Railway Sciences, for their contributions to this project.

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Effect of Measurement Errors on Car Rollability Distribution in a Yard

ROBERT L. KIANG

The importance of car rollability data is generally recognized in the railroad community, and such data are routinely measured in modern classification yards to use in speed-control algorithms for real-time control of the cars. These data are also compiled and presented in various statistical formats, one of which is a histogram showing number of cars as a function of rolling resistance, that serve as critical input data to a yard designer. Although large quantities of rollability data are being collected, insufficient attention has been paid to the accuracy of such data. A small error in a wheel-detector measurement could result in a large error in the computed rolling resistance. Because of the large errors, the true rolling-resistance histograms may be quite different from the apparent histogram compiled from the measured data, and this distortion could cause overdesign of the yard speed-control systems. A method to compensate for uncertainties in rollability data is presented.

Control of car movement in a classification yard is crucial to the safety and operational efficiency of the yard. In a conventional yard, control points (the retarder sections) are few and widely spaced, so the motion of a free-rolling car in between and beyond these control points must be accurately predicted. The success of such a prediction depends on information about the rollability or, equivalently, the rolling resistance of the car.

The importance of car-rollability data is generally recognized in the railroad community, and such data are routinely measured in modern classification yards. These data are used both in algorithms that provide real-time control of the cars and in various statistical displays, one of which is a histogram showing number of cars as a function of rolling resistance, that serve as critical input data to a yard designer.

Although much effort has been devoted to acquiring large quantities of rollability data, too little attention has been given to the quality of these data. Measurement inaccuracies distort the data. In a recent study sponsored by the Federal Railroad Administration (1), a statistical analysis indicated that good rollability data demand extremely high measurement accuracy.

The effects of measurement errors in car movement on the rolling-resistance histogram are explored. A current method of measuring rolling resistance could result in large errors in its value. Such an error in rolling resistance is not a constant for all cars; its functional dependence on the true rolling resistance of a car is derived. One consequence of these errors is that they will distort, sometimes greatly, the compiled rolling-resistance histogram. This is demonstrated and conclusions and recommendations are given later in this paper.

ERROR MAGNIFICATION

One standard method of measuring a car's rolling resistance in a classification yard is to place four wheel detectors along a section of track. The first two determine the entering velocity of a car within this measurement section, and the last two determine the exit velocity. The distance between the first two wheel detectors is usually kept the same as that between the last two. That distance is denoted by ℓ. The total length of this measurement section, that is, the distance between either the first and the third or the second and the fourth wheel detectors, is denoted by L. It is assumed that this section lies on a constant grade G. As a car with constant rolling resistance travels through this section, its transit times through these two pairs of wheel detectors are measured. They are denoted by t_a and t_b. Given the values of the aforementioned parameters, the rolling resistance of this car can be calculated by the following equation:

$$R = G - (1/2gL)\,[(\ell/t_b)^2 - (\ell/t_a)^2] \quad (1)$$

Consider the following typical values:

G = 0.40 (a 4 percent grade, typical of a master retarder measuring section),
g = 32.2 ft/sec^2,
L = 100 ft,
ℓ = 20 ft,
t_a = 1.04 sec, and
t_b = 0.81 sec.

By using Equation 1, this car's rolling resistance can be readily calculated:

$R = 2.76 \times 10^{-3}$ or 5.5 lb/ton.

Most wheel detectors rely on wheel-induced disturbance of a magnetic field around the detector to sense the presence of a passing wheel. Because of several variables, ranging from wheel size to wheel material, a wheel detector does not locate a passing wheel precisely every time. Unfortunately the accuracy specifications of the commercial wheel detectors are unknown. A plausible value of 0.08 ft (i.e., 1 in.) is assumed. By using a value of 20.08 ft in the first of the two ℓ-terms in Equation 1, the calculated rolling resistance becomes

$R = 2.00 \times 10^{-3}$ or 4.0 lb/ton,

a difference of nearly 30 percent from the original value.

What happened? A 0.4 percent error in one of the ℓ-measurements has translated to a 30 percent error in R. The reason is error magnification as a result of multiplication and subtraction of two large quantities to obtain a small quantity. In the previous example, three error magnifications are involved. The first one is associated with the term $(\ell/t_b)^2$. The squaring operation doubles the error from 0.4 to 0.8 percent.

The second magnification is associated with the term $[(\ell/t_b)^2 - (\ell/t_a)^2]$. In this expression, the difference between the two terms is roughly half the value of either of these two terms. Hence, an error of 0.8 percent in either term becomes an error of about 1.6 percent in the resulting difference.

The third magnification is associated with the right-hand side of Equation 1. Here the difference between these two terms is more than a factor of 10 smaller than either of the two terms. A 1.6 percent error is translated into a 30 percent error in the difference.

Once the compounding effect of error magnification has been recognized, the following can be deduced by a careful examination of Equation 1:

1. On a given grade, a car with smaller R will attain higher velocity when compared with a car with larger R. Both small R and high velocity will accentuate the error in R.
2. For a car with a constant R, the larger the grade, the larger the error in R.

In the next section, a functional relationship between R and its error as a result of the uncertainties in the ℓ-measurements is derived.

ΔR AS FUNCTION OF TRUE R

It is assumed that each rail car has a single-valued rolling resistance in the following analysis. This assumption is not realistic because it is commonly accepted that a car's rolling resistance can depend on such factors as velocity, wheel-bearing temperature, and track condition. Nevertheless, for the purpose of demonstrating the effect of measurement errors on a rolling-resistance histogram, this assumption is acceptable. Equation 1 can be rewritten as follows:

$$R = G - (1/2gL)(V_b^2 - V_a^2) \quad (2)$$

where V_a and V_b represent the entering and exit velocity of a car, respectively. A registration error in a wheel detector will reflect as errors in these velocities, which in turn will reflect as an error in the rolling resistance (R). If the error of a quantity is denoted by Δ, a statistical theory (2) dictates that ΔR as a result of ΔV_a and ΔV_b can be calculated according to the following:

$$R = \left\{[(\delta R/\delta V_a)^2 (\Delta V_a)^2] + [(\delta R/\delta V_b)^2 (\Delta V_b)^2]\right\}^{1/2} \quad (3)$$

By using Equation 2 as well as $V_a = \ell/t_a$, $V_b = \ell/t_b$, and $\Delta V_a = |\partial V_a/\partial \ell|\Delta\ell = \Delta\ell/t_a$ and $\Delta V_b = \Delta\ell/t_b$, the following equation is obtained:

$$\Delta R = \Delta\ell(\ell/gL)\,[(1/t_a^4) + (1/t_b^4)]^{1/2} \quad (4)$$

Equation 4 indicates that ΔR is proportional to $\Delta\ell$; ΔR is also a function of R. This dependence on R is implicitly contained in t_a and t_b. In the rollability measurement section just ahead of a master retarder, a car with small R will have a higher average velocity through that section than a car with larger R. The measured transit times (t_a and t_b) will have smaller values. From Equation 4 it can be determined that this car will have a relatively large ΔR as a result of its inherently small R. This corroborates one of the deductions made at the end of the previous section.

The derivations of t_a and t_b as functions of R are straightforward; the results are

$$t_a \approx (J_2 - J_1)/g(G - R)$$

$$t_b \approx (J_4 - J_3)/g(G - R) \quad (5)$$

where

$$J_i = (V_0^2 + 2gGX_i)^{1/2} \qquad i = 1,2,3,\text{ and } 4 \quad (6)$$

In Equation 6, V_0 denotes the hump speed and X_i denotes the distances of the four wheel detectors from the crest. Equations 5 are approximate because certain small terms have been neglected. If Equations 5 are substituted into Equation 4 and a quadratic term of R is dropped, the desired equation is as follows:

$$\Delta R = \Delta\ell(\ell/L)gG^2\,[1 - 2(R/G)]\left\{[1/(J_2 - J_1)^4] + [1/(J_4 - J_3)^4]\right\} \quad (7)$$

With a hump speed of 2.3 mph, a G of 0.04, an ℓ of 20 ft, and an L of 100 ft, Equation 7 becomes $\Delta R = 0.012\Delta\ell(1 - 50R)$. For a specific $\Delta\ell$, ΔR assumes the form

$$\Delta R = m - nR \quad (8)$$

For two examples, $\Delta\ell$ is set to be 0.04 ft (0.5 in.) and 0.06 ft (0.75 in.).

$$\Delta R\ (\text{lb/ton}) = \begin{cases} 0.95 - 0.024R & \text{for } \Delta\ell = 0.04 \text{ ft} \quad (9) \\ 1.4 - 0.036R & \text{for } \Delta\ell = 0.06 \text{ ft} \quad (10) \end{cases}$$

To illustrate again how a small error in ℓ can translate to rather large errors in R, a few values

Figure 1. Error distortion in rolling-resistance histogram.

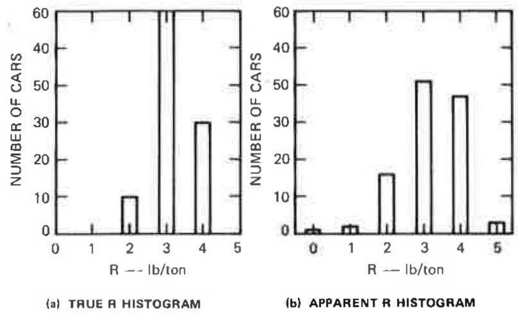


Table 1. Probability distributions of measured R.

	Probability (%) by Measured R-Value (lb/ton)					
True R (lb/ton)	0	1	2	3	4	5
2 (10 cars)	10	20	40	20	10	
3 (60 cars)			20	60	20	
4 (30 cars)				10	80	10

of ΔR are calculated by using Equations 9 and 10. The results are tabulated as follows:

$\Delta\ell$ = 0.04 ft		$\Delta\ell$ = 0.06 ft	
R (lb/ton)	ΔR (lb/ton)	R (lb/ton)	ΔR (lb/ton)
2	0.90	2	1.3
6	0.81	6	1.2
10	0.71	10	1.0
18	0.52	18	0.75

DISTORTION OF ROLLABILITY DISTRIBUTION

An example of a discrete rollability histogram is given in the following. To illustrate the error-induced distortion in an exaggerated fashion and yet to confine the amount of computation within a manageable limit, all numerical values in this example are hypothetical. A sample of 100 cars is assumed. Each car has a true rolling resistance of one of three values: 2, 3, or 4 lb/ton. It is further assumed that there are 10 cars with R of 2 lb/ton, 60 cars with R of 3 lb/ton, and 30 cars with R of 4 lb/ton. The true rollability histogram of this sample of cars is plotted in Figure 1a.

When the rolling resistances of these cars are measured in a yard, the measured R for each car may or may not be equal to its true R. The probability distributions of the values of measured R are assumed to be those shown in Table 1. For example, when a 2-lb/ton car rolls through the measurement section, there is a 40 percent chance that the measured R will be 2 lb/ton, that is, equal to its true R; there is a 20 percent chance that the measured R will indicate either 1 or 3 lb/ton; and there is a 10 percent chance that the measured R will indicate either 0 or 4 lb/ton.

From Table 1, the measurement errors have widened the range of R from its original values of 2 to 4 lb/ton to 0 to 5 lb/ton. The expected number of cars for each measured R can readily be obtained by multiplying the number of cars in each true-R category with the probability value and then summing over all the categories. The results are as follows: 0 lb/ton, 1 car; 1 lb/ton, 2 cars; 2 lb/ton, 16 cars; 3 lb/ton, 41 cars; 4 lb/ton, 37 cars; and 5 lb/ton, 3 cars. These values represent the measured, or the apparent, rolling-resistance histogram, which is plotted in Figure 1b for easy comparison with the true-R histogram. The word "apparent" is used because that is the histogram compiled from the yard data. The true-R histogram is masked by the measurement errors and is usually not known.

This hypothetical example not only illustrates the distortion to the rolling-resistance histogram caused by measurement errors but also indicates the multiplication and summation procedure one has to use to find the apparent histogram. When this procedure is extended from a discrete to a continuous distribution, it becomes a proven statistical operation called convolution (3, p. 317):

$$f_a(R') = \int_R f_t(R) f_e(|R' - R|)\, dR \tag{11}$$

In this convolution integral, f denotes a probability distribution and subscripts a, t, and e stand for apparent, true, and error, respectively. $f_e(|R' - R|)$ denotes the error distribution of the measured rolling resistance R' around a true rolling resistance value of R. For lack of experimental data, it is assumed that $f_e(|R' - R|)$ is a Gaussian distribution with its standard deviation σ equal to the ΔR values calculated from Equations 9 and 10.

Equation 11 allows the calculation of $f_a(R')$ if both $f_t(R)$ and $f_e(|R' - R|)$ are given. Because $f_t(R)$ is usually unknown, an inverse transformation is required to allow the calculation of $f_t(R)$ for a given $f_a(R')$. Such an inverse transformation is quite complicated. With the help of a computer, a shape for $f_t(R)$ can be assumed and iterations around that shape can be performed until the resulting $f_a(R')$ agrees with the rollability distribution measured in a yard. By using this method, an example of a realistic $f_a(R')$ and its corresponding true distributions $f_t(R)$ for various assumed measurement errors are now shown.

Rolling-resistance data were collected in December 1957 at the Robert E. Young Yard in Elkhart, Indiana. The measured rolling resistances for 1,225 cuts are plotted in a histogram shown in Figure 2. This distribution is typical of many other rollability distributions, which is the reason for using it in this example. The Elkhart data can be closely approximated by a continuous distribution function, the shape of which is also shown in Figure 2. This continuous distribution is used as the $f_a(R')$ here, and it is replotted in Figure 3 with the ordinate changed from number of cuts to a probability

Figure 2. Apparent rollability distribution measured in Robert Young Yard in December 1957.

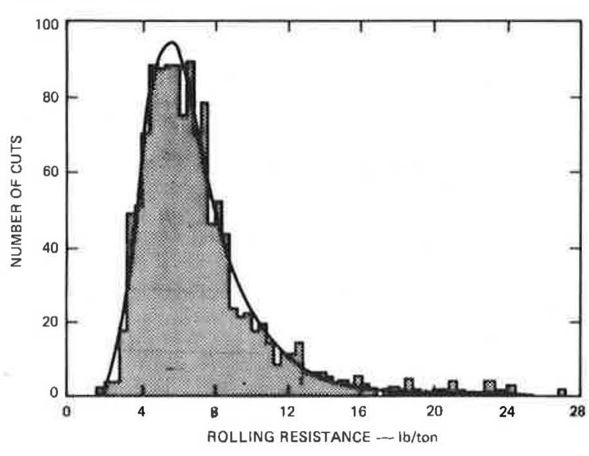


Figure 3. Measured rolling-resistance distribution.

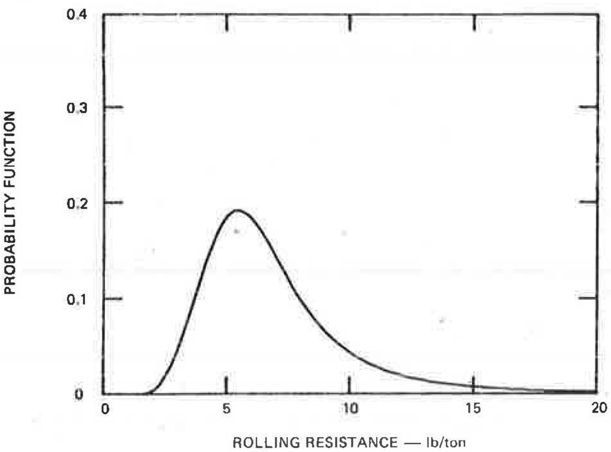
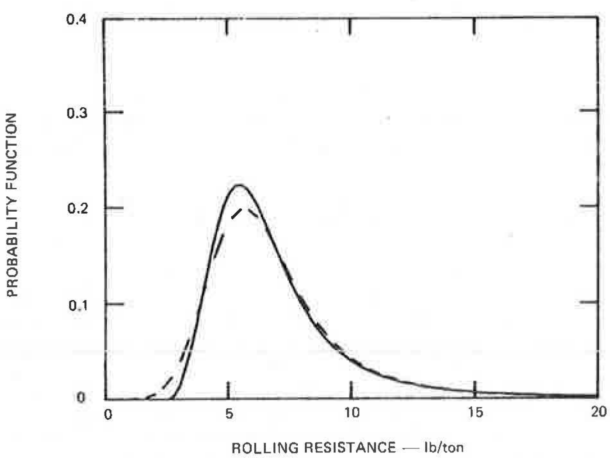


Figure 4. True (solid curve) versus apparent (dashed curve) distribution: $\Delta\ell = 0.4$ ft.



function. The smooth curve in Figure 3 is represented by

$$f_a(R') = \begin{cases} (ab/10^b)\left((R' - c)^{b-1}/\left\{1 + a[(R' - c)/10]^b\right\}^2\right) & \text{for } c \leq R' \quad (12) \\ 0 & \text{for } R' < c \quad (13) \end{cases}$$

where a = 11.9, b = 3.29, and c = 1.565.

As mentioned before, the error distribution is assumed to be a Gaussian distribution:

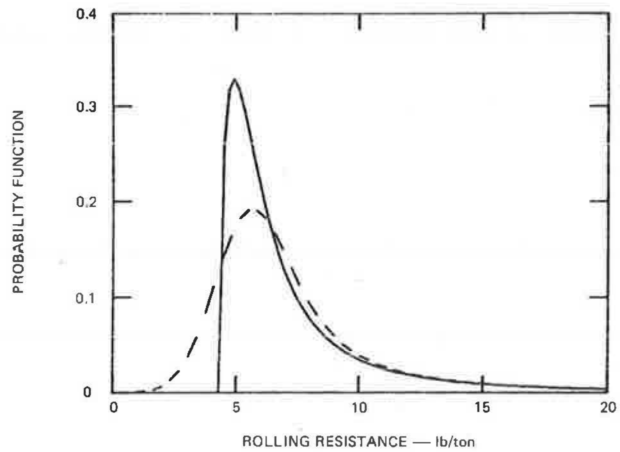
$$f_e(|R' - R|) = [1/\sigma(2\pi)^{1/2}] \exp\left\{-\tfrac{1}{2}[(R' - R)/\sigma]^2\right\} \tag{14}$$

with

$$\sigma = m - nR \tag{15}$$

The values of m and n depend on the registration error of the wheel detectors ($\Delta\ell$). The two sets of m and n used are given in Equations 9 and 10. One set corresponds to a $\Delta\ell$ of 0.04 ft (0.5 in.), the other to a $\Delta\ell$ of 0.06 ft (0.75 in.); both represent relatively small errors. The convolution integral in Equation 11 is then evaluated numerically for different $f_t(R)$ until the resulting $f_a(R')$ matches that shown in Figure 3. These results are shown in Figures 4 and 5. The solid curve in each figure is $f_a(R)$, the true rollability distribution. The dashed curve is $f_a(R')$, the apparent rollability distribution, which closely matches the measured rollability distribution of Figure 3. Figure 4 is for the case of $\Delta\ell = 0.04$ ft, and Figure 5 for $\Delta\ell = 0.06$ ft. Although these assumed errors are small, the distortions they inflict on an $f_t(R)$ are not negligible. This is especially so for the case shown in Figure 5. Although hardly any car incurs less rolling resistance than 4 lb/ton in the true distribution, the apparent distribution shows a significant fraction of cars with rolling resistances below that value. An overdesign of the speed-control system will result if a yard is designed according to the apparent rollability distribution.

Figure 5. True (solid curve) versus apparent (dashed curve) distribution: $\Delta\ell = 0.6$ ft.



CONCLUSIONS AND RECOMMENDATIONS

Several conclusions are evident from this study:

1. Small errors in wheel position or car velocity measurement can result in large errors in the calculated rolling resistance.
2. The error in rolling resistance is a function of the true rolling resistance of a car; the errors become larger for cars with smaller rolling resistance.
3. These errors in rolling resistance can greatly distort the shape of a rollability distribution; they tend to broaden the distribution so that it appears that there are more cars at the upper and lower extremes of resistance than there really are.

Because a rollability distribution is an important input in yard design, knowing the true distribution will reduce the cost of yard speed-control hardware. As shown by the example given in the preceding section, the convolution integral provides a way to derive the true rollability distribution once the error distribution is known. The error distribution of a specific instrument, be it a wheel detector or a Doppler radar, should be obtained in a yard where realistic operating conditions prevail. For example, the registration errors of a wheel detector can be obtained by comparing its output with a highly accurate optical measurement.

ACKNOWLEDGMENT

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Semiautomatic Operation for Upgrading Intermediate-Sized Hump Yards

ROBERT E. HEGGESTAD

A simplified control-system concept is described that may be applied to older manual hump yards to improve operating efficiencies, car handling, and volume and allow semiautomatic operation with one operator where two or three may have been needed for manual operation. The system provides automatic routing of cars based on manual handling of the entry of cars onto tracks during humping or on use of a switch list received in advance directly from a host computer. It offers speed control with a closed-loop radar system and manual inputs that allow the operator to specify a group-retarder exit speed for each individual classification track. These exit speeds are modified automatically according to car weight as determined by a conventional weight rail. No rolling-resistance calculations are made. The effect of track fullness is compensated for manually by the operator, but another option offers automatic fullness compensation based on cars counted into each classification track. Corrections for the effects of misroutes or stalls need manual intervention. Although this approach is not fully automatic, it is much more cost effective for lower-volume yards than a fully automatic system. This has been proven in two yards handling volumes of 1,000 to 1,500 cars per 24-hr day.

There are many older hump yards in the United States that still use manual retarder operation and manual switching of cars from a lever-type operator console. Depending on size, many of these yards employ several retarder operators in addition to the person who routes the cars to their destination tracks. These yards typically process between 500 and 1,500 cars per 24-hr day and have from 24 to 48 classification tracks--truly the middle-sized classification yard.

The control system described in this paper is a method of greatly improving the efficiency of such a yard without going to the expense of a completely automatic yard. It consolidates control in one operator, who monitors both retardation and routing; it improves the reliability of switching; it improves the speed control with resulting reduction in damage; and it raises the overall operating efficiency of the yard. This system has been installed in two yards of the Consolidated Rail Corporation (Conrail) and has provided outstanding results.

In general design concept, the system is two systems in one package: a switching or route-control system using microprocessor logic and manual pushbutton entry and a semiautomatic speed-control system with individually selectable exit speeds for each track. The speed control uses radar speed monitoring with a closed-loop control that drives the retarder to reduce the speed of each car to the value called for by the microprocessor. Speeds called for are values entered by the operator, modified slightly according to car weight and ambient temperature. An optional enhancement also provides automatic compensation for track fullness, which will be discussed later. Another optional enhancement, to be discussed later, is direct entry of the switch list from a host computer, eliminating the operator pushbutton entry other than corrections as needed. The system also provides a full operator's console permitting manual override of any automatic function and a test and simulation panel employed in maintenance and system testing.

AUTOMATIC SWITCH OPERATION

In the automatic switching portion of the system, new data are entered in one of two modes, selected by the pushbuttons marked TRACK SELECT and DEFAULT SELECT. Following system clearout, the system will automatically revert to DEFAULT SELECT. In this mode, the DEFAULT SELECT button lights and a two-digit number entered on the keyboard will appear in the DEFAULT display window. That number track will subsequently be used as a destination track for any car humped without an entry for destination. The default track selection will remain in effect and the number will remain in the window until it is changed by the entry of a new number. The system will not accept an invalid number as a default track and will respond to such a request by issuing an INVALID TRACK alarm.

To enter the track-select mode the TRACK SELECT button must be pushed. It will then light and remain lighted, and the DEFAULT SELECT light will go out. In the track-select mode, track entries are made as two-digit numbers from the number keyboard. Track numbers 1 through 9 are entered with a leading zero. The first two digits entered will appear in the CUT 1 display window, each digit appearing as it is entered. This is the destination track for the first cut. The next two digits entered will appear in the CUT 2 display window, representing the destination track for the second cut. Subsequent entries may be made for the third and fourth cuts; the numbers appear in the CUT 3 and CUT 4 windows. If an invalid track number is entered, it will not appear in the CUT window, and an invalid-track alarm will be issued. If a valid track number already entered must be deleted or changed, this is done with the CUT CANCEL button. Pushing this button cancels the last full track number entered and removes it from the cut display window. A second push of this button cancels the next prior track number entered, and so forth. For example, if four track numbers are entered and the operator wishes to change the number