad (C.17)$$

This was done for the 39 points shown in Figure A-6, and the resulting straight-line R as a function of V relationships were shown in Figure A-7.

However, in the primary data base for this project static relationships were used in estimating rolling resistances both in the on-line process control system and in the software developed for this project. One common relationship used to estimate rolling resistance was discussed in equation C.3. This equation was derived under the assumption that rolling resistance is independent of speed. Therefore, SRI wished to determine what the errors would be if a relationship such as equation C.3 were used to estimate rolling resistance, when rolling resistance in fact depended on speed. An analytical solution to this question proved to be cumbersome; consequently, a simple Monte Carlo simulation program, ERRDE (error-ignoring differential equation), was written. This program simulates the four (numbered 1 through 4) measurement sections for a yard data collection system similar to Hinkle Yard. In fact, the Hinkle Yard geometry is programmed into ERRDE. No attempt was made in ERRDE to model detailed aspects of the yard, such as the process control system or the detailed geometry. Nor were retarder let-out speeds correlated with resistances, as in a real-life system. The emphasis in ERRDE was to replicate only those features most pertinent to arriving at a valid conclusion.

Each simulated car in ERRDE was assumed to be governed by equation A.1. Assuming that both parameters $R_s$ and $R_v$ were normally distributed, the information of Table C-1 was used to generate a correlated pair (i.e., jointly bivariate normal) of values $R_s$ and $R_v$ for each simulated car. A separate set of cars was generated for each of the four measurement sections; however, the underlying parameters for each of the car populations were identical—namely, those in Table C-1. Each measurement section was simulated in a simplified manner. Within the simulation of the behavior of a single car, a constant grade was assumed (from one car to the next, the grade could change, see Table C-2). The speed of the car was obtained at two points, $X_1$ and $X_2$ (the speeds at these points were $V_1$ and $V_2$, respectively). These speeds were computed by using equation A.6 to

*$R_s$ is assumed to be the algebraic sum of all static resistances, and $R_v$ is the sum of all velocity-dependent resistances. The above-mentioned parameterization is obtained by substituting equations A.11 and A.12 into A.1.

Table C-2

ASSUMED PARAMETER VALUES OR DISTRIBUTIONS
USED IN THE ERRDE SIMULATION

| Parameter | Measurement Section 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Zero point for simulated motion | Crest | Exit from master retarder | Exit from group retarder | Tangent point |
| $X_1$ | Constant value; entrance to speed trap, 160 feet from crest | Start of speed trap; four different lengths for each of the four track groups. Each car's group was selected randomly, each group with an equal probability | Exit from group retarder | Tangent point |
| $X_2$ | Constant value; exit from speed trap, 240 feet from crest | End of speed trap as appropriate to the track group selected as above. | End of measurement section 3; 40 different lengths depending on destination classification track. Destination classification tracks selected randomly, each with an equal probability. | Target coupling point (car may have stopped sooner). Assumed uniformly distributed in interval (100, 2,500 feet), approximating Hinkle. |
| $V_o$ | Constant value; hump speed (2.933 ft/sec at Hinkle) | Normally distributed exit speed from master retarder calibrated from available Hinkle data: mean = 22.3 ft/sec; SD = 2.8 ft/sec | Normally distributed exit speed from group retarder calibrated from available Hinkle data: mean = 14.8 ft/sec; SD = 2.5 ft/sec | Normally distributed tangent point velocity calibrated from available Hinkle data: mean = 11.3 ft/sec; SD = 2.4 ft/sec |
| G | Constant 0.03 as per Hinkle geometry (crest dynamics ignored) | Depended on track group selected as for $X_1$ above. | Depended on destination classification track selected as for $X_2$ above. | Constant 0.0008 as per Hinkle geometry. |

find the times the car passed points $X_1$ and X . These times, $t_1$ and $t_2$, had to be obtained by solving this equation numerically for t. The values obtained for $t_1$ and $t_2$ were then fitted into equation A.5 to find $V_1$ and $V_2$.* $V_1$ and $V_2$ were then used to compute a static value of rolling resistance, using equation C.3.

Table C-2 elaborates on the assumed parameters and on the distributions of those parameters that were assumed to be random. Occasionally, normally for measurement section 4, a solution for $X_2$ could not be obtained. This meant that the car had stopped before it reached $X_2$. In this case, $V_2$ was set to zero, and a revised value for $X_2$ was obtained by using equation C.16 (i.e., with V set to zero) to find the point where the car stopped. This was also analogous to the way in which the measurement section 4 data were computed, such as obtained from Hinkle Yard.

The measured, or total static, rolling resistance, R, computed by equation C.3 could then be compared with the average test section speed, $\bar{V}$. Ideally, the linear regression of R as a function of V should yield a relationship close to the original relationship--that is, with intercept $\hat{R}_s$ approximately equal to the mean of all the $R_s$ and with slope $R_v$ approximately equal to the mean of all the $R_v$. The average speed V used in this calibration was computed as

$$\bar{V} = (V_1 + 2\,V_M + V_2)/4, \qquad (C.18)$$

where

$V_M$ = speed in the middle of the measurement section.

$V_M$ was computed using the measured rolling resistance, R. This is in conformance with the definition of average speed used for long measurement sections (i.e., 3 and 4) in the primary data base (see Section 4.2.5).

### C.3.3 Results and Conclusions

ERRDE was applied in a run consisting of 320 simulated cars (cases) equally split among the four measurement sections. Figures C-7 and C-8 and the top portion of Table C-3 present the results. In Figure C-8, a marked heteroskedasticity (unequal spread of data about the regression line at different points along the line) is evident. Thus, these confidence intervals (and significance tests) can at best be used only as a general guide in making evaluations.* The

*In measurement sections 3 and 4, $X_1$ was at the origin, so that $V_1 = V_0$. Therefore, in these cases, only $V_2$ had to be obtained.

*The regression line itself is not affected by the heteroskedasticity--the least squares slope and intercept are derived from mathematical assumptions requiring no more of the variance than that it be finite. However, the heteroskedasticity does violate the underlying distributional assumption of the statistical tests.

Table C-3

ERRDE SIMULATION RESULTS

| | Estimated Parameter Value* | Sample Standard Deviation | 95% Confidence Interval |
|---|---|---|---|
| **Parameter values based on Englewood Yard Data** | | | |
| Generated population | | | |
| $R_s$ | 1.646 lb/ton | 2.911 | -- |
| $R_v$ | 0.223 lb/ton/ft/sec | 0.441 | -- |
| Regression of total static R as a function of $\bar{V}$ | | | |
| $\hat{R}_s$ | 4.361 | -- | 2.556 to 6.167 |
| $\hat{R}_v$ | 0.026 | -- | -.072 to 0.124 |
| Parameter values based on higher average $R_v$ | | | |
| Generated population | | | |
| $R_s$ | 1.089 | 2.708 | -- |
| $R_v$ | 0.874 | 0.410 | -- |
| Regression of total static R as a function of $\bar{V}$ | | | |
| $\hat{R}_s$ | 1.299 | -- | -.085 to 2.683 |
| $\hat{R}_v$ | 0.813 | -- | 0.727 to 0.899 |

*Sample mean in the case of $R_s$ and $R_v$; estimated parameters in the case of $\hat{R}_s$ and $\hat{R}_v$.

confidence intervals of both $\hat{R}_s$ and $\hat{R}_v$ clearly do not include the means of their respective generated populations. This might have been due in part to the heteroskedasticity. However, the overall region occupied by the data points in Figure C-8 is not unlike the region occupied by the straight-line relationships in Figure A-6, except that the range of speeds generated in Figure C-8 extends considerably beyond that for which the data in Figure A-6 were obtained. These higher speeds generally correspond to measurement section 2; in a simulation run omitting this test section, the estimated parameters $\hat{R}_s$ and $\hat{R}_v$ came much closer to the population means for $R_s$ and $R_v$.** Considering that the average speed dependence (mean $R_v$) in the simulated population was not especially strong, the computed values $\hat{R}_s$ and $\hat{R}_v$ were believed to be sufficiently accurate for practical use.+ However, when the average speed dependence is stronger, the analysis must represent it accurately. Therefore, the ERRDE simulation was repeated in exactly the same manner, except with two changes, both increasing the mean $R_v$:

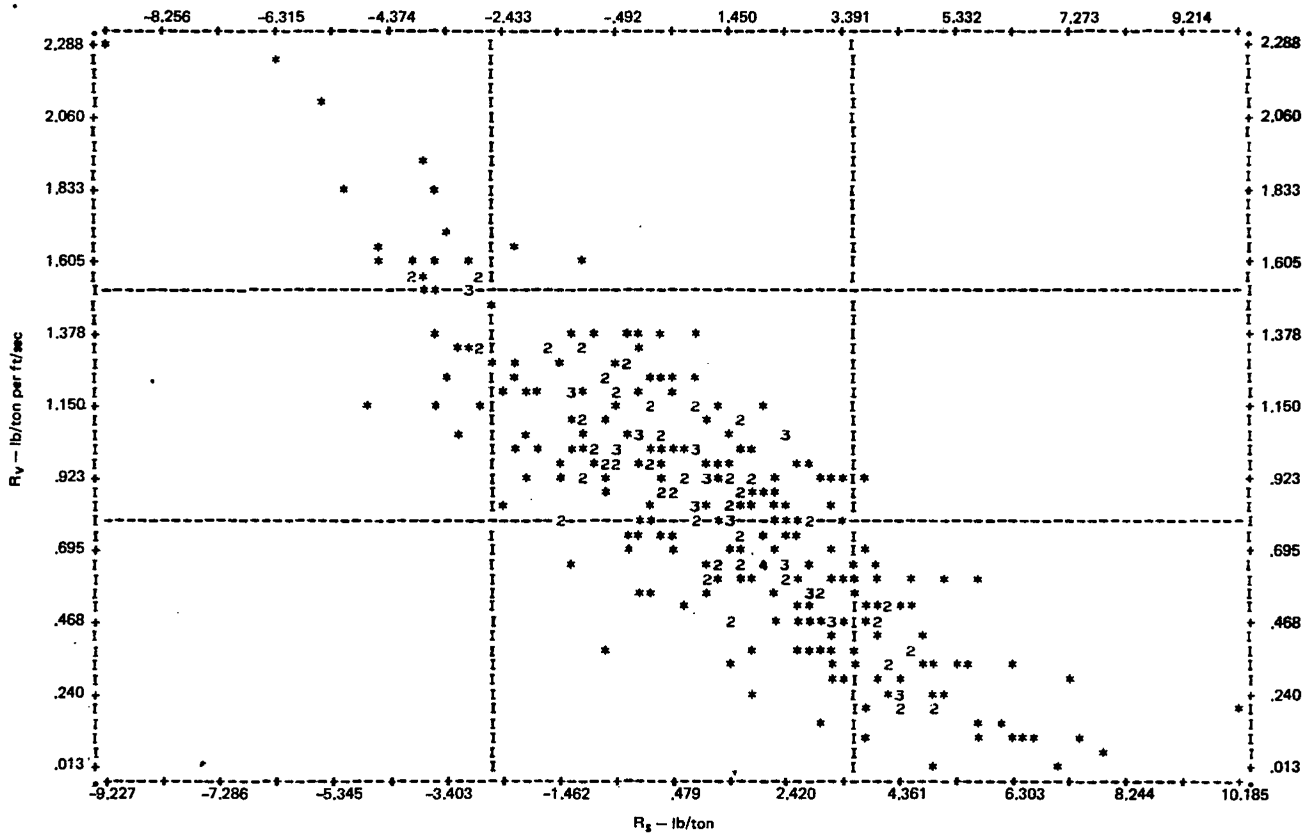
- The intercept term in the estimation equation in Table C-1 was increased from 0.444 to 1.0.
- When generating the bivariate pair ($R_s$, $R_v$) any $R_V$ less than zero was rejected, and another pair was generated.*

The results of this run are shown in Figures C-9 and C-10 and in the lower portion of Table C-3. Table C-3 indicates that the 95% confidence intervals for both $\hat{R}_s$ and $\hat{R}_v$ do include the sample means of the $R_s$ and $R_v$. However, in Figure C-10 a strong heteroskedasticity is still evident; thus, this test should be used only as a general guide. In the case reported here, both the intercept $\hat{R}_s$ as well as the slope $\hat{R}_v$ were believed to be sufficiently close to

**The confidence interval for $\hat{R}_s$ included the mean $R_s$, while the confidence interval for $R_v$ was such that the mean $R_v$ fell just about at the upper boundary of the confidence interval.

+Most designers, seeing such a comparatively low speed dependence, would probably compute an overall R using some "typical" speed in equation C.17 and then use the more convenient static computational relationships.

*This truncates the bivariate distribution below zero $R_v$, distorting the distribution away from true bivariate normality. Because of the correlation between $R_s$ and $R_v$, this also tends to reduce the mean $R_s$.

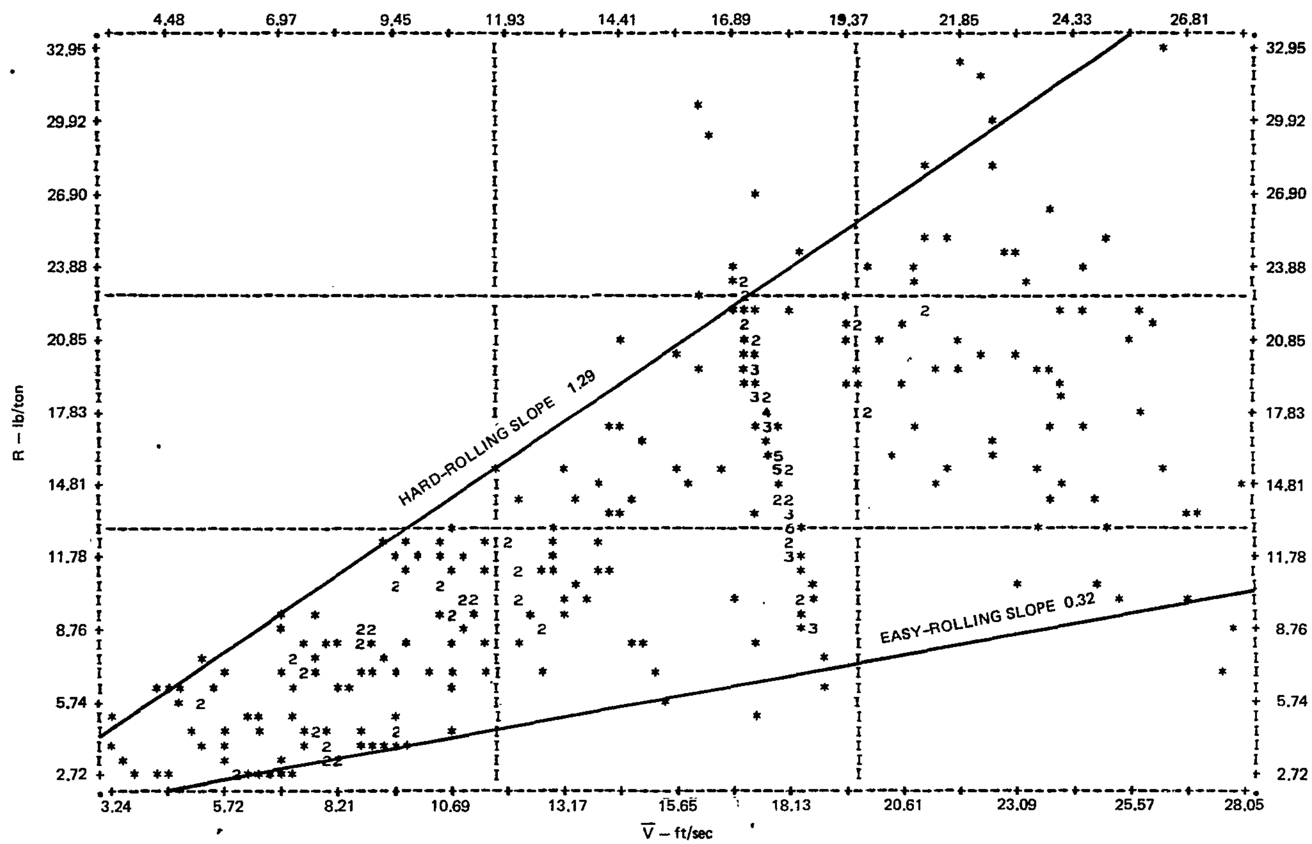



STATISTICS . .

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CORRELATION (R) – | -.86384 | R SQUARED – | .74622 | SIGNIFICANCE R – | .00001 |
| STD ERR OF EST – | .20688 | INTERCEPT (A) – | 1.01678 | STD ERROR OF A – | .01247 |
| SIGNIFICANCE A – | .00001 | SLOPE (B) – | -.13081 | STD ERROR OF B – | .00428 |
| SIGNIFICANCE B – | .00001 | | | | |

PLOTTED VALUES – 320 EXCLUDED VALUES – 0 MISSING VALUES – 0

FIGURE C-9 SCATTER DIAGRAM OF ERRDE SIMULATION RANDOMLY GENERATED VALUES OF $R_V$ VERSUS $R_S$, WITH MORE PRONOUNCED SPEED SENSITIVITY – 320 CASES IN FOUR MEASUREMENT SECTIONS




STATISTICS . .

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CORRELATION (R) – | .72822 | R SQUARED – | .53030 | SIGNIFICANCE R – | .00001 |
| STD ERR OF EST – | 4.60890 | INTERCEPT (A) – | 1.29873 | STD ERROR OF A – | .89190 |
| SIGNIFICANCE A – | .03071 | SLOPE (B) – | .81331 | STD ERROR OF B – | .04292 |
| SIGNIFICANCE B – | .00001 | | | | |

PLOTTED VALUES – 320 EXCLUDED VALUES – 0 MISSING VALUES – 0

FIGURE C-10 SCATTER DIAGRAM OF ERRDE SIMULATION STATISTICALLY COMPUTED RESISTANCES (R) VERSUS CAR's MEASUREMENT SECTION AVERAGE SPEED ($\overline{V}$), FROM RUN WITH MORE PRONOUNCED SPEED SENSITIVITY – 320 CASES IN FOUR MEASUREMENT SECTIONS their respective sample means to yield results of practical value for design and control applications.

The heteroskedasticity in Figures C-8 and C-10 was not unexpected. With the speed dependence, the range of total resistance computed in equation C.3 would be much higher at higher speeds. The slopes for the straight-line hard- and easy-rollers (drawn by eye) of the swarm of points in Figures C-8 and C-10 should roughly equal the extreme values of $R_v$ in Figures C-7 and C-9, respectively. For the straight lines drawn in Figures C-8 and C-10, this is so.

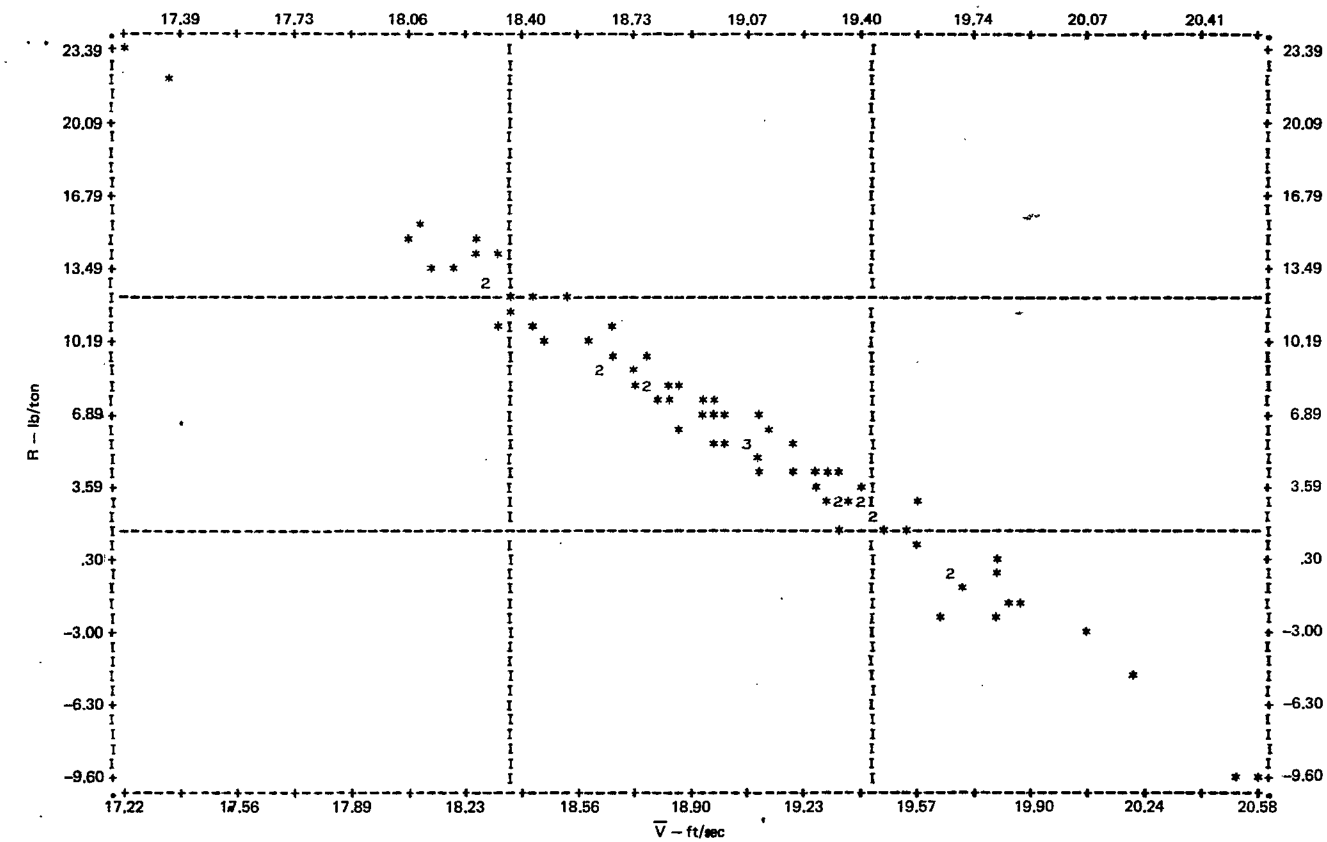
The behavior of the simulated data does, in a broad sense, accurately replicate much of the observed behavior of the Hinkle Yard data. Especially noticeable is the band of data points with negative slope through the centers of Figures C-8 and C-10. This represents the data from measurement section 1 and can be seen more clearly in Figure C-11. This figure is a simulation run of ERRDE using the Englewood Yard parameterization, which simulated only measurement section 1. The low amount of variation from a straight line evident in this figure is due to the relatively small "degrees of freedom" contributing to each data point in measurement section 1. The hump speed is a constant, so that only the parameters $R_s$ and $R_v$ vary within a single case (and $R_s$ and $R_v$ are not independent, but highly correlated, so collectively they do not provide a full 2 degrees of freedom). The negative slope is a reflection of the fact that hard-rolling cars roll slowly, rather than of the underlying dependence of resistance on speed (compare Figures C-8 and C-11 with Figures C-6 and C-2, respectively).

Figures C-12, C-13, and C-14 show ERRDE runs of measurement sections 2, 3, and 4, respectively. Again, the Englewood parameterization was used. The behavior of the measurement section 4 data (Figure C-14) also resembles the equivalent real-life data for this section from Hinkle Yard (Figure C-5). The envelopes of both sets of points appear to reach a maximum roughly at about a car speed of 10 ft/sec and a minimum at about a car speed of 13 ft/sec (excluding the two outlying points in Figure C-5). At lower car speeds, the rolling resistances measured seem to be concentrated in a small band clustered roughly around 4 lb/ton.

An erroneous relationship between total car resistance, R, and average test section car speed, V, would be drawn were any of these measurement sections analyzed in isolation. All four measurement sections yielded a significant negative dependence of R on $\bar{V}$ (i.e., a higher V is predicted to give a lower R, in an average sense). The combined results, however, yielded a reasonable relationship between R and $\bar{V}$. Thus, it was believed to be that the rollability analyses combine data from a wide variety of car speeds and geometric conditions--such as the four measurement sections from one yard or, preferably, from more than one yard.* This lends further support to the decision to combine the Hinkle and DeWitt Yard data bases for analysis.

Measurement section 1, despite the strong but erroneous relationship obtained there, did add accuracy to our ability to obtain the correct relationship between R and $\bar{V}$ in the combined sample from all four measurement sections. This was shown by making ERRDE runs that simulated only measurement sections 2, 3, and 4. The effect was especially noticeable for the population with increased speed sensitivity (i.e., increased mean $R_v$) discussed earlier. Figure C-15 is the scatter diagram of measured resistance, R, plotted against speed; Table C-4 summarizes the related numerical results. As can be seen in Table C-4, the confidence interval for $R_v$ did not include the sample mean of $R_v$. Thus, the accuracy obtained by increasing the variety of data by including measurement section 1 in the analysis more than offsets the detrimental effects of the strong but erroneous negative correlation between R and V in that section.

*Provided that no unexplainable biases exist between the yards.

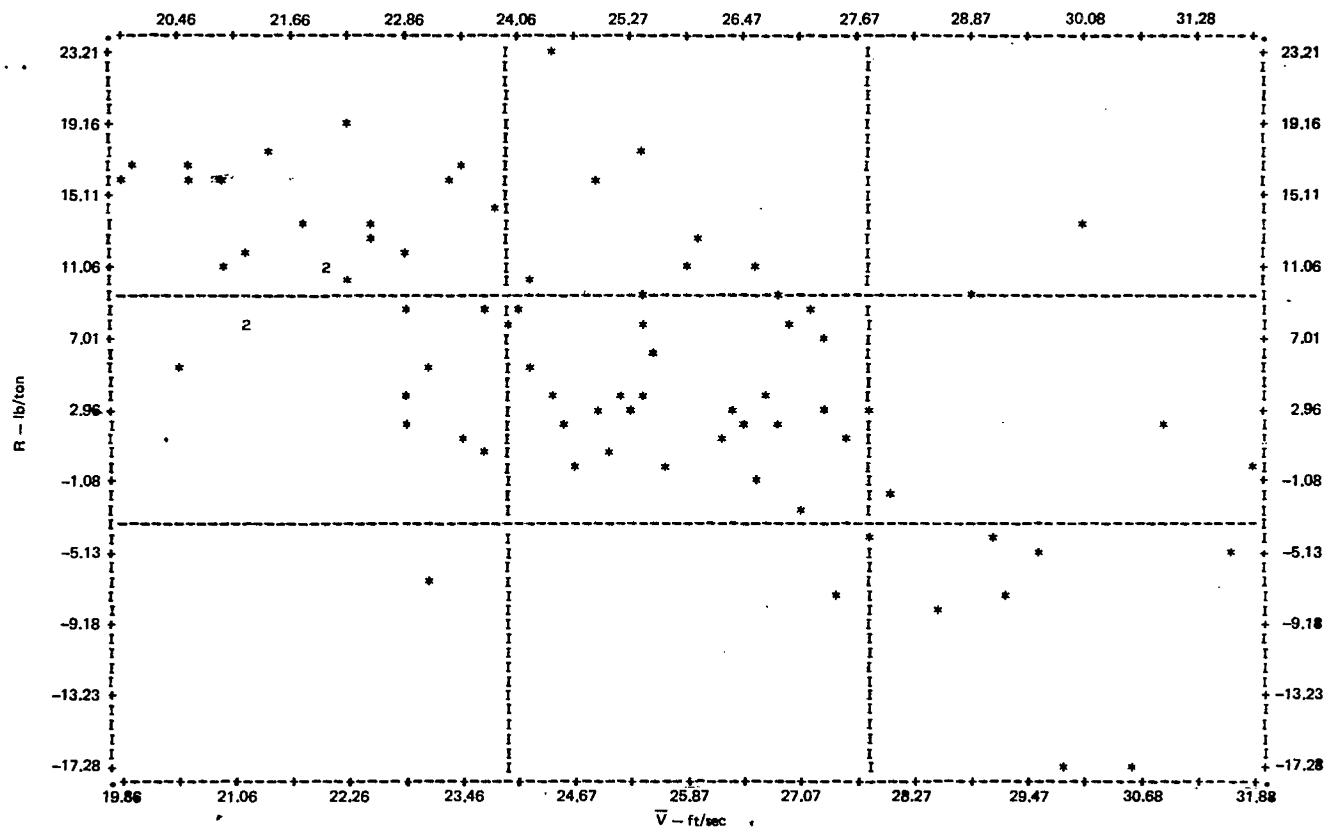



STATISTICS . .

| | | | | | |
|---|---|---|---|---|---|
| CORRELATION (R) – | -.98932 | R SQUARED – | .97875 | SIGNIFICANCE R – | .00001 |
| STD ERR OF EST – | .87885 | INTERCEPT (A) – | 188.00355 | STD ERROR OF A – | 3.08081 |
| SIGNIFICANCE A – | .00001 | SLOPE (B) – | -9.54698 | STD ERROR OF B – | .15928 |
| SIGNIFICANCE B – | .00001 | | | | |

PLOTTED VALUES – 80 EXCLUDED VALUES – 0 MISSING VALUES – 0

FIGURE C-11 SCATTER DIAGRAM OF ERRDE SIMULATION STATISTICALLY COMPUTED RESISTANCES (R) VERSUS CAR's MEASUREMENT SECTION AVERAGE SPEED ($\overline{V}$), FROM RUN USING ENGLEWOOD YARD PARAMETERIZATION – 80 CASES IN MEASUREMENT SECTION 1 ONLY

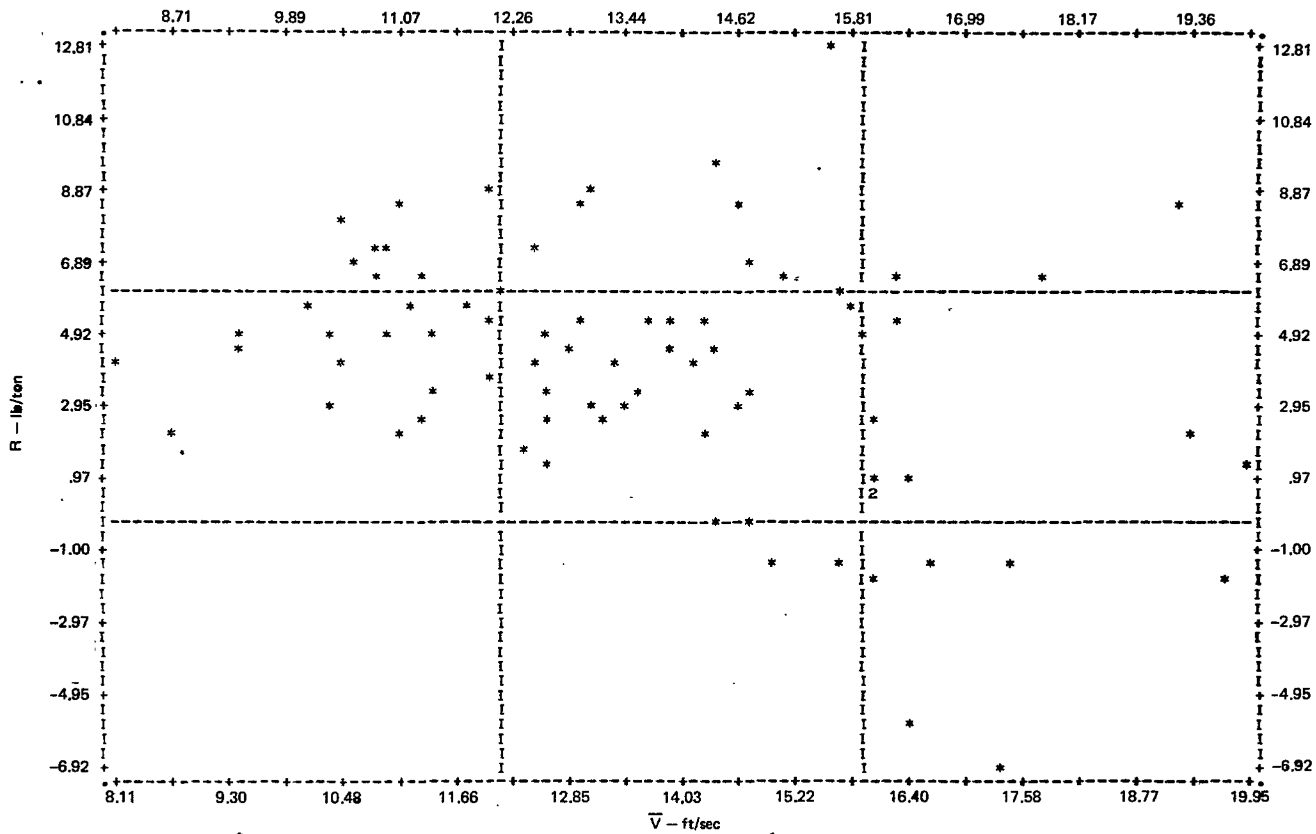



STATISTICS . .

| | | | | | |
|---|---|---|---|---|---|
| CORRELATION (R) – | -.63135 | R SQUARED – | .39860 | SIGNIFICANCE R – | .00001 |
| STD ERR OF EST – | 6.28363 | INTERCEPT (A) – | 50.17360 | STD ERROR OF A – | 6.13177 |
| SIGNIFICANCE A – | .00001 | SLOPE (B) – | -1.74811 | STD ERROR OF B – | .24313 |
| SIGNIFICANCE B – | .00001 | | | | |

PLOTTED VALUES – 80 EXCLUDED VALUES – 0 MISSING VALUES – 0

FIGURE C-12 SCATTER DIAGRAM OF ERRDE SIMULATION STATISTICALLY COMPUTED RESISTANCES (R) VERSUS CAR's MEASUREMENT SECTION AVERAGE SPEED ($\overline{V}$), FROM RUN USING ENGLEWOOD YARD PARAMETERIZATION – 80 CASES IN MEASUREMENT SECTION 2 ONLY

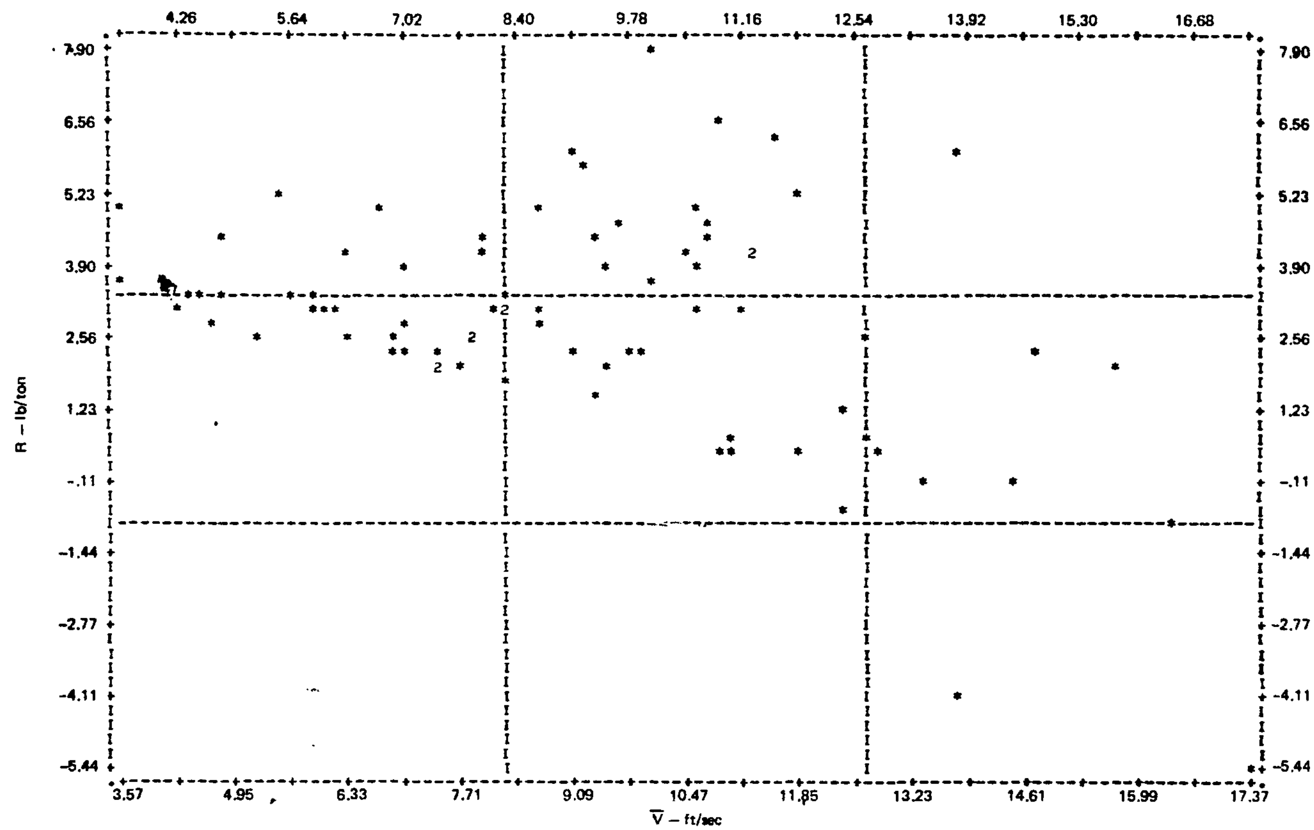



STATISTICS . .

| | | | | | |
|---|---|---|---|---|---|
| CORRELATION (R) – | -.34480 | R SQUARED – | .11889 | SIGNIFICANCE R – | .00087 |
| STD ERR OF EST – | 3.17911 | INTERCEPT (A) – | 10.21749 | STD ERROR OF A – | 1.89756 |
| SIGNIFICANCE A – | .00001 | SLOPE (B) – | -.44366 | STD ERROR OF B – | .13682 |
| SIGNIFICANCE B – | .00087 | | | | |

PLOTTED VALUES – 80    EXCLUDED VALUES – 0    MISSING VALUES – 0

FIGURE C-13 SCATTER DIAGRAM OF ERRDE SIMULATION STATISTICALLY COMPUTED RESISTANCES (R) VERSUS CAR's MEASUREMENT SECTION AVERAGE SPEED ($\overline{V}$), FROM RUN USING ENGLEWOOD YARD PARAMETERIZATION – 80 CASES IN MEASUREMENT SECTION 3 ONLY

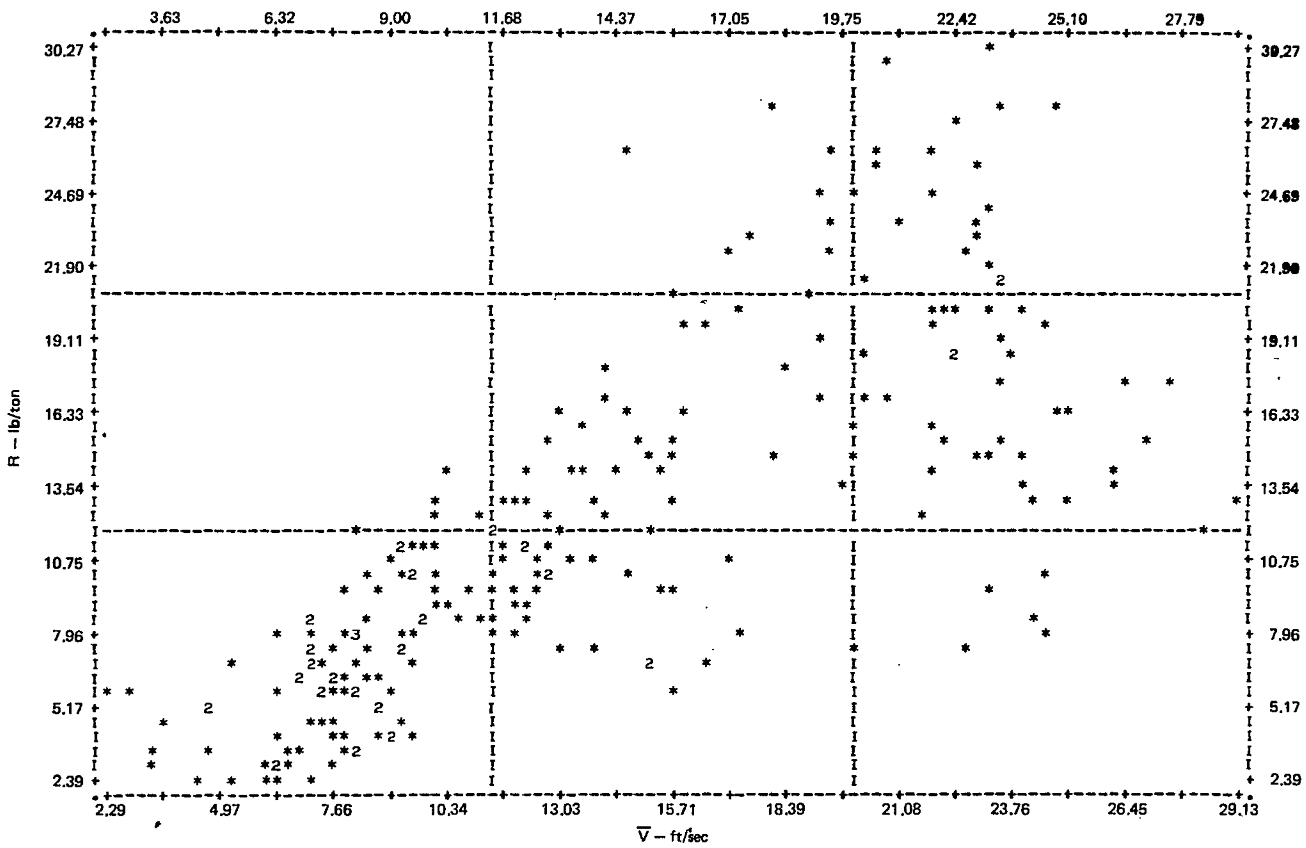



STATISTICS . .

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CORRELATION (R) | – -.40029 | R SQUARED | – | .16507 | SIGNIFICANCE R | – | .00009 |
| STD ERR OF EST | – 1.93552 | INTERCEPT (A) | – | 5.59389 | STD ERROR OF A | – | .68442 |
| SIGNIFICANCE A | – .00001 | SLOPE (B) | – | -.27872 | STD ERROR OF B | – | .07097 |
| SIGNIFICANCE B | – .00009 | | | | | | |

PLOTTED VALUES - 80 EXCLUDED VALUES – 0 MISSING VALUES – 0

FIGURE C-14 SCATTER DIAGRAM OF ERRDE SIMULATION STATISTICALLY COMPUTED RESISTANCES (R) VERSUS CAR's MEASUREMENT SECTION AVERAGE SPEED ($\overline{V}$), FROM RUN USING ENGLEWOOD YARD PARAMETERIZATION – 80 CASES IN MEASUREMENT SECTION 4 ONLY




STATISTICS . .

| | | | | | |
|---|---|---|---|---|---|
| CORRELATION (R) – | .74789 | R SQUARED – | .55934 | SIGNIFICANCE R – | .00001 |
| STD ERR OF EST – | 4.37876 | INTERCEPT (A) – | 1.73238 | STD ERROR OF A – | .67198 |
| SIGNIFICANCE A – | .00527 | SLOPE (B) – | .75590 | STD ERROR OF B – | .04349 |
| SIGNIFICANCE B – | .00001 | | | | |

PLOTTED VALUES – 240  EXCLUDED VALUES – 0  MISSING VALUES – 0

FIGURE C-15 SCATTER DIAGRAM OF ERRDE SIMULATION STATISTICALLY COMPUTED RESISTANCES (R) VERSUS CAR's MEASUREMENT SECTION AVERAGE SPEED ($\overline{V}$), FROM RUN WITH MORE PRONOUNCED SPEED SENSITIVITY – 240 CASES IN MEASUREMENT SECTIONS 2, 3, AND 4

Table C-4

ERRDE SIMULATION RESULTS: SECTIONS 2, 3, AND 4 ONLY

| **Parameter Values Based on Higher Average $R_v$** | Estimated Parameter Value* | Sample Standard Deviation | 95% Confidence Interval |
|---|---|---|---|
| Generated population | | | |
| $R_s$ | 1.046 lb/ton | 2.834 | -- |
| $R_v$ | 0.883 lb/ton/ft/sec | 0.419 | -- |
| Regression of total static R as a function of $\bar{V}$ | | | |
| $\hat{R}_s$ | 1.732 | -- | 0.388 to 3.076 |
| $\hat{R}_v$ | 0.756 | -- | 0.669 to 0.843 |

*Sample mean in the case of $R_s$ and $R_v$; estimated regression parameters in the case of $\hat{R}_s$ and $\hat{R}_v$.

# APPENDIX D: DESCRIPTION OF SOFTWARE INTERFACE AND PROCESSING PROCEDURES

Each yard required the development of specialized software to process the available yard data into a common file structure for further processing by SPSS. However, the overall structure of the processing was the same for each yard, as diagramed in Figure D-1.

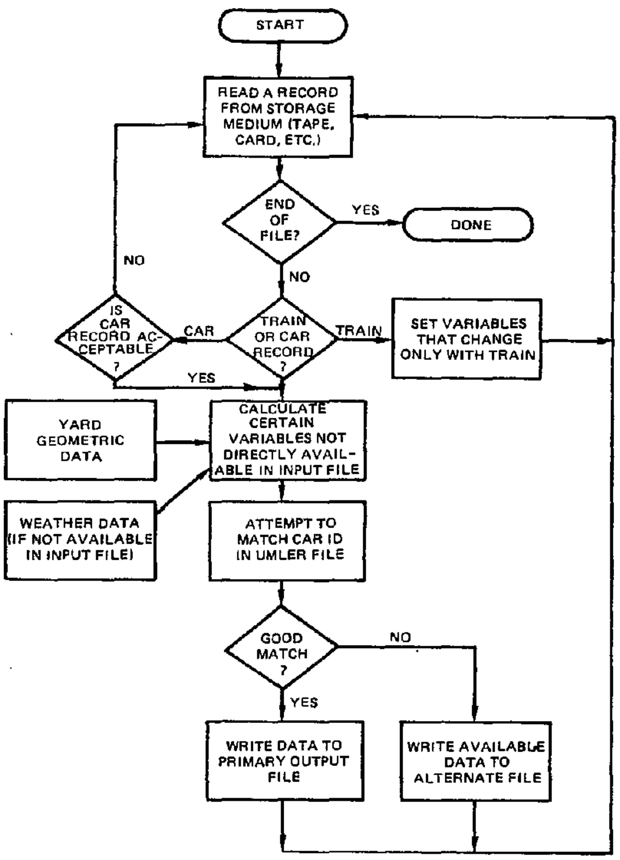



FIGURE D-1 STRUCTURE OF OVERALL PROCESSING PERFORMED WITH SRI-DEVELOPED SOFTWARE TO PROCESS RAW YARD DATA

First, the raw yard data were put into a form readable on SRI's CDC 6400 computer. The storage medium for the raw yard data varied markedly among yards. At Hinkle Yard, a computer tape in coded form was available, and developing the software to read this tape was relatively straightforward. The DeWitt Yard data were available only on a NOVA disk pack incompatible with SRI's CDC 6400. Therefore, these data were copied onto tape and then read on the SRI computer using a special software program developed to convert the NOVA 16-bit word to the CDC 60-bit word. Argentine Yard data were received on cards. For Northtown and Linwood yards, however, no machine-readable data were available, so a sample of these data were manually coded and punched onto cards.

From this point on, the data processing software was relatively similar for all the yards and was built around a common library of procedures. DeWitt and Hinkle yards had certain variables that changed only with the train being humped. This train information comprised a special record preceding the individual records for each car on the train.

Further processing of unacceptable records was undesirable. Consequently, SRI checked certain variables or "flags" to determine whether the car record was acceptable for inclusion in an output file. Based on certain parameters, the following cars (cuts) were excluded from the yard output data file and discarded at this point:

- Multiple car cuts (two or more coupled cars humped together).*
- Cars invoved in a catch-up before coupling or stall in the classification yard.
- Cars for which the classification track was unknown or questionable (usually misswitches).

For each car, certain geometric data were combined with the data read from the tape or cards to produce additional variables for the output file. For example, curve data for the appropriate classification track were added to the information written into the Hinkle and DeWitt output files.

For most of the yards, environmental parameters were contained within the yard data for each car or train. For Linwood and Argentine yards, however, certain parameters were missing or data on them were missing. For Argentine Yard, missing temperature data and occurrence of precipitation were obtained from the records of the National Weather Service Office at Kansas City International Airport. Precipitation information for Linwood Yard was also obtained from the records of the National Weather Service Office at Douglas Municipal Airport in Charlotte, North Carolina. The supplemental weather data, based on the recorded time the car was humped, was combined with the data read from the tape or cards. (Wind direction is reported as the direction the wind is blowing toward, in conformance with standard vector notation.)

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*Certain of these multiple car cut data were saved in an additional alternate file for DeWitt Yard. These data were not analyzed, however.

The car ID was used as an index to search the UMLER file for the matching record. Development of software to use the UMLER file was a major effort in this project. The UMLER file, as it existed on the SRI computer, comprised approximately 1.1 million random-access records; a binary search routine was used to search this file.* Car records successfully matched were then written into the primary output file and included information obtained from the UMLER file; car records not matched were written to an alternate output file without the UMLER data. For the Hinkle Yard tapes that were processed, approximately 87% of the cars were successfully matched. For DeWitt Yard, the matching rate was considerably lower (68%) because the UMLER file made available to SRI dated from 1977 (early in CONRAIL's history) and so had comparatively few cars renumbered to CONRAIL IDs. Consequently, for DeWitt Yard, with its low rate of UMLER matches, it proved necessary to use the alternate file not matched with UMLER data.**

The primary and alternate output files for all yards were as similar as possible but could not be identical because of variations in the available data bases at the yards. The majority of the information in the Hinkle and DeWitt yard files did consist of a common subset, thus permitting the two yards' data to be combined for regression analysis.

During data processing, SRI calculated the following parameters, which were not directly available in the yard's process control (PC) system or from supplementary data:

- Average velocities
- Headwind component
- Sidewind component
- Car rolling resistance
- Car behavior in the tangent point and on the classification track.

These variables were calculated as follows:

Average Velocities--Two types of car velocities were calculated: midpoint velocity and average velocity. A midpoint velocity was calculated in the processing of Hinkle, DeWitt, Northtown, and Linwood yard data for the following measurement sections:

- Hinkle--Measurement sections 1, 2, 3, and 4.
- DeWitt--Measurement sections 1, 2, 3, and 4.
- Northtown--Measurement sections 1 and 2.
- Linwood--Measurement sections 1 and 2.

These were measurement sections where a car's velocity before it entered the section was known. The calculated midpoint velocity was used to further calculate an average velocity for those measurement sections where car velocities at the entrance and exit of the measurement section were known (i.e., Hinkle and DeWitt yards' measurement sections 3 and 4 and Linwood Yard's measurement sections 1 and 2). At all measurement sections where one of the available speed points was located at the exit of a retarder, the assumption was that the given speeds were recorded without residual retardation applied by the retarder. The midpoint velocity ($V_m$) was calculated in feet per second by use of the following equation and parameters:

$$V_M = \sqrt{V_1^2 + 2(G_{1M} - R)\, geL_{1M}} \qquad (D.1)$$

where

ge = effective acceleration of gravity (ft/sec$^2$) based on the weight class of the car, as follows:

Light, 30.23 tons
Medium, 30.92 tons
Heavy, 31.39 tons
Extra heavy, 31.70 tons

$V_1$ = car velocity at the start of the track segment (ft/sec)

$G_{1M}$ = average grade from start of the track segment to the middle of the measurement section (ft/ft)

R = car's effective rolling resistance before modification through measurement section (lb/lb)

$L_{1M}$ = distance from the start of the track segment to the middle of the measurement section (ft).

The midpoint velocity was used as follows to calculate the car's average velocity ($V_a$) through a measurement section:

$$V_A = \frac{V_1 + 2V_M + V_2}{4} \qquad (D.2)$$

where

$V_1$ = car velocity at the start of the measurement section (ft/sec)

$V_M$ = car velocity at the middle of the measurement section (ft/sec)

*At most, 21 records must be examined to either find the desired matching record or determine that the desired record does not exist in the file.

**Processing of these data with SPSS presented no problem, because SPSS has a provision for handling missing data.

$V_2$ = car velocity at the exit of the measurement section (ft/sec).

Headwind Component--The headwind component ($V_H$) was calculated in feet per second at all measurement sections for Hinkle and DeWitt yards. The following equation and parameters were used in this calculation:

$$V_H = V_c - V_w \cos \phi \quad , \qquad (D.3)$$

where

$\theta_w$ = direction wind is blowing (degrees), measured clockwide from north

$V_w$ = wind speed (ft/sec)

$\theta_T$ = degree of track orientation in direction of car movement, measured clockwise from north*

$V_c$ = car velocity at the middle of measurement sections 1 and 2 (ft/sec) or average car velocity in measurement sections 3 and 4 (ft/sec)

$\phi$ = wind direction relative to the moving car $(\theta_w - \theta_T)$

$V_H$ = component of wind speed in direction of car.

Sidewind Component--The sidewind component was calculated in feet per second at all measurement sections for Hinkle and DeWitt yards using the above parameters and the following equation:

$$V_s = |V_w \sin \phi| \quad , \qquad (D.4)$$

where $V_s$ = sidewind component.

Car Rolling Resistance--Sufficient information was obtained to calculate rolling resistance for cars at measurement sections 3 at Hinkle and DeWitt yards and 2 and 3 at Argentine Yard.

The rolling resistance equation used was:

$$R = G_{12} - \frac{V_1^2 - V_1^2}{2geL_{12}} \quad , \qquad (D.5)$$

where

$V_2$ = measurement section exit speed (ft/sec)

$L_{12}$ = measurement section length (ft)

$G_{12}$ = average grade over length of measurement section.

(The other parameters were defined previously.)

*A weighted average track orientation was used on longer measurement sections with changes in direction.

Car Behavior in Tangent Point and Classification Track--Each car's motion in the tangent point and classification areas was calculated to obtain midpoint and average speeds and effective measurement section length (in cases where the car stalled).

This calculation was done by integrating the values provided by the PC system for tangent point speed, coupling speed, and tangent track rolling resistance with the relevant track geometry. In this manner, for a stopped car the effective test section length could be obtained as the distance from the entry to the estimated stall point. For a section on a constant grade, the stall point was estimated by the equation

$$L_{1s} = \frac{V_1^2}{2ge(R - G_{1s})} \quad , \qquad (D.6)$$

where

$L_{1s}$ = distance to stall from entry of section (ft)

$G_{1s}$ = grade to stall point (%)

and other parameters were as previously defined.* By using the value for the stall point or for the coupling point when the car did not stop, the measurement section midpoint speed and average speed** could be calculated in a manner similar to that described earlier.

In addition, an objective was to determine the effect of changes in the parameters listed in Table 4-1 on the rolling resistance values at various yard locations.

SRI attempted to determine, insofar as possible, the mean, standard deviation, and extreme values of the rolling resistance distributions at each location as a function of these parameters. Of particular importance was the variation of rolling resistance among the various yard locations.

This was accomplished by placing the data obtained on the items in Table 4-1 for each car and yard into SPSS data files. Then the SPSS statistical analysis techniques were used to reveal underlying relationships between rolling resistances and attributed parameters. Multiple regression analysis was used to examine the influence and relationship of the variables on rolling resistance.

*The calculation was slightly more complex when the measurement section consisted of varying grades.

**$V_2$ in equation D.2 was equal to zero if the car had stopped; otherwise, it was equal to the coupling speed.