Figure 6. Cut of 10 bogie cars, long cars in front part.

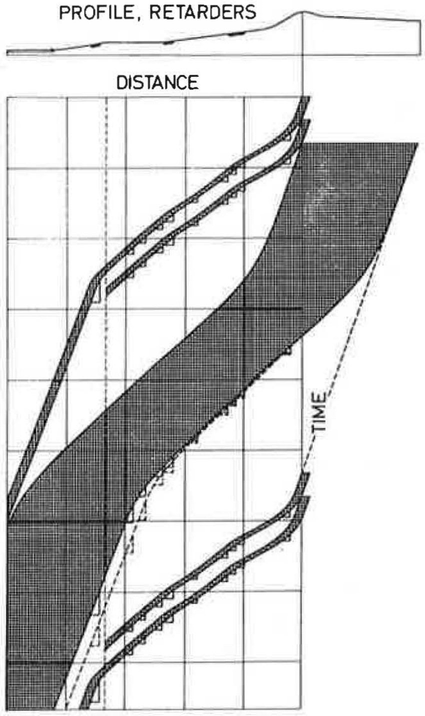
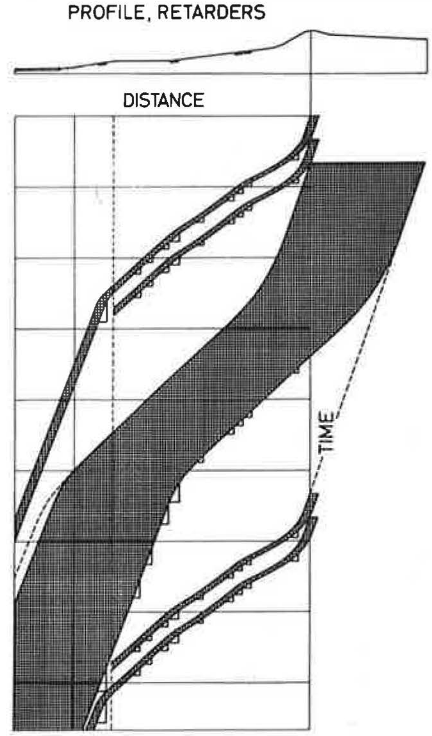


Figure 7. Cut of 10 bogie cars, short cars in front part.



determine the coefficients of the equations for calculation of exit velocity.

But at least for yards equipped with continuous speed control throughout from hump to bowl (by Dowty retarders, for example), a far more elegant method has been found: simulation of cut behavior shortly before humping when cut makeup is known. This procedure, which might be called operative simulation, governs not only load distribution but also axle distribution. Research conducted so far appears to show that operative simulation is feasible with respect to computer hardware and software and time needed for simulation. The first application is envisaged for the Vienna central classification yard in Austria (48 classification tracks, 6,000 cars per day). It could probably be applied to conventional speed control by clasp retarders also.

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Empirical Results from Freight Car Rollability Study

WILLIAM A. STOCK, MARY ANN HACKWORTH, AND PETER J. WONG

A knowledge of freight car rolling resistance is critical in the design and operation of rail freight yards, yet published data on this subject have been scant in the past. In a project sponsored by the Transportation Systems Center and the Federal Railroad Administration, SRI International gathered data on freight car rollability at five rail yards. Complete data were obtained only from Hinkle Yard (Union Pacific) and DeWitt Yard (Consolidated Rail Corporation). In the empirical approach used, the distributional characteristics of rolling resistance were obtained for the two yards during the winter and the summer. These samples were combined and the results of a regression analysis exploring the underlying causal factors are presented. Generally, resistance was found to depend on those factors frequently cited in the literature, although some notable deviations were found.

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 determine the hump height, classification-track grades, and the placement and length of retarders 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 industrywide data base has not been developed. Reports available in the literature have tended to present parameter estimates for theoretical models rather than reviews of actual data.

Summarized in this paper are the empirical results of the Freight Car Rollability Study sponsored by the American Railway Engineering Association (AREA) Committee on Yards and Terminals. The study was limited to the collection and analysis of existing data on car rollability and to data that could be obtained by using existing yard sensing devices (e.g., velocity, position, time, distance to couple) and yard computers. No special instrumentation was installed in yards, tracks, or freight cars.

Five rail yards were selected to represent a variety of yard characteristics and climatic conditions so that designers of new or rehabilitated yards could use them as references. These yards were Hinkle Yard (Union Pacific), Northtown Yard (Burlington Northern), DeWitt Yard [Consolidated Rail Corporation (Conrail)], Linwood Yard (Southern Railway), and Argentine Yard (Atchison, Topeka, and Santa Fe). Only Hinkle Yard and DeWitt Yard, however, provided complete data on rolling resistance at four locations between the crest and the bowl as well as a complete set of matching parameters for each car.

Rolling-resistance data summarized in this paper are of two types: (a) distributional characteristics of rolling resistance by yard for winter and summer and (b) the causal factors underlying rolling resistance as revealed by regression analyses.

Details of all discussion points in this paper may be found in the final report of the Freight Car Rollability Study (1), which also contains a comprehensive review of past literature on rollability.

DATA COLLECTED

Hinkle and DeWitt are relatively new General Railway Signal Company (GRS) yards, so the data available from these yards are similar. Velocity measurements stored by the process-control (PC) computer systems are recorded as follows: from the hump crest to the master retarder [measurement section (MS) 1], from the master retarder to the group retarder (MS 2), from the group retarder to the tangent point (MS 3), and from the distance-to-couple bond to the point of coupling (MS 4).

Rolling-resistance data and the associated parameters that might influence rolling resistance were extracted for each car for the four measurement sections (denoted MS 1 through MS 4). MS 1, 2, and 4 are an integral part of the PC computer systems of these yards, and car rolling resistance is measured automatically. Thus, these data were extracted directly as recorded by the PC computer. Car rolling resistance in MS 3 was calculated by using PC computer-recorded velocities, the length and grade of the measurement section, and the rate of acceleration. MS 3 for both yards included oilers, some curvature, and switches; the average rolling resistance includes these effects over distances ranging from 280 to 615 ft. In all four measurement sections, the rolling resistances collected were raw values; that is, they were uncorrected for headwind. This was necessary because an independent assessment of headwind effects was desired.

Further, the owning railroad and number of each car were recorded. This enabled extraction of additional information, unavailable from the yard's PC data, from a Universal Machine Language Equipment Register (UMLER) file, a computer-based file maintained by the Association of American Railroads (AAR), which lists nearly all railroad rolling stock in North America. The information obtained for each car is listed as follows:

1. Cut statistics

   a. Wind direction
   b. Wind speed
   c. Precipitation (wet or dry conditions)
   d. Temperature (°F)
   e. Headwind component
   f. Sidewind component
   g. Humped weight of car
   h. Weight class of car
   i. Average velocity of car
   j. Rolling resistance of car

2. Track characteristics

   a. Total curvature traversed (sum of central angles)
   b. Total curved length of track
   c. Number of changes in car direction
   d. Number of consecutive track links
   e. Total length of track
   f. Number of switches

3. UMLER car characteristics

   a. Bulkhead cross-sectional area
   b. Type of car
   c. Bearings (roller or journal)

DISTRIBUTIONAL CHARACTERISTICS OF ROLLING RESISTANCE

Hinkle Yard

Union Pacific's Hinkle Yard is in Hermiston, Oregon. 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.

Figures 1 and 2 are histograms of rolling resistance at the four measurement sections during the winter and summer, respectively. Tables 1 and 2 show the mean, standard deviation, standard error, 95 percent confidence interval, minimum, and maximum for the rolling resistances and average velocities at each of the four measurement sections.

For design, the selection of values of hard and easy rolling resistance for the worst-case analysis is a critical issue. Basing this selection on the extreme values of hard and easy rolling resistance observed in a sample is not economically or statistically sound. A more credible approach is to base the selection on a percentile criterion, such as the 2.5-percentile value (the resistance value below which 2.5 percent of the observations in the sample occur) as the easy roller and the 97.5-percentile value as the hard roller. Collectively, these two percentile values contain 95 percent of the sampled resistance values. Tables 1 and 2 give the percentile values for 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 include these rolling-resistance factors because they are implicitly included in the measurements.

A rolling-resistance model 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 rolls more easily on its journey to the classification track. The data in the figures and tables, however, contradict this model. In

Figure 1. Distribution of Hinkle Yard car rolling resistances by measurement section: winter observations.

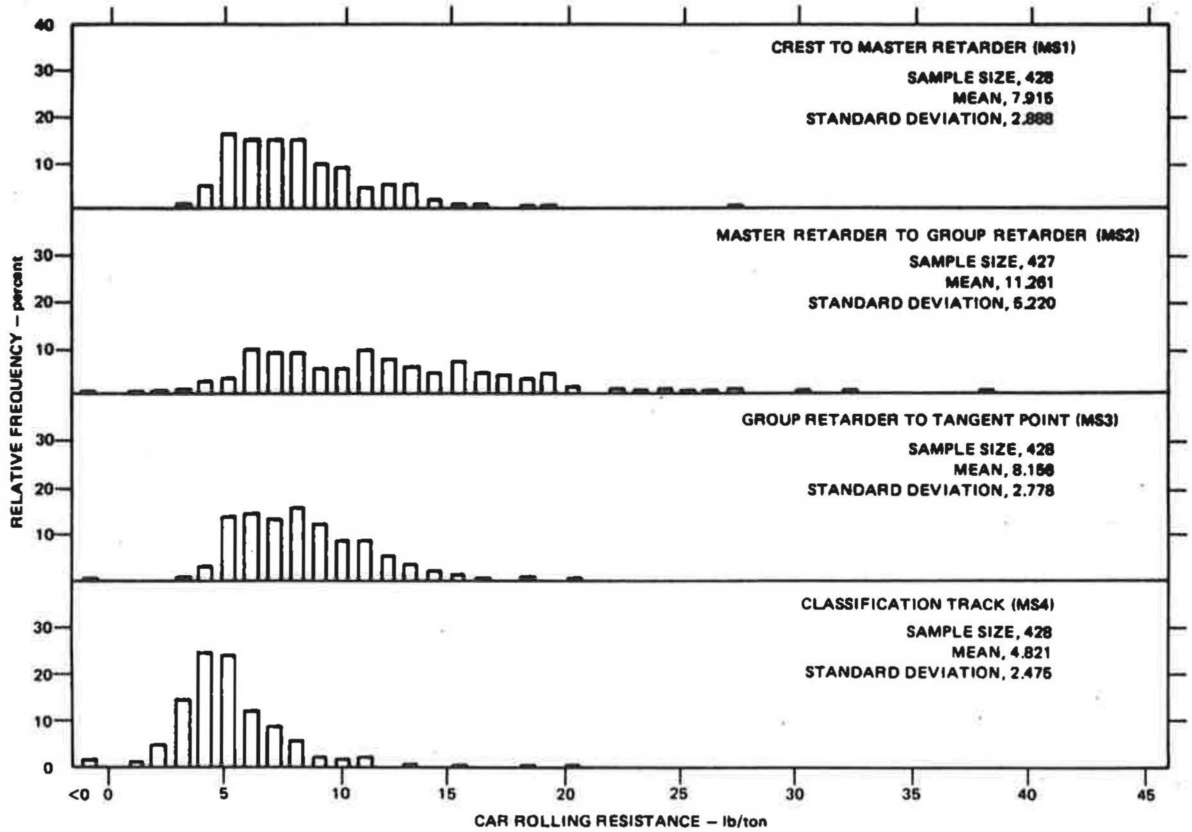


Figure 2. Distribution of Hinkle Yard car rolling resistances by measurement section: summer observations.

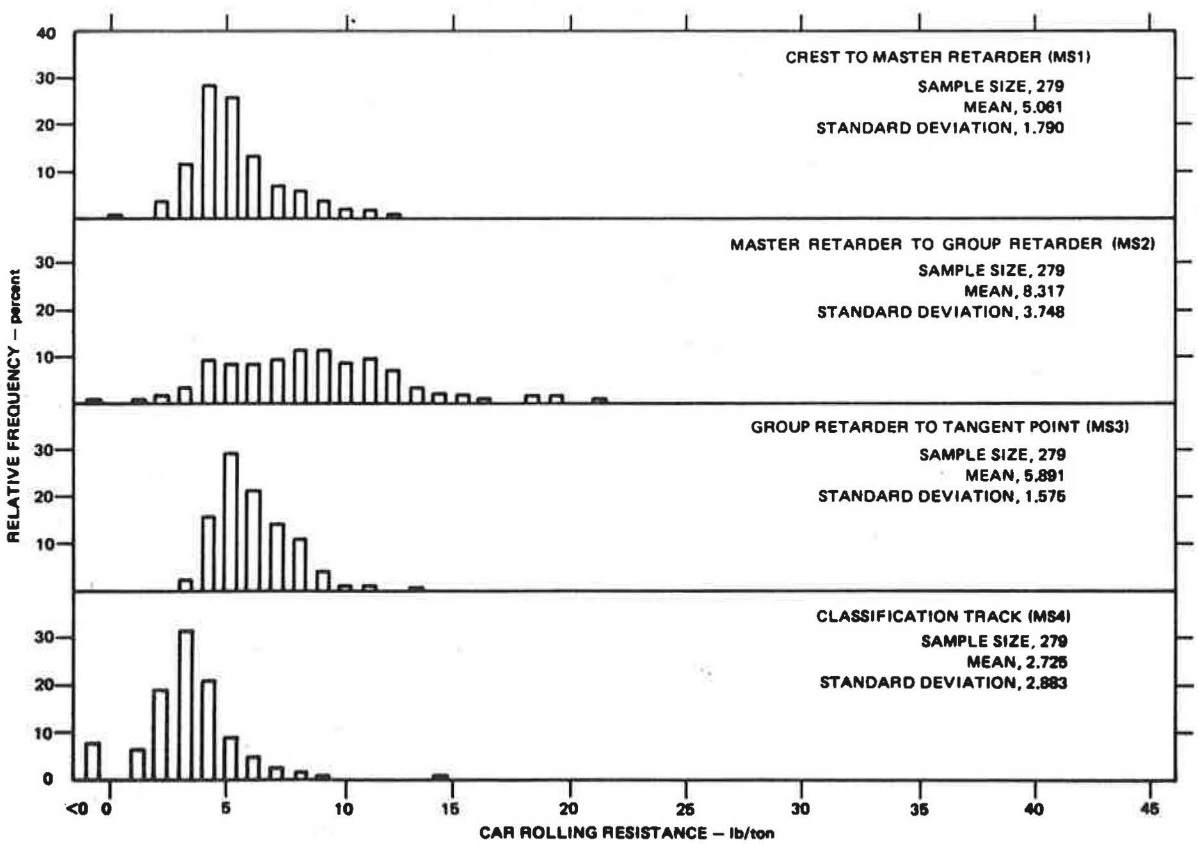


Table 1. Rolling resistance and velocity statistics at Hinkle Yard measurement sections: winter observations.

	Rolling Resistance (lb/ton)						Avg Velocity (ft/sec)					
Measurement Section	Mean	SD	SE	95 Percent CI	Mini-mum	Maxi-mum	Mean	SD	SE	95 Percent CI	Mini-mum	Maxi-mum
1	7.915	2.888	0.140	7.640-8.189	2	27	18.161	0.617	0.030	18.102-18.219	14	19
2	11.261	5.220	0.253	10.764-11.757	-19	38	25.050	2.049	0.099	24.855-25.245	19	31
3	8.156	2.778	0.134	7.892-8.420	-1	22	13.273	2.202	0.107	13.063-13.482	8	18
4	4.821	2.475	0.120	4.586-5.056	-11	20	9.081	1.996	0.097	8.891-9.271	4	15

Note: SD, standard deviation; SE, standard error of mean; CI, confidence interval for mean.

Table 2. Rolling resistance and velocity statistics at Hinkle Yard measurement sections: summer observations.

	Rolling Resistance (lb/ton)						Avg Velocity (ft/sec)					
Measurement Section	Mean	SD	SE	95 Percent CI	Mini-mum	Maxi-mum	Mean	SD	SE	95 Percent CI	Mini-mum	Maxi-mum
1	5.061	1.790	0.107	4.850-5.272	0	12	18.665	0.402	0.024	18.618-18.712	17	19
2	8.317	3.748	0.224	7.875-8.758	-15	21	23.640	1.767	0.106	23.432-23.849	18	31
3	5.891	1.575	0.094	5.705-6.077	3	13	11.650	2.199	0.132	11.391-11.909	7	18
4	2.725	2.883	0.173	2.385-3.065	-13	14	8.823	2.303	0.141	8.545-9.101	4	16

Note: SD, standard deviation; SE, standard error of mean; CI, confidence interval for mean.

Figure 1 it is suggested that the nominal rolling-resistance values are initially low in MS 1, increase in MS 2, and then decrease into the classification area. This is verified by examination of the mean rolling-resistance values in Tables 1 and 2.

Figures 1 and 2 also show that the variance in the rolling-resistance values is initially small in MS 1, increases in MS 2, and then decreases in MS 3 and MS 4. This is verified by the standard deviation and the minimum and maximum values for each measurement section in Tables 1 and 2. This spread can be explained, at least in part, by the error characteristics of the method used to collect rollability data (1).

At first, these histograms appeared to be counterintuitive, but closer examination provided an explanation. Rolling resistance increases with car velocity, so 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 Tables 1 and 2 verify this.

DeWitt Yard

DeWitt is a Conrail yard in Syracuse, New York. 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.

Figures 3 and 4 are histograms of winter and summer rolling resistances at the four measurement sections, and descriptive statistics for the rolling resistances and average velocities at these measurement sections for the winter and summer railcar populations are shown in Tables 3 and 4. These results are similar to those from Hinkle Yard; they show low rolling-resistance values in MS 1, an increase in the values in MS 2, followed by decreasing values in MS 3 and MS 4 for both populations. A larger variance in the rolling resistances for the winter population than for the summer population is also suggested. This is verified by examining the standard deviation and the 95 percent confidence intervals for each population in Tables 3 and 4. A correlation between the increase or decrease of mean rolling-resistance values and the increase or decrease of mean car velocities for the four measurement sections in both the winter and the summer is also suggested in Tables 3 and 4.

EXPLORING CAUSAL FACTORS UNDERLYING ROLLING RESISTANCE

Factors that traditionally have been believed to underlie rolling resistance are 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 in this study because all the yards had welded rail (common to all modern yards with PC systems).

The linear regression technique was used to explore 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, given a constant value for all these factors.

The regression analysis results presented here, unless specified otherwise, include only first-order terms, with rolling resistance as the dependent variable. Details of this analysis are presented in the final report of the Freight Car Rollability Study (1), which 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

Figure 3. Distribution of DeWitt Yard car rolling resistances by measurement section: winter observations.

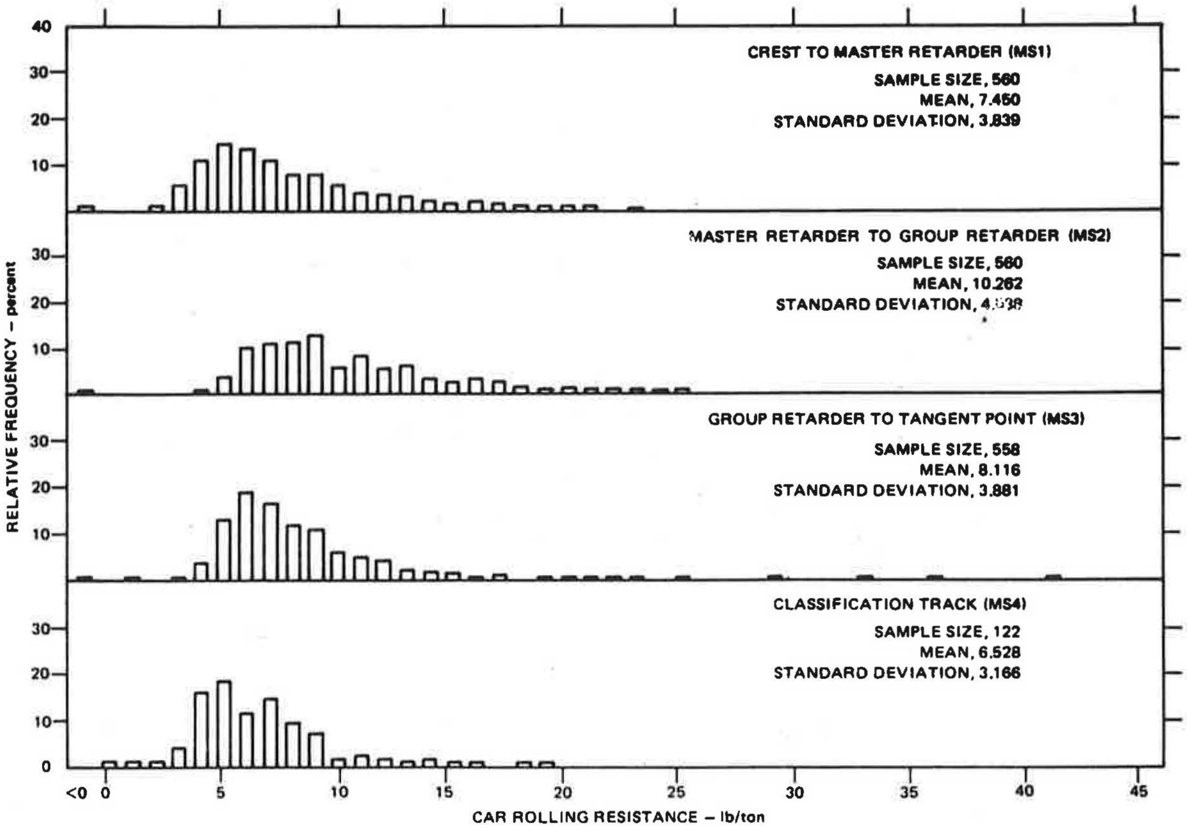


Figure 4. Distribution of DeWitt Yard car rolling resistances by measurement section: summer observations.

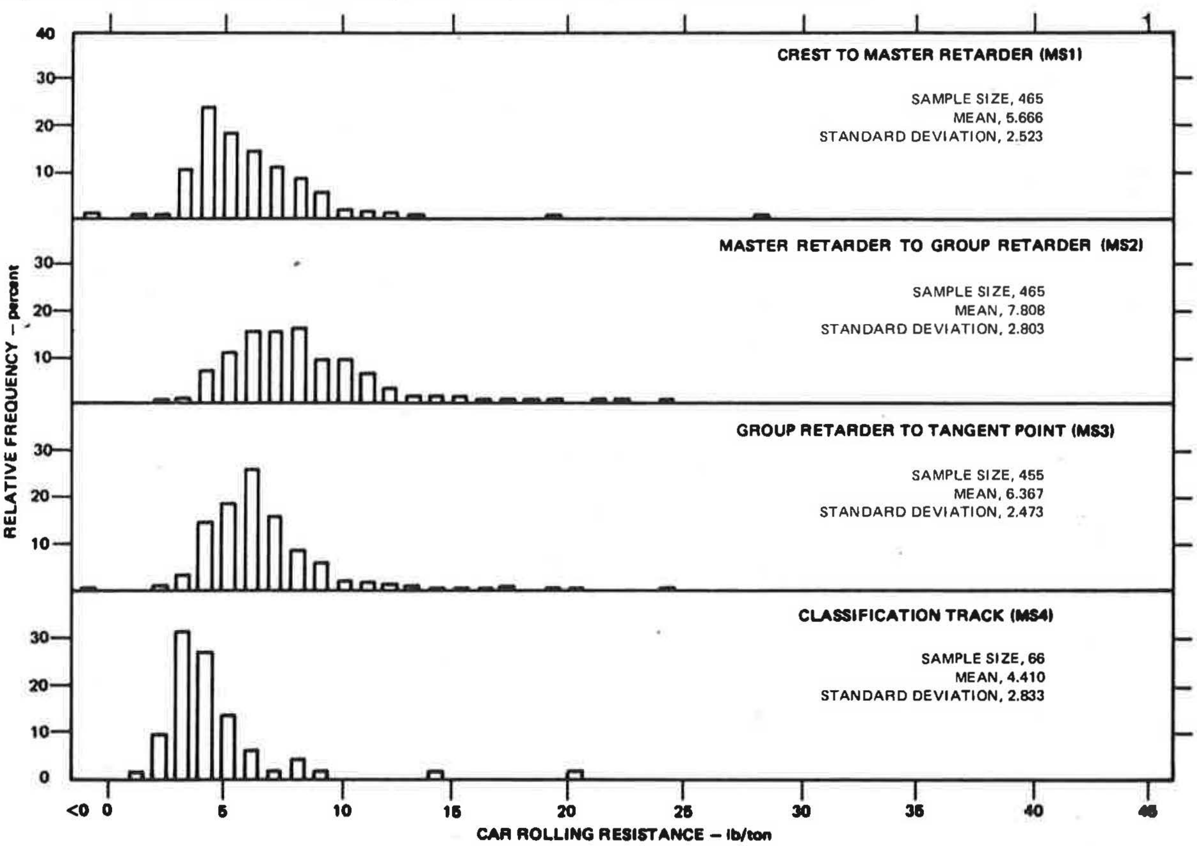


Table 3. Rolling resistance and velocity statistics at DeWitt Yard measurement sections: winter observations.

	Rolling Resistance (lb/ton)						Avg Velocity (ft/sec)					
Measurement Section	Mean	SD	SE	95 Percent CI	Minimum	Maximum	Mean	SD	SE	95 Percent CI	Minimum	Maximum
1	7.450	3.839	0.162	7.132-7.769	-14	23	19.895	0.872	0.037	19.823-19.968	16	22
2	10.262	4.038	0.171	9.927-10.597	-5	26	20.692	1.861	0.079	20.537-20.847	15	25
3	8.116	3.881	0.164	7.793-8.438	-17	41	15.043	2.287	0.097	14.853-15.233	7	22
4	6.528	3.166	0.287	5.960-7.095	1	19	10.921	2.560	0.231	10.464-11.378	5	18

Note: SD, standard deviation; SE, standard error of mean; CI, confidence interval for mean.

Table 4. Rolling resistance and velocity statistics at DeWitt Yard measurement sections: summer observations.

	Rolling Resistance (lb/ton)						Avg Velocity (ft/sec)					
Measurement Section	Mean	SD	SE	95 Percent CI	Minimum	Maximum	Mean	SD	SE	95 Percent CI	Minimum	Maximum
1	5.666	2.523	0.117	5.436-5.896	-10	28	20.313	0.621	0.029	20.256-20.370	15	21
2	7.808	2.803	0.130	7.552-8.063	2	24	20.479	0.956	0.044	20.392-20.566	17	24
3	6.367	2.473	0.116	6.139-6.595	-1	24	11.777	2.906	0.136	11.509-12.045	6	18
4	4.410	2.833	0.349	3.713-5.106	1	20	7.202	2.638	0.325	6.554-7.851	2	13

Note: SD, standard deviation; SE, standard error of mean; CI, confidence interval for mean.

presented here should be adequate for most design purposes.

These regression analyses were performed by combining the data from Hinkle and DeWitt Yards into a single data base. After cases where one or more of the independent variable values were missing had been deleted, 4,465 complete data points were available from the two yards for the regression. About 72 percent of these were Hinkle Yard observations; the rest were from DeWitt Yard. (The reason for the comparatively few observations from DeWitt Yard was that a high percentage of cars had no matches in the UMLER file because of the state of flux in car numbers owing to the Conrail merger.) Any variation in the data between the two yards not explainable by the other independent variables was handled by special dummy variables, 0 and 1, corresponding respectively to Hinkle and DeWitt. No distinction was made in the analysis between the up to four separate observations on the same car at the four measurement sections. The regression is summarized in Table 5.

Isolating the influence of any single factor on rolling resistance is difficult because all the factors vary simultaneously. Although the regression technique generally suggests the effects of the various factors, the multidimensional equation that results from the analysis can still be difficult to grasp. Therefore, for presentation purposes, an artifice called a nominal car or nominal conditions is used here. This artifice permits selection of nominal values for all factors except the one being studied, which is allowed to vary. Summary results follow.

Difference Between Two Yards

A small but nonetheless statistically significant difference existed in the rolling resistances between Hinkle and DeWitt Yards. This difference, about 0.5 lb/ton, persisted even when the explanatory power of all the available factors was taken into account (the quantification of these factors should be capable of explaining most, if not all, regional differences between the two yards). This residual difference could represent a bias in the data from the PC systems, an error in the location of and distance between sensors, or the omission from the analysis of some unknown factor varying between the two yards.

Car Weight

An inverse relationship exists between rolling resistance and car weight: As cars become lighter, they roll with more difficulty. Figure 5 shows this relationship for certain nominal conditions. For example, an average 30-ton boxcar has a rolling resistance of about 8.3 lb/ton, whereas an average 80-ton boxcar has a rolling resistance of about 5.4 lb/ton.

Car Type

Relative to the boxcar (the nominal car), on the average, gondola cars incur about 1.2 lb/ton more resistance, flatcars about 0.55 lb/ton, and tank cars about 0.66 lb/ton. The other car types considered--hoppers, refrigerator cars, and vehicular cars--were not significantly different from the reference boxcar. 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.

Table 5. Regression results with rolling resistance as dependent variable.

Description	Mean	Coefficient
Independent variable		
1/(weight of car) (tons)		89.19
Speed of car (ft/sec)	16.72	0.2546
[Speed of car (ft/sec) – mean speed]^2		0.003775
Term for total central angle of curve; its coefficient can be read directly as feet of velocity head lost per degree of central angle		0.006904
Term for average degree of curvature in measurement section		NS
Term for switch loss		NS
1/[distance from oiler (ft) to middle of measurement section]		NS
Natural logarithm of distance from crest (ft) to middle of measurement section		0.3457
Dummy variable: 0 = dry, 1 = wet		NS
Temperature (°F)	44.11	–0.03788
[Temperature (°F) – mean temperature]^2		0.0001948
Sidewind component (ft/sec)		NS
Headwind term		0.001031
Truck center-to-center length (ft)		NS
Dummy variable: 0 = roller bearings, 1 = friction bearings		NS
Car types:		
Dummy variable: 1 = gondola car, 0 = otherwise		1.174
Dummy variable: 1 = flatcar, 0 = otherwise		0.5543
Dummy variable: 1 = hopper, 0 = otherwise		NS
Dummy variable: 1 = refrigerator car, 0 = otherwise		NS
Dummy variable: 1 = tank car, 0 = otherwise		0.6595
Dummy variable: 1 = vehicular car, 0 = otherwise		NS
Dummy variable: 0 = Hinkle Yard, 1 = DeWitt Yard		–0.5475
Constant		–0.8629

Notes: N = 4,465; R^2 = 0.478; $\hat{\sigma}$ = 2.61 lb/ton; coefficient of variation = 35.1 percent; F = 340.5.
NS = not significant at 5 percent.
Regression and all variables whose coefficients are given are significant at 5 percent.
Variable mean values are given only where needed for prediction equation.

Bearing Type

The traditional assumption has been that cars with roller bearings roll more easily 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 percent of the regression sample--an amount more than adequate to detect any statistically significant difference.

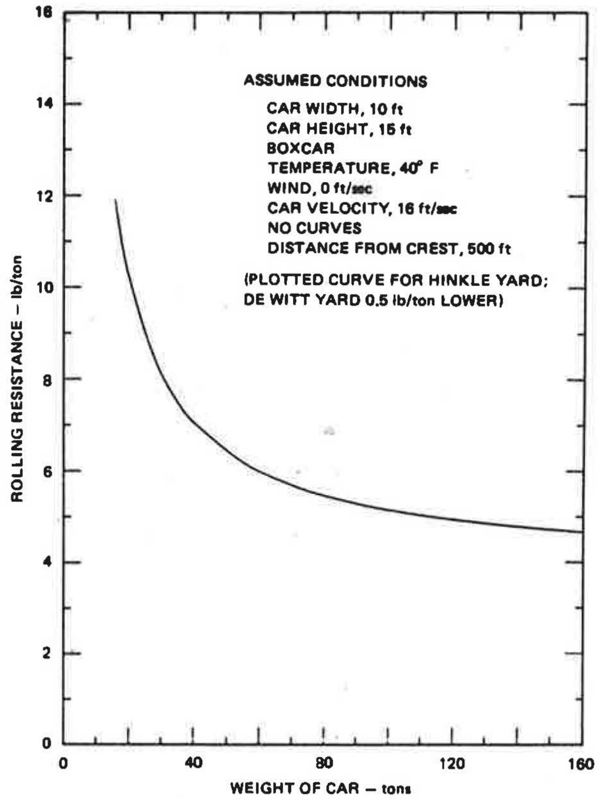
Truck Center Length

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 incur more resistance because of a binding effect. No significant interaction was found between truck center length and the curve variables.

Car Speed

Rolling resistance increases with car speed. Figure 6 shows this speed relationship for certain nominal conditions. Although a V^2 (velocity squared) dependence exists, the curvilinearity appears to be small under zero ambient wind conditions and even with a headwind of 10 ft/sec. The V^2 dependence consists of a component owing to headwind (even in zero wind conditions, a car moving at 15 ft/sec has a 15-ft/sec relative headwind) and a V^2 term with all headwind effects removed. A statistically significant first-power V term also exists. For most yard applications, curvilinearity can be ignored when headwinds are slight.

Figure 5. Rolling resistance as a function of car weight.



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

These relationships were obtained only for cars moving at yard speeds; these results should not be extrapolated to trains moving at line-haul speeds.

Wind Velocity

A headwind can contribute significantly to the rolling resistance of a nominal car (this term is proportional to the square of the headwind times the car's cross-sectional area divided by the car's weight). This effect is shown in Figure 7 for the nominal conditions given, where negative values of wind velocity are headwind and impede the motion of the car. Each foot-per-second headwind contributes about 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 7.

Temperature

Cars roll more easily with increasing temperature. The available data sample did not include extremely low temperatures. A slight but nonetheless statistically significant variation with T^2 (temperature squared) was noted, as Figure 8 shows. There is also a statistically significant T first-power term. In the temperature ranges investigated, on the average a car incurs 0.39 lb/ton more resistance for every drop in temperature of 10°F.

Moisture

The assumption has been that a car incurs less re-

Figure 6. Rolling resistance as a function of car velocity.

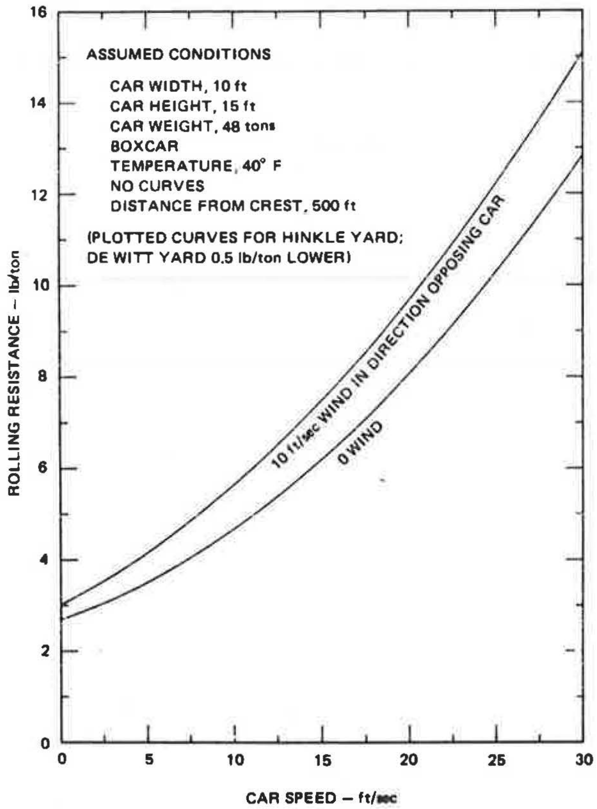


Figure 7. Rolling resistance as a function of wind velocity.

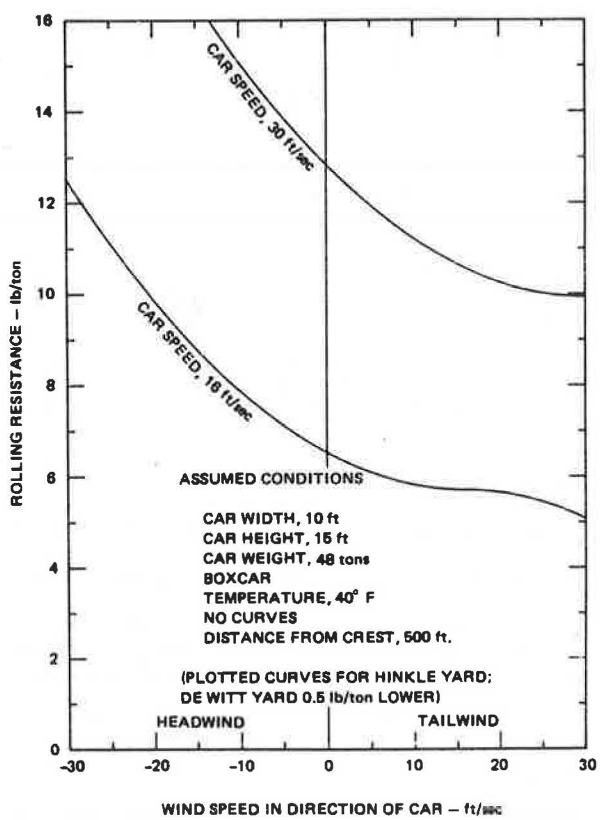
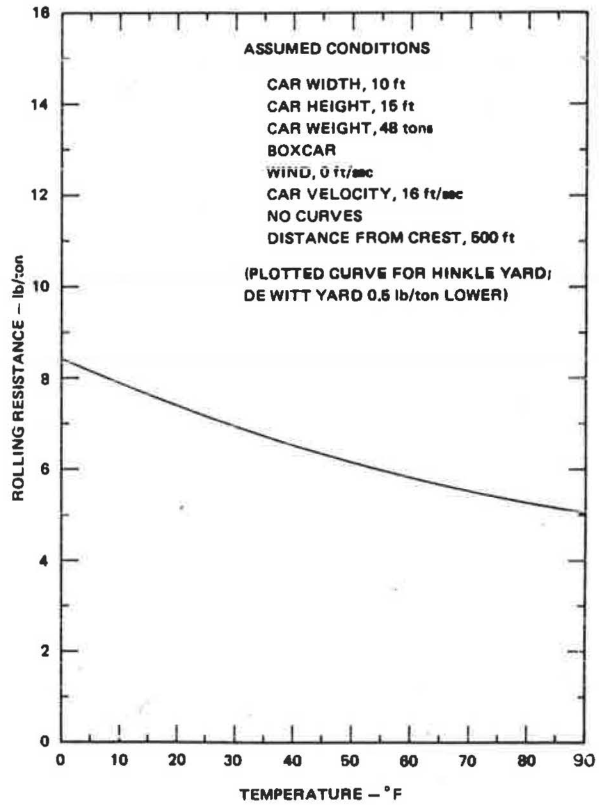


Figure 8. Rolling resistance as a function of temperature.



sistance 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 present but did not differentiate between rain and snow. In addition, only about 3.4 percent of the data was 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.

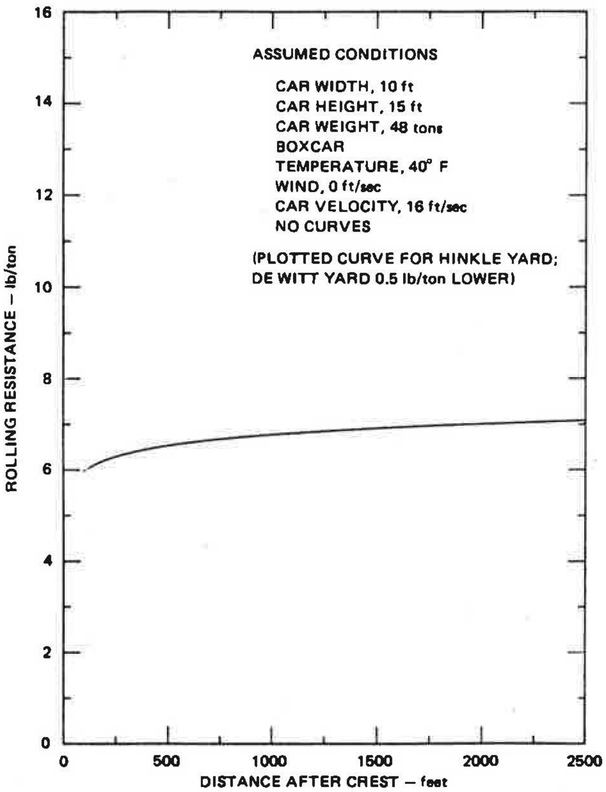
Switches and Curves

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 usually the same; thus, the effects of each variable were confounded. Further, these sections were located just after the oilers, introducing further statistical difficulties.

Distance from Crest

A statistically significant counterintuitive trend was found for the effect of distance from the crest on rolling resistance: Rolling resistance increased farther from the crest. As Figure 9 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 com-

Figure 9. Rolling resistance as a function of distance from crest.



monly held hypothesis that cars incur less resistance farther from the crest.

Presence of Oilers

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

CONCLUSIONS

The results of this study have greatly augmented knowledge 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 PC 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.

ACKNOWLEDGMENT

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Appreciation is expressed to the following for their cooperation in providing data for the project: the late B. Gallacher (Southern Pacific); M.J. Anderson, J. Conway, and S. Shelton (Union Pacific); J. Wetzel, T. O'Dwyer, and C. Williams (Conrail); W. Butler (Burlington Northern); J.A. Rice (Southern Railway); W.L. Henry (Atchison, Topeka, and Santa Fe); and B.B. Laves (General Railway Signal Company).

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Classification Yard Computer Control Systems

YINGHUA MIN AND LIANLONG YANG

A scheme for classification yard computer control systems (CYCCS) is proposed based on the analysis of experimental data collected from Chinese yard environments. The speed-control system configuration proposed includes a four-level retarder arrangement, various sensors, a process-control computer, and a system redundancy scheme. Much attention is given to measurement of car-rollability data. It is noted that the accuracy of some rollability data collected during past years is unacceptable because of the measurement techniques and the devices for measuring rollability. The primary error sources are analyzed, and some solutions to this problem are also discussed. The strong relationship between rollability and velocity of cars, however, has been widely noticed recently. Based on this idea, a piecewise-linear mathematical model is suggested for target-shooting control systems.

The main operations in a classification yard include receiving inbound trains, classifying cars, and making up outbound trains. According to these operations, a classification hump yard is usually partitioned into receiving yard, classifying yard, and dispatching yard. In a classifying yard, switching and coupling processes are the central activities. As cars roll down the hump grade, retarders slow down the cars to a proper speed so that the free-rolling cars can safely couple with preceding cars on bowl tracks (1). After the switching process had been automated, attention was focused on automatic speed-control systems. The following subjects were considered:

1. Safety: So-called iron shoes are put on bowl tracks in front of the wheels of free-rolling cars to ensure proper coupling of cars. Many workers are needed inside the bowl tracks throughout the classi-