TRANSPORTATION RESEARCH RECORD 927

Innovation in Classification Yard Technology: Proceedings of the Third Railroad Classification Yard Workshop

TRANSPORTATION RESEARCH BOARD

NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1983

IN COOPERATION WITH THE AMERICAN RAILWAY
ENGINEERING ASSOCIATION

Transportation Research Record 927
Price $10.80
Edited for TRB by Naomi Kassabian

mode
3 rail transportation

subject area
21 facilities design

Library of Congress Cataloging in Publication Data
National Research Council. Transportation Research Board
Railroad Classification Yard Workshop (3rd: 1983: Toronto, Ont.)
Innovation in classification yard technology.

(Transportation research record; 927)
Reports presented at the 62nd annual meeting of the Transportation Research Board.
1. Railroads–Yards–Congresses. I. National Research Council (U.S.). Transportation Research Board. II. Title. III. Series.
TE7.H5 no. 927 [TF590] 380.5s [625.1'8] 84-8213
ISBN 0-309-03617-8 ISSN 0361-1981

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Introduction

JAMES A. WETZEL

Classification yard design and freight car performance were the featured topics at the third railroad classification yard workshop, October 19-21, 1983, in Toronto, Ontario, Canada. The program included presentations at three working sessions and a keynote address by William J. Harris, vice president of research and testing at the Association of American Railroads. The workshop closed with an inspection tour of the Canadian Pacific (CP) Agincourt Yard.

Deregulation and the impact of large railroad system mergers are the new challenges for the railroad industry, Harris told the workshop audience. Deregulation has also affected traffic by car type as well as railroad classification yards according to J.A. Hagen, senior vice president of marketing and sales, Consolidated Rail Corporation (Conrail), who addressed the workshop's luncheon following the second session.

A session reviewing knowledge of freight car rollability and prediction of car performance was led by John F. McGinley. It included a panel discussion by the authors of written presentations and discussion of the causes and results of the principal characteristics of rolling resistance by Alexander Wilson of Union Switch and Signal Division, Charles N. Morse of General Railway Signal Company, and Earl E. Frank of Abex Corporation.

The second session covered yard-control systems; Alain L. Kornhauser of Princeton University presided. The third session covered yard design tools and practice; Carl M. Martland of Massachusetts Institute of Technology presided.

Agincourt Yard, recently converted from its original analog system to digital computer control, was the site of the workshop's final session. Hosts for this tour were CP general manager G.A. Swanson and B.F. Dixon, assistant superintendent of Agincourt Yard.

As chairman of this workshop, I emphasize, in summary, that the rollability of cars remains one of our greatest unknowns and that equating the measured rolling characteristics of cars with their true performance remains an open field for further research. I believe that even the future need for yards is in doubt. With boxcar traffic moving in Trailvans and other traffic moving in unit trains, industries are changing their transportation requirements, which significantly affects the need for and the design of classification yards. If the rail industry is to continue to grow, the role of the railroads for best serving the nation must be determined.

Below are listed 16 yard design suggestions, previously outlined at the first classification yard design workshop, held in Chicago in 1979 (1). These yard design features may or may not suit all requirements, but based on my 30 years of experience, I believe that they can serve as guidelines. They are as follows:

1. A hump yard should never be built unless it is needed, and two hump yards should not be built at the same location. The site for a yard requires a sufficient number of originating and terminating cars to justify its cost. If there are more cars than can be handled through one yard, a site at another terminal should be located to construct the second yard. The number of times cars are switched should be minimized.
2. Construction of a receiving yard in line or parallel to the classification yard is dependent on the terrain and the size of inbound trains. If the site for a yard has sufficient width and the majority of trains are short (less than 80 cars), I recommend use of the parallel receiving yard. A yard primarily to be used for long road trains is normally suited for an in-line design.
3. The classification yard should be a teardrop design with the long track in the center and short tracks on either side. This provides minimum curve resistance for the majority of the cars. If the yard is a high-volume yard with two parallel departure yards, the teardrop design also provides greater operating flexibility in classifying cars to tracks.
4. The departure yard should be parallel to the classification yard. A parallel departure yard will minimize interference in assembling trains and provide greater use of the classification tracks.
5. The receiving yard and departure yard should be constructed with wide track centers to provide access to the cars for bleeding of air brakes and car inspection.
6. The distance between the receiving yard and the hump crest and between the hump crest and the clearance point in the classification yard should be kept to a minimum. It is desirable to minimize the time to shove a cut up the hump from the receiving yard, and it is critical to maintain a short distance between the crest and the body of the yard because this is the region of potential catchup; this distance governs the humping speed.
7. The lead between the receiving yard and the hump should be constructed with No. 10 turnouts; 75 ft of tangent track should be the minimum distance between reverse curves to prevent long lightweight cars from lifting off the track while they are being shoved up the hump.
8. The vertical curve at the hump crest should be at least 80 ft (approximately 12 ft per degree of change). The flat vertical curve will reduce problems that result from the uncoupling of long cars.

9. I recommend constructing 10 track groups with a maximum curve of 12 degrees 30 min. The total central angle should be kept to a minimum, and, if necessary, depending on the total number of classification tracks, two master retarders may be required. Curve lubricators on both rails should be installed below the group retarder to reduce curve resistance.

10. The initial hump grade at the end of the crest vertical curve should be 5 to 6 percent. This will achieve maximum separation between cars.

11. The classification yard body should be graded at 0.08 percent and track centers constructed at 14 ft. The minimum track length should be 30 cars; the maximum (depending on the total number of classification tracks) should be 60 to 80 cars.

12. Inert retarders should be located 300 ft from the end of the clearance point on a +0.3 percent grade.

13. The end of the classification yard should be built with No. 8 turnouts in a tandem ladder arrangement at about an 18-degree angle. The number of tracks connected to separate ladders is a function of the yard size and car volume. If two crews are used, the yard should be subdivided into four leads.

14. Two or three stub-end pullout leads (depending on the size of the classification yard) should be used to connect the classification yard with the departure yard. These pullout leads should be constructed on a zero grade and about 10 car lengths longer than the longest classification track. Power-operated crossovers should be installed to permit parallel moves. The distance between the pullout leads and the classification yard and between the pullout leads and the departure yard should be kept as short as possible. Pull distance should be sacrificed for shove distance.

15. The car repair tracks should be located between the classification yard and the departure yard and accessible from both the hump and the pullout.

16. The locomotive service and repair facilities should be located between the receiving and the departure yards.

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On the Behavior of Long Cuts with Uneven Load and Axle Distribution in Classification Yards

H. KOENIG

The behavior of long cuts being humped in classification yards is determined not only by rolling, curve, and wind resistance but also by load and axle distribution. Most retarder control algorithms keep cuts at a constant velocity notwithstanding rollability and cut makeup. This has been shown to cause simple and corner impacts. One method of overcoming such difficulties is continuous speed control combined with operative simulation of cut behavior shortly before humping when cut makeup is known.

The behavior of cuts being humped in a classification yard is generally thought to be determined by the rolling resistance, the curve resistance, and the wind resistance. Distribution of load and axles also plays an important role.

On September 6, 1979, in Limmattal Yard of the Swiss Federal Railways (SBB), which is a carefully designed automatic yard that has 64 tracks in the bowl and a capacity of 6,000 cars per day, a long cut suffered a corner impact and subsequent derailment. Examination in situ provided no clues as to the cause; the computer system controlling the retarders had evidently done what it had been programmed to do.

SBB tried to verify by means of computer simulation what had happened. The results of the simulation showed that the cut had accelerated ahead of the master retarder extraordinarily quickly, had accordingly been slowed down by the master retarder, and had then been caught by one of the following cuts. The reason for the extraordinary acceleration was uneven load distribution: The first cars of the cut were loaded, the following cars were more or less empty, and the loaded cars pulled the remaining cut over the hump.

Speed is controlled in hump yards by means of retarders of different types, for example, by clasp retarders or Dowty hydraulic retarder units. All retarders attack the rims of the wheels. If all other parameters of a cut, notably its length and weight, are held constant and for the moment the weight sensitivity of clasp retarders is ignored, the retarding action will be stronger if the cut has many axles than if it has few. Many European cars have only two axles and are nevertheless longer than or as long as bogie cars, and there are bogie cars that are nearly twice as long as standard ones. If the front of a cut has two-axle cars and the rear part has equally long bogie cars, such a cut will be slowed down in a retarder more gently at first and more strongly later. When the bogie cars are in the front of the cut and the two-axle cars are in the rear, the result will be the opposite. In both cases time-distance diagrams will be different.

Procedures intended to overcome the problems created by uneven load or axle distribution or both should not resort to splitting the cut because this causes a succession of cuts following each other immediately into the same classification track and requires a substantial reduction in humping speed given the probable error in nominal exit velocity from the retarders.

The most convenient means of studying cut behavior is computer simulation. The time-distance diagrams shown in this paper are the result of such simulations. They refer to Limmattal Yard. The hump layout of this yard is shown in detail in Figure 1.

INFLUENCE OF LOAD DISTRIBUTION

Figure 2 shows the time-distance diagram of a cut consisting of 14 bogie cars each 14 m long and weighing 60 t. The total length of the cut is 196 m; the total weight is 840 t. The load is evenly distributed. The cut is framed by two single-car cuts running into neighboring tracks and two other single-car cuts, the first two preceding and the other two following the cut of 14 cars. The singles are easily running cars (rolling resistance is 0.83 kg/t); the behavior of the cut of 14 cars is average (rolling resistance is 1.63 kg/t).

Because it is difficult to measure the true rollability of longer cuts, speed-control algorithms normally provide that they be kept at a constant velocity by master or group retarders or both, regardless of rollability.

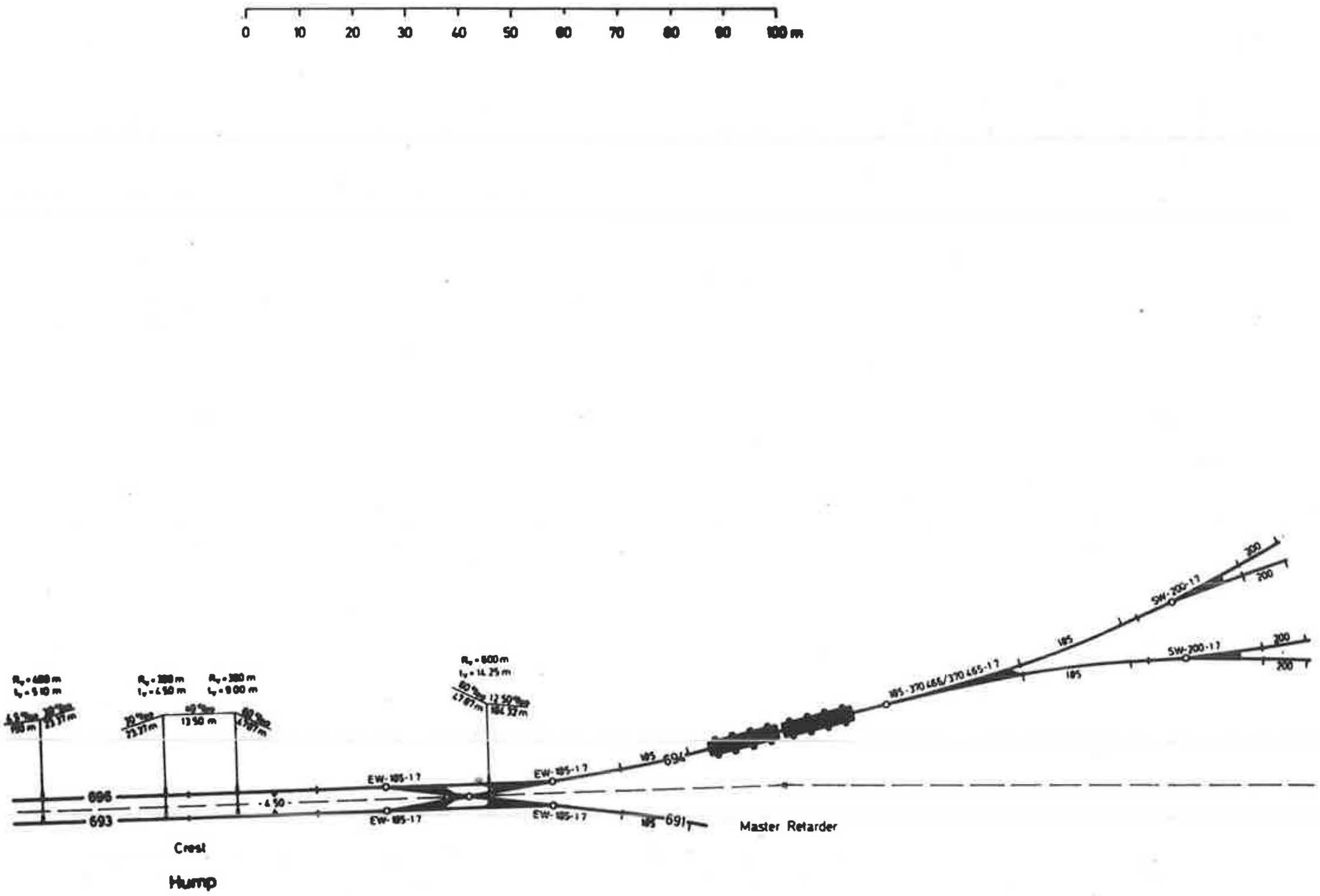
To show the influence of load distribution only, it is assumed that the optimal exit velocity of both master and group retarders is known; the long (14-car) cut then will be filed optimally between the preceding and the following singles as shown. Because these are easily running cars, they would be slowed down even with target shooting in the bowl to a more or less safe coupling speed (in Europe, buffing speed) of 1.5 m/sec. Spacing in Figure 2 is by definition excellent.

Figure 3 shows the same cut succession as that in Figure 2 except that the loaded cars are now in the front of the 14-car cut and the empties are in the rear. Total cut weight is the same as that of the 14-car cut in Figure 2. The long cut accelerates much better than before. For purposes of easy comparison the hatched curve gives the rear coupler of the cut, which has an even load distribution. It may be observed that spacing is no longer optimal. The cut of 14 cars is now much nearer the preceding single after being slowed down by the siding retarder (the term "siding retarder" is used intentionally; in Limmattal Yard the siding retarders are situated only 10 m behind the clearance marker of the last switch and not at the tangent point, which is 90 m farther down). Nevertheless, the cut behavior in this situation causes no conflicts.

The situation becomes dramatically worse when the loaded cars are in the rear part of the cut (Figure 4). This cut starts to accelerate from humping speed (1.4 m/sec) fairly late and then only to 1.44 m/sec; by then the empty cars have passed over the hump with the remainder of the cut. The loaded cars then enter the hump access gradient. The cut decelerates from 1.44 to 1.35 m/sec and the rear coupler again touches the front coupler of the rest of the train. With the old European side buffers and screw couplers this would have no consequences but with automatic couplers it does; they engage anew, provided they had not been put in the locked position. Normally this would make no sense because automatic couplers should engage when the cuts arrive in the bowl. Finally, when enough empty cars are in the accelerating gradient, the cut accelerates strongly. It is then kept at the same speed as the cut that has an even load distribution and later slowed down to safe coupling speed.

Because the cut is late, much later than the cut

Figure 1. Limmattal Yard: northern half of main hump.



with loaded cars in the front was early, it is caught in a corner impact by the immediately following single car, the destination of which is the neighboring track. In Europe corner impacts with cars that have side buffers usually cause derailment.

Even the second following single-car cut, the destination of which is assumed to be the same track, catches the cut of 14 cars. Under European conditions (screw couplers) the catching car would stop immediately due to the ratio of mass of both cars involved (88 versus 840 t) because there is no more gradient in the lower part of the switch area. Thus the catching car would be an obstacle and perhaps cause further problems.

INFLUENCE OF AXLE DISTRIBUTION

It is not easy to show the influence of axle distribution on the behavior of cuts isolated from any other influence, notably load distribution, because if cuts are made up simply of long and short bogie cars and if all cars have the same axle load, then load distribution would vary with car arrangement. Evidently it must be assumed that longer cars have a higher axle load, so load per unit of length would be the same for all cars.

Problems in this case may even arise from internally weight-responsive retarders. The influence of low axle density would be offset by higher clasp pressure generated by the higher axle load.

Externally weight-responsive retarders are often controlled by setting the clasp pressure proportional to the mean axle load of the whole cut; this pressure is kept constant for all axles of the cut. This procedure is applied in Limmattal Yard. There is no risk that the wheels will climb the rail because there is a fairly wide margin between the clasp pressure needed for retardation and that needed to prevent climbing so that even short cuts made up of a leading empty car and a trailing loaded car (the worst case, because the first axle of the empty car has to cut the clasp) are treated without the occurrence of climbing.

Figure 5 shows the behavior of another cut 196 m long but made up of six short cars (each 14 m long) and four long cars (each 28 m long). Car distribution is such that axle density is nearly even: Each half of the cut consists of a short, a long, another short and another long, and finally a short car. Cut succession is the same as that in Figures 2 to 4 as is the exit velocity from master and group retarders. Spacing, indeed, is optimal.

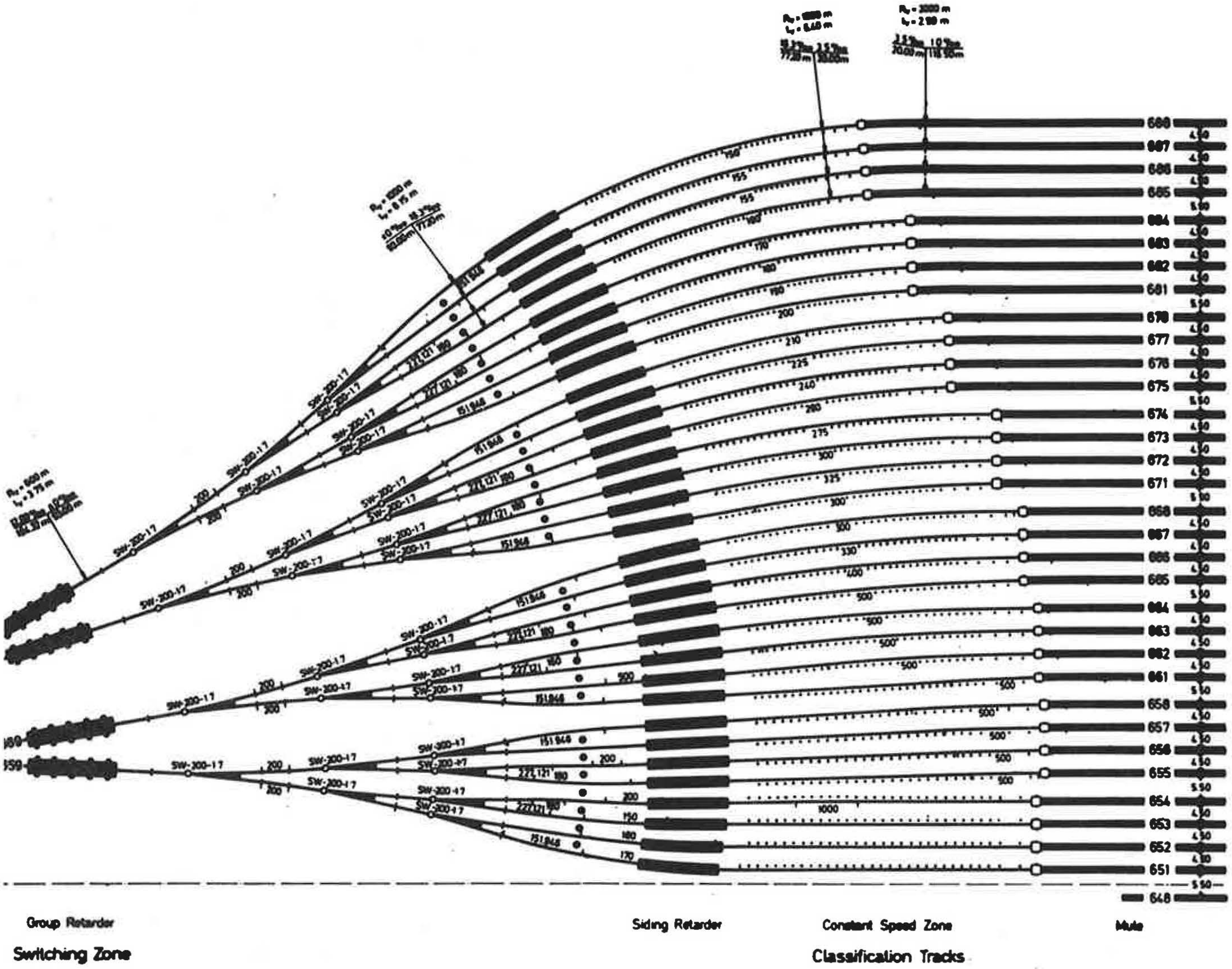


Figure 6 shows the same cuts except that the four long cars are now in the front of the long cut and the six short cars are in the rear. Until the cut is slowed down by the siding retarder, this new configuration does not behave significantly differently; the hatched curve of the cut that has even axle distribution closely resembles the curve of the cut considered here. This is because both master and group retarders keep the cut at a constant speed without really having to slow it down. It is only in the siding retarder that curves begin to diverge; lack of axles in the front part of the cut slows it down late. The final difference between the curves is appreciable; the 14-car cut nearly catches the second preceding single-car cut, assumed to run into the same track of the bowl. Should the exit speed from master, group, or siding retarder of this preceding car accidentally be less than the nominal calculated value, then an impact could occur. Such errors in exit velocity do occur with a certain frequency.

Figure 7 shows the same cuts, but now the six short cars are in the front of the long cut and the four long cars are in the rear. Of course, the cut is now slowed down early by the siding retarder as compared with the cut with even axle distribution. But even in this case no corner impact or simple catching occurs if the following single cars are treated correctly by master, group, and siding retarders. Yet there is not much tolerance left.

Effects of load and axle distribution may interfere with proper positioning of the car. Such effects may be partly or completely cancelled or amplified. It should be mentioned that all cases given here are not the worst cases. Still longer cuts with still more uneven loads or axle distributions do occur.

CONCLUSIONS

Control schemes for clasp retarders usually take the acceleration measured ahead of the retarder to calculate the exit velocity needed for adequate spacing of single cuts and shorter groups. For longer groups a constant suitable velocity is chosen. This procedure cannot deal adequately with longer cuts in high-capacity yards.

In an algorithm called F*DELTV, SBB uses a more integrated measure for rollability--the speed ahead of the retarder (1). This procedure is capable of filing cuts of any length and rollability more or less optimally between preceding and following cuts, provided that load and axle distributions are fairly even. The only parameter needed is length of the cut.

It is tempting to see whether a still more integrated measure of rollability--the time needed by the cut to run from the crest of the hump to the retarder--would be able to space cuts of any makeup correctly. Simulations show that the time for running from the crest of the hump to the retarder is a measure of rollability and perhaps load distribution also (but not axle distribution). However, exit velocity would have to be calculated with the length and mean axle load of the cut as parameters. Therefore this procedure would be somewhat troublesome. Many simulations would be needed to cover the whole range of length and axle load and that would only

Figure 2. Cut of 14 bogie cars, load evenly distributed.

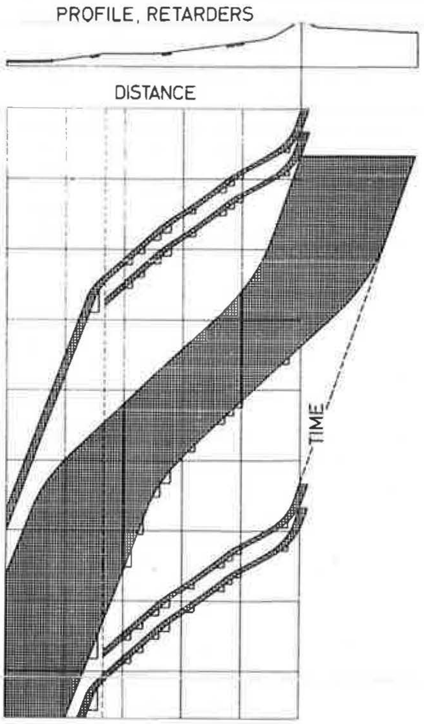


Figure 3. Cut of 14 bogie cars, load in front part.

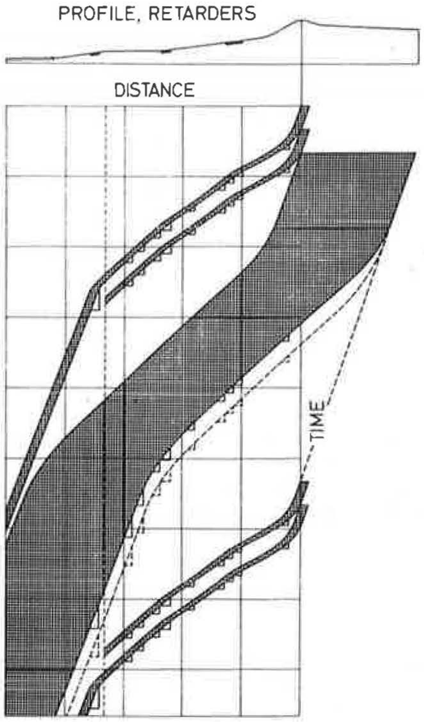


Figure 4. Cut of 14 bogie cars, load in rear part.

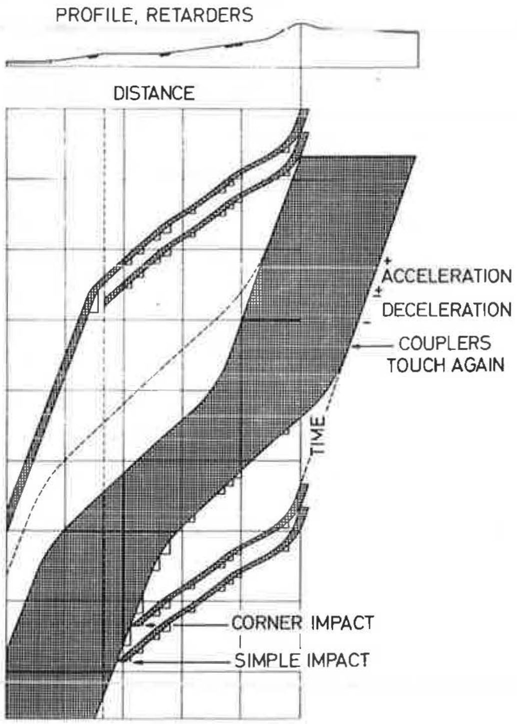


Figure 5. Cut of 10 bogie cars, long and short mixed.

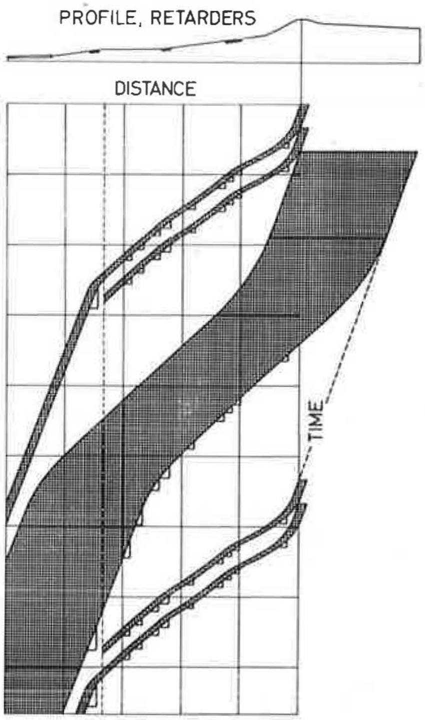


Figure 6. Cut of 10 bogie cars, long cars in front part.

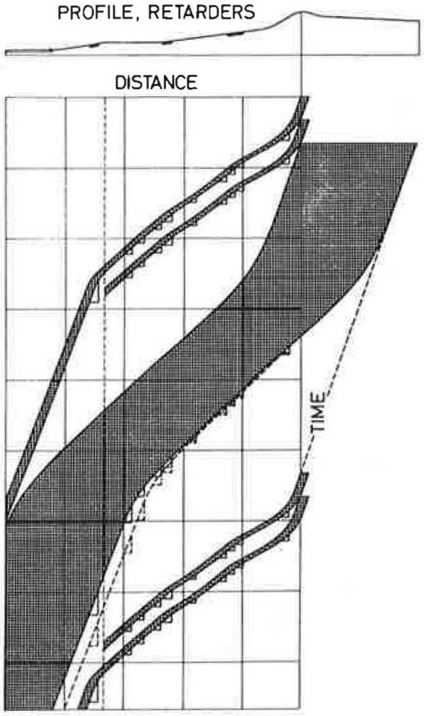
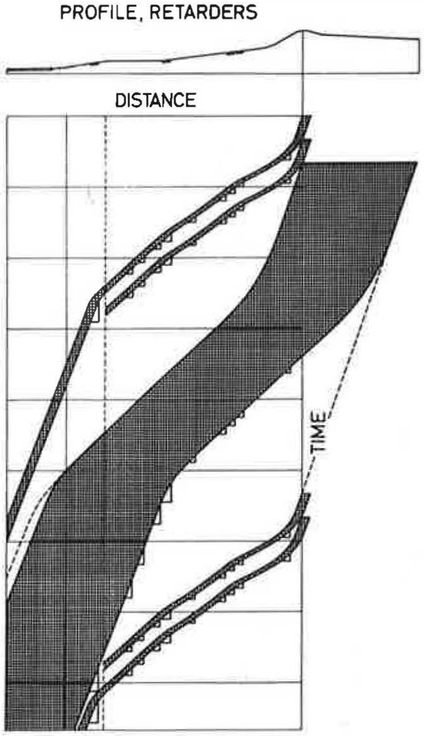


Figure 7. Cut of 10 bogie cars, short cars in front part.



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.

REFERENCE

1. H. Koenig. Ablaufsteuerung auf optimales Einfädeln in die Richtungsglise von Rangierbahnhöfen. Eisenbahntechnische Rundschau, Vol. 22, Nos. 1 and 2, 1973, p. 30.

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.

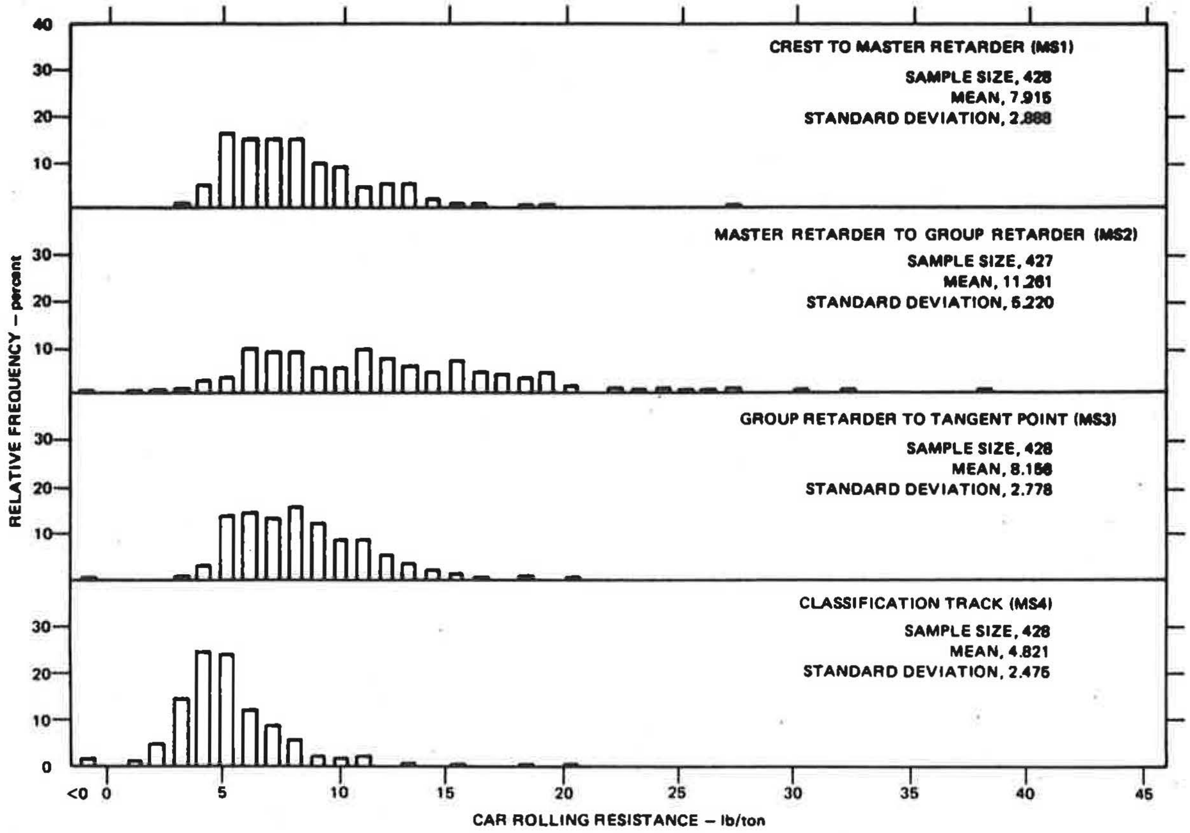


Figure 2. Distribution of Hinkle Yard car rolling resistances by measurement section: summer observations.

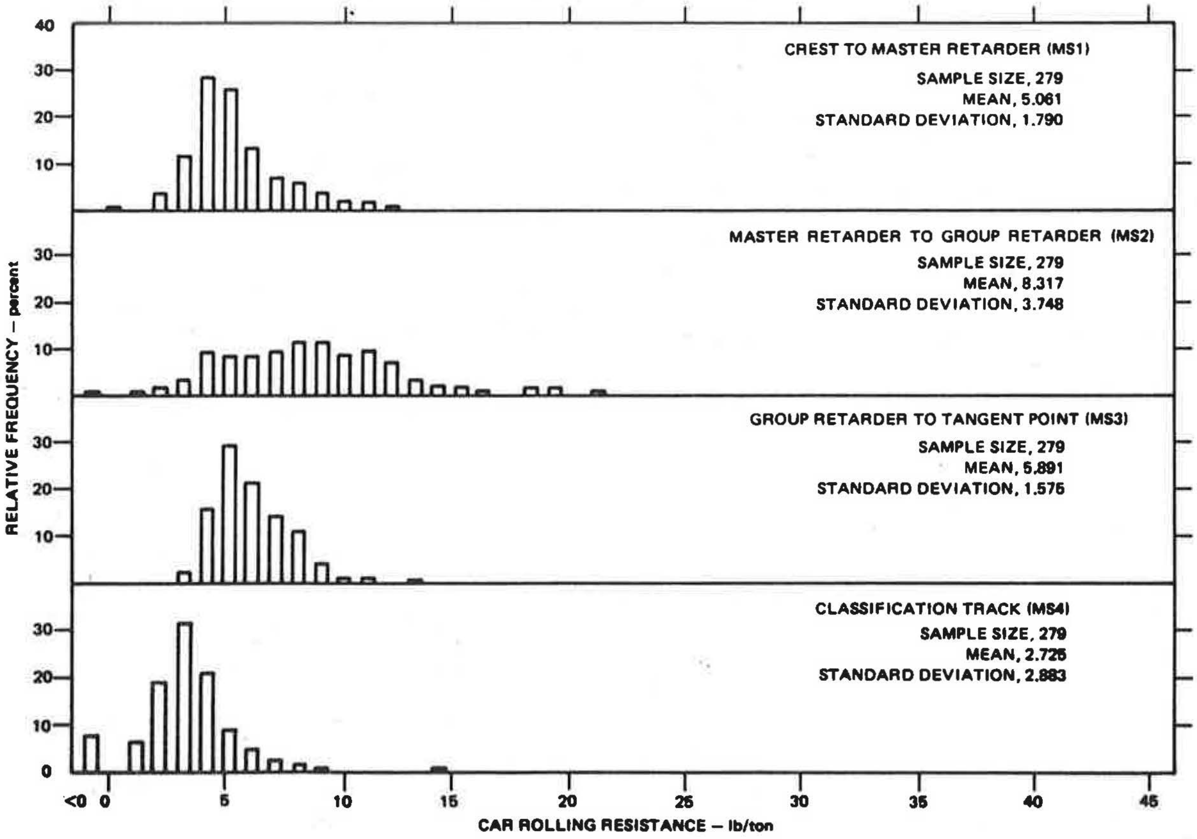


Table 1. Rolling resistance and velocity statistics at Hinkle Yard measurement sections: winter observations.

	Rolling Resistance (lb/ton)						Avg Velocity (ft/sec)					
Measurement Section	Mean	SD	SE	95 Percent CI	Minimum	Maximum	Mean	SD	SE	95 Percent CI	Minimum	Maximum
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	Minimum	Maximum	Mean	SD	SE	95 Percent CI	Minimum	Maximum
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.

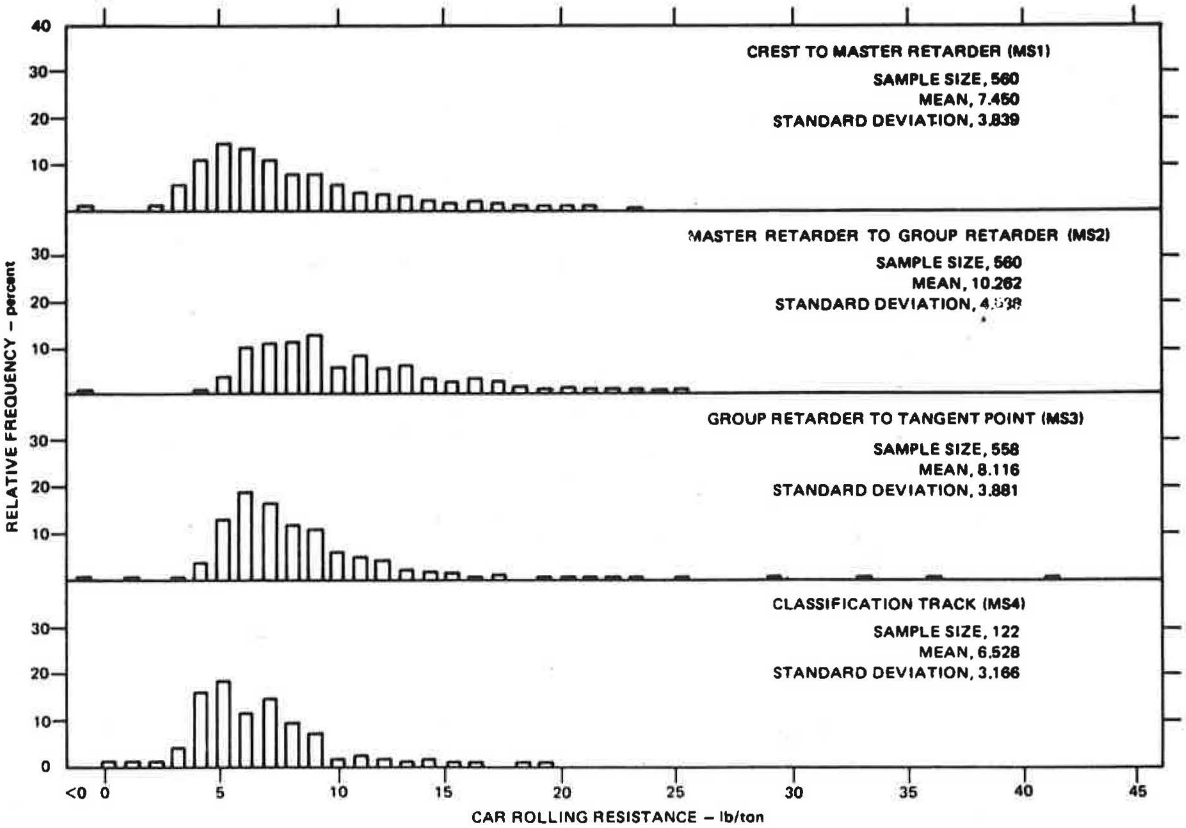


Figure 4. Distribution of DeWitt Yard car rolling resistances by measurement section: summer observations.

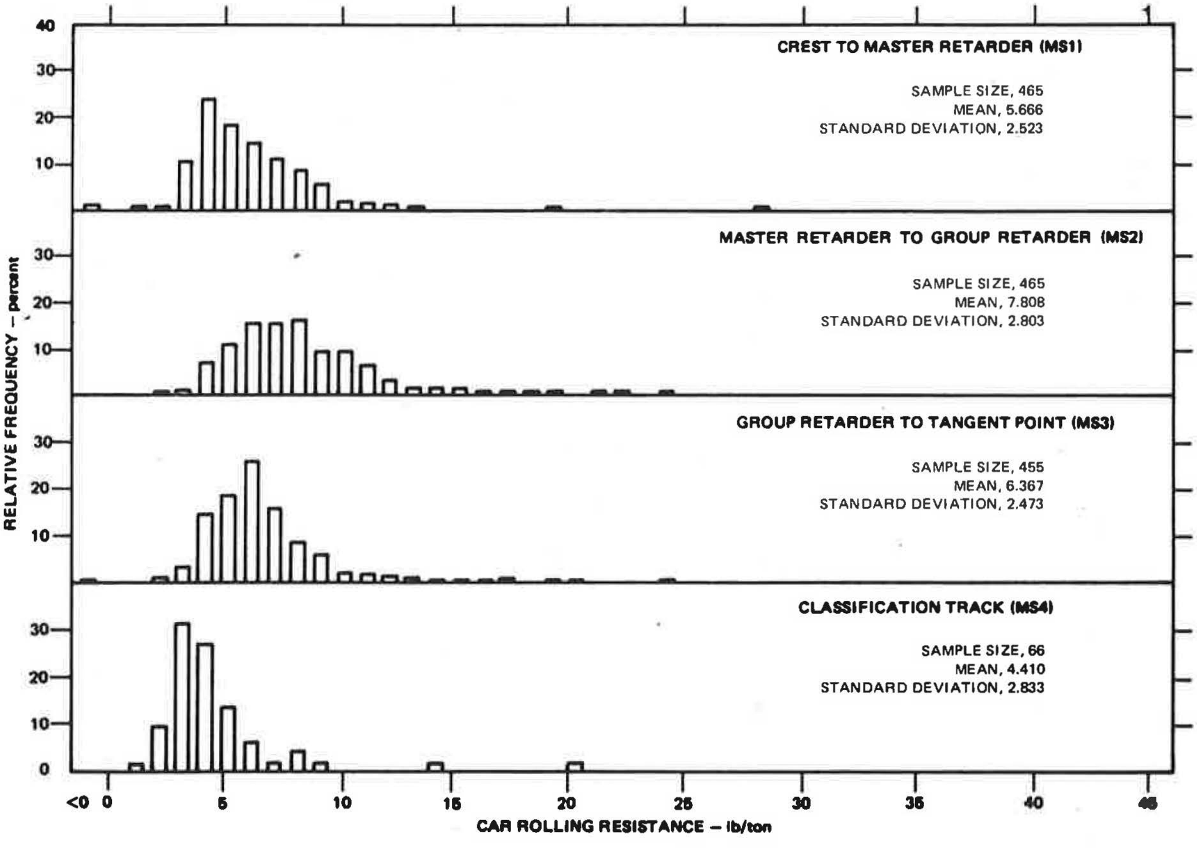


Table 3. Rolling resistance and velocity statistics at DeWitt Yard measurement sections: winter observations.

	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: $N = 4{,}465$; $R^2 = 0.478$; $\bar{\sigma} = 2.61$ 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.

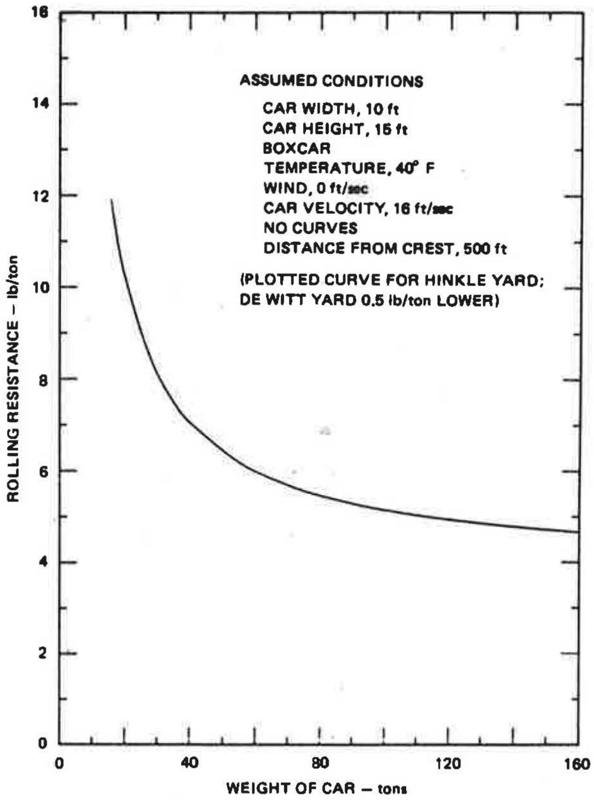
Truck Center Length

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.

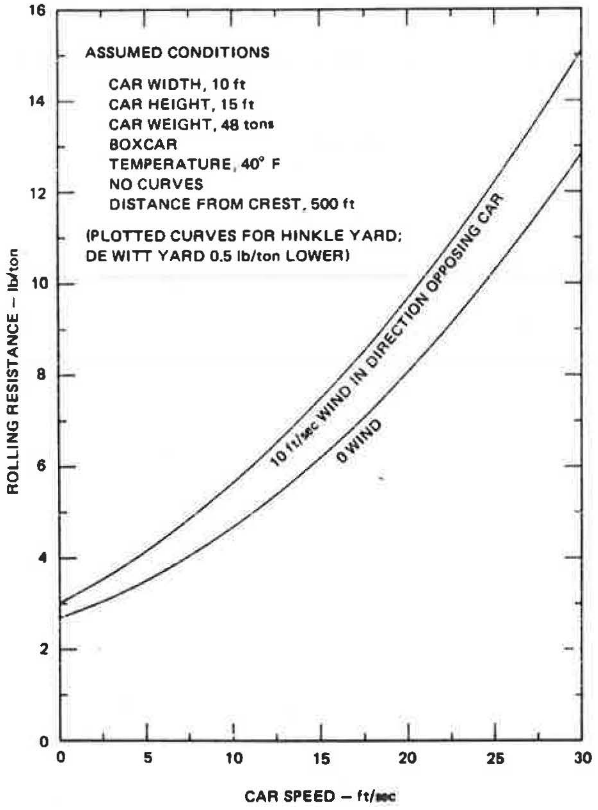


Figure 7. Rolling resistance as a function of wind velocity.

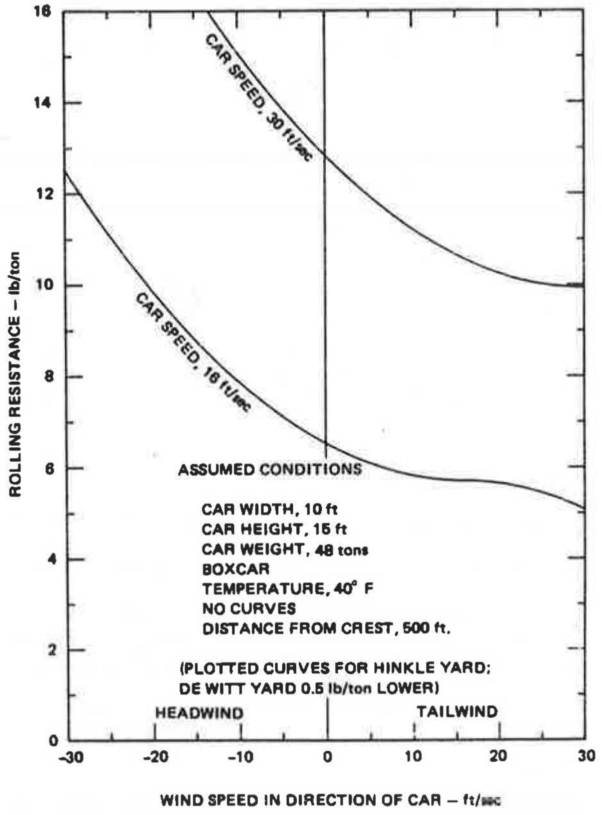
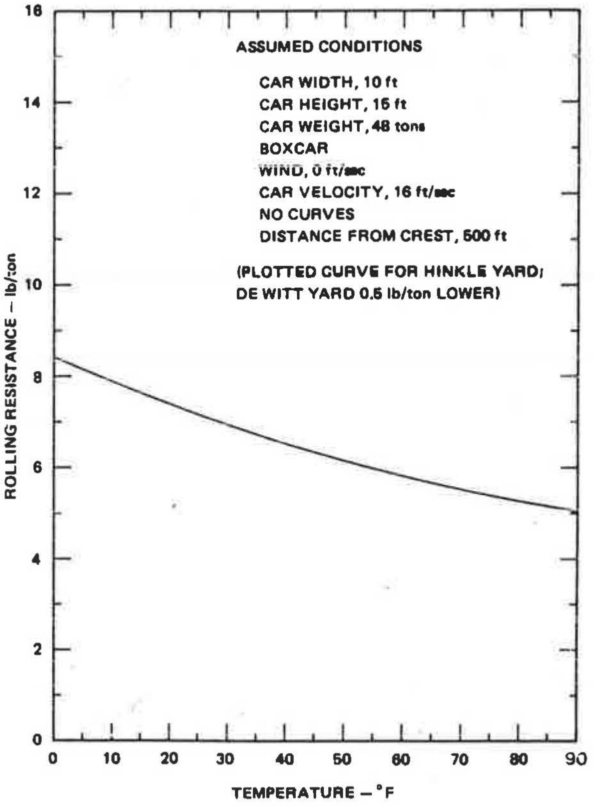


Figure 8. Rolling resistance as a function of temperature.



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-

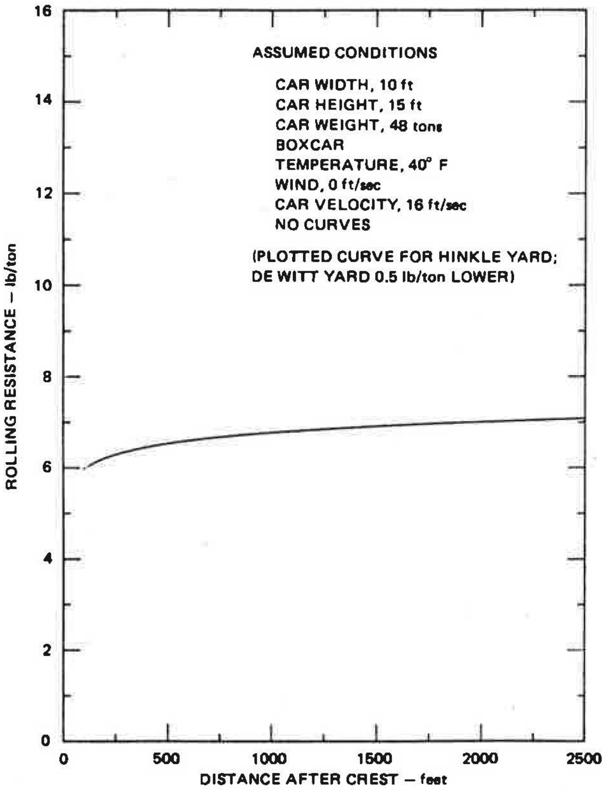


Figure 9. Rolling resistance as a function of distance from crest.

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

The freight-car rollability study was performed by members of the Transportation Operations and Information Systems Center of SRI International for the Department of Transportation's Transportation Systems Center (TSC), Cambridge, Massachusetts. John Hopkins of the TSC was technical monitor for the project. The effort was sponsored by the Office of Freight and Passenger Systems, Federal Railroad Administration, as part of a program managed by William F. Cracker, Jr.

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

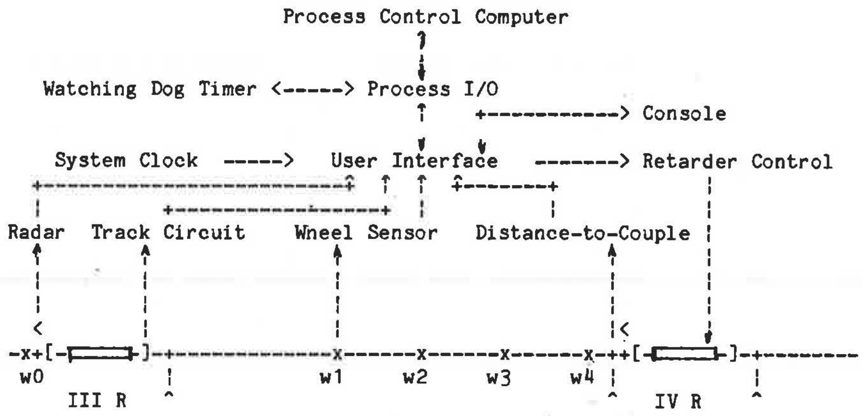
YINGHUA MIN AND LIANLONG YANG

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-

Figure 1. Target speed-control system configuration.



fying yard 24 hr a day to accomplish this heavy and dangerous job. Some injuries occur every year. In addition, freight cars and their contents are frequently damaged. A large percentage of railway accidents occur in classification yards.

2. Efficiency: When these control functions are performed by labor-intensive manual systems, to ensure safety a lower retarder release velocity is preferred to a faster one. In addition, free-rolling cars are usually stopped quite a long way before preceding cars. These two factors consequently result in the so-called free window--a free section between cars on the bowl tracks. When a bowl track does not hold as many cars as planned because of these free windows, the yard engine has to go down the hump to push the cars to couple. This takes about 20 min each time, which is inefficient. The application of classification yard computer control systems (CYCCS) reduces the need for the yard engine and improves the efficiency of the classification operation.

3. Economy: Braking cars with iron shoes causes serious wear and tear to rails. As a result, many rails have to be changed in classification yards every year.

These considerations, in part, show the necessity of CYCCS in China. Therefore, much attention has been given to classification yard automatic control systems, including CYCCS (2). Automatic speed-control systems are emphasized in this paper.

It is more difficult to implement CYCCS in China than in some other countries because of the following reasons:

1. The speed allowed for coupling is restricted to less than 5 km/hr, which is usually called the allowed coupling speed. As is known, the higher the allowed coupling speed, the easier it will be to implement CYCCS, but because of the loading situation and the construction of Chinese freight cars, it is hard to determine whether the allowed coupling speed can be increased.

2. The bowl tracks can be as long as 800 m. This also presents some sophisticated problems in CYCCS.

3. The wide variety in car rolling resistance (rollability) makes implementing CYCCS more difficult, even though the range of rollability variety is not so large as has been reported. There has been some misunderstanding because of the questionable rollability measurement techniques and devices that have been used. This problem will be discussed later.

In the next section the proposed system configuration is presented, including a four-level retarder arrangement, various sensors, a process-control (PC) computer, and a system redundancy scheme. In the third section, measurement of car rollability, which is important and extremely difficult, is discussed in some detail. It is noted that some rollability data collected during past years have been unreliable. The large error in rollability measurement is caused by the measurement techniques and the rollability measurement devices. The primary error sources are analyzed, and some approaches to this problem are discussed. The strong relationship between the rollability and the velocity of cars, however, has been widely noted recently. Based on this idea, a piecewise-linear mathematical model is suggested for target-shooting control systems.

SYSTEM CONFIGURATION

The CYCCS considered here is essentially a speed-control system. Although the switching-control systems, master retarder, and group retarder control systems are important, they will not be considered in this paper. The discussion will be restricted to speed control, especially to target-shooting control systems. The term "target shooting" refers to the coupling of a free-rolling car with the preceding car at an allowed coupling speed. In the target speed-control system, retarders are employed to accomplish the car speed-control function. Because of the difficulty of implementing CYCCS in China, a four-level retarder arrangement is suggested. In addition to master retarders and group retarders, a tangent retarder, denoted III R, is placed at the beginning of each bowl track. A track retarder, denoted IV R, is placed about 200 m after III R on each bowl track. The target speed-control system configuration is shown in Figure 1.

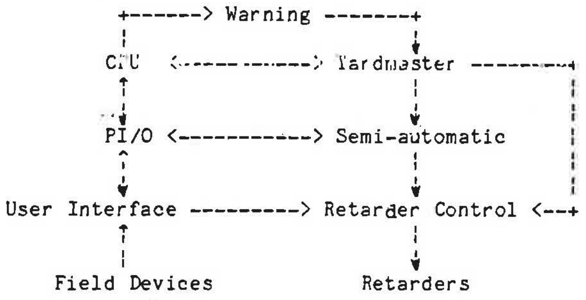
The system includes the following field inputs:

1. Wheel sensor w0 senses the presence of rolling car wheels and signals the computer to begin a car control task in the real-time operating system (RTOS). From this input, the computer knows how many cars make up a cut. If it is a long cut (more than five cars), the so-called tail control technique has to be used, which means that the retarder is activated after several cars in the cut have passed through it.

2. Track circuits III and IV are closed or open contacts of track relays that indicate whether the track section is occupied by cars.

3. Radars III and IV measure the car's velocity

Figure 2. System-redundancy scheme suggested.



from its entrance into a track section to its exit. For long cuts of cars, radars indirectly provide information about how many cars have passed through the retarder for the use of real-time control. The PC computer accepts the information and sends retarder control commands to the specified retarder.

4. Wheel sensors w1-w4 measure rollability. When a wheel passes through a wheel sensor, a pulse is generated to signal the computer. From the system clock, the computer times the car's passage, accurate to the millisecond, so that the variation of car velocities can be computed, which indicates the rollability. It is possible to use three wheel sensors instead of four.

5. There are two track circuits on each bowl track to estimate the distance to couple; one is between retarders III and IV, and one is from the retarder IV exit point to the end of the bowl track.

Outputs to fields of the system are to control retarder activity through retarder control units to ensure proper coupling speed. However, there are other units with which the PC computer should also communicate; a console is one. The console is actually an on-line terminal for yardmasters. Yardmasters have higher priority in controlling cars than the computer. They can take back the control power from the computer at any time, so that they can adopt emergency measures. A watchdog timer is employed to supervise the operation of the computer and to process input and output.

If a preceding car is located after retarder IV, retarder IV is basically responsible for the rolling-car control on the bowl track. In some cases, it might be necessary to let retarder III share in the control. If the preceding car is located between retarders III and IV, retarder III is responsible for the rolling-car control.

In order to provide acceptable reliability, many redundant-system schemes have been suggested and adopted. A complete duplicate redundant system is used in the Musashino classification yard in Japan. Two central processing units (CPUs), two input and output processors (PI/Os), and other double critical components run concurrently, but only one of the redundant components has outputs to field devices. There is test equipment in the system to detect failures, and there is also a large relay switching subsystem to switch outputs from the faulty component to the fault-free side.

Although a number of redundant-system schemes can be chosen to provide acceptable reliability, the decision has to be made according to a unified consideration of performance and expense. Three redundant-system schemes are discussed and compared in reports by Min and others (3,4). The results show that the proper redundancy scheme for the situation in China is that shown in Figure 2. Normally, the CPU communicates with the field devices through the PI/O and an interface with the user. If failures occur in the CPU or the PI/O or user interface, the warning system notifies the yardmaster to switch control to a semiautomatic control system, which basically is a hot standby system. If the semiautomatic control system also fails, the yardmaster is able to operate the retarders manually.

ROLLABILITY MEASUREMENT

An understanding of rollability (car rolling resistance) is critical in the design and operation of railway hump yards. Rollability is measured in two ways: off line or on line. Off-line measurement determines rollability of specific cars in specific environments. The data collected are used by engineers to design hump height and classification-track grades and to determine the placement, length, and capacity of retarders. On-line rollability measurement is needed in CYCCS as a real-time measurement for the purpose of automatic control (5). The importance of information on rollability is widely recognized, but the difficulty of rollability measurement has not been well appreciated. In this section, some rollability measurement techniques are discussed from the point of view of error analysis. Important aspects in gathering correct data for the use of yard design and CYCCS design are pointed out.

Basic Formula for Computing Rollability

The rollability of a cut of cars is usually determined by measuring the velocity of the cars at two points. The traditional formula is as follows:

$$R = [G - (V_2^2 - V_1^2)]/2\underline{g}\,L * 10^{-3} \qquad (1)$$

where

R = measured rollability (kg/ton),
G = grade (%),
V_1 = car speed at upstream point 1 (m/sec),
V_2 = car speed at downstream point 2 (m/sec),
L = distance from point 1 to point 2 (m), and
$\underline{g}$ = conversion acceleration of gravity (m/sec^2).

Each variable to be measured in Equation 1 is subject to an error called the absolute error, denoted ΔV_2, ΔV_1, $\Delta \underline{g}$, ΔL, and ΔG, respectively; thus, the rollability (R) to be computed must be subject to an error ΔR. The relative error δR is defined as $\Delta R/R$. Similarly, δV and δL are defined as $\Delta V/V$ and $\Delta L/L$, respectively. For simplicity of expression, $\Delta \underline{g}$ and ΔG are ignored and the approximate expression of δR is obtained by using the total differential formula. That is,

$$\delta(R - G) = (V_1^2 \delta V_1 - V_2^2 \delta V_2)/[\underline{g}\,L(R - G) * 10^{-3}] - \delta L \qquad (2)$$

Suppose that $\Delta V_2 = \Delta V_1 = \Delta V$ and $\delta L = 0$, $\underline{g} \doteq 10$. In the worst case, ΔV_1 might be positive and ΔV_2 might be negative, or vice versa. Hence,

$$|\Delta (R - G)| \leqslant 2V^2 \delta V/L * 10^{-2} \qquad (3)$$

Determining Rollability by Using Radar

One way to determine rollability is to use radar to measure the velocity of cars at two points as implemented in the Musashino CYCCS in Japan. Radar measures the velocity by sending out a beam of radio waves and receiving the reflection of those waves from the moving car by using the principle of Doppler frequency shift. Every 50 msec, the number

Figure 3. Determining rollability by using radar.

```
Radar ---> 8-bit Counter ---> CPU
               ↑
               |
         reset every 50 ms
```

Figure 4. Field situation.

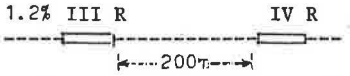


Figure 5. Determining rollability by using four wheel sensors.

```
    |<------- L ------>|
    |                  |
|<--d-->|          |<--d-->|
-X---+---X----------X---+---X--
 w1  1   w2         w3  2   w4
```

Figure 6. Determining rollability by using three wheel sensors.

```
  |    t1   |   t2    |
  |         |         |
  |<-- L -->|<-- L -->|
--X----+----X----+----X--
  w1   1    w2   2    w3
```

of Doppler pulses is sent to the CPU through an 8-bit counter, as shown in Figure 3. The CPU resets the counter every 50 msec. Some typical data are as follows: There are 70 pulses/sec for a car speed of 1 m/sec. Suppose that the rollability is measured at a car speed of about 3 m/sec, i.e., 210 pulses/sec, which is equal to 10 pulses/50 msec. Unavoidably the error of the counter is ±1 pulse. Hence, the relative error of V is $\delta V = 1/10$. The rollability is measured on a track with a grade of 1.2 percent between the tangent retarder III R and the track retarder IV R (L = 200 m), as shown in Figure 4. From Equation 3 the following equation may be obtained:

$$\Delta R = V^2 \delta V \qquad (4)$$

If the preceding values are substituted into Equation 4, the result is $\Delta R = 0.9$ kg/ton, which is much larger than desired.

Determining Rollability by Using Four Wheel Sensors

Determining rollability by using four wheel sensors is quite common and has been done for a long time. Much confidence is placed in the data collected by this methodology. Nevertheless, it is not necessarily accurate if some important factors are not carefully taken into account. The placement of wheel sensors is shown in Figure 5. If t_1 and t_2 represent the length of time that it takes cars to pass through [w1,w2] and [w3,w4], respectively, speeds V_1 and V_2 are obtained by $V_1 = d/t_1$ and $V_2 = d/t_2$, where d is the distance between w1 and w2 or w3 and w4. The relative error in the speed is $\delta V = \delta d - \delta t$. Then

$$|\delta V| \leqslant |\delta d| + |\delta t| \qquad (5)$$

Suppose that G = 0, d = 5 m, L = 50 m, Δd = 1 cm, Δt = 6.8 msec, and $v \doteq 4$ m/sec. Thus, $t \doteq 1200$ msec, $\delta t = \Delta t/t = 0.0056$, $\delta d = \Delta d/d = 0.002$, and from Equation 5 $|\delta V| \leq 0.0076$. From Equation 3

$$\Delta R = 4V^2 \delta V \qquad (6)$$

If the preceding values are substituted into Equation 6, the result is $|\Delta R| \leq 0.49$ (kg/ton). But in practice, the situation may be even worse than this.

Determining Rollability by Using Three Wheel Sensors

A revised approach to measuring rollability is to use three wheel sensors instead of four (6,7). This approach computes rollability by using the following equation:

$$R = [G - (2L/g)(t_1 - t_2)]/[t_1 t_2 (t_1 + t_2) * 10^{-3}] \qquad (7)$$

where

L = distance from w1 to w2 or from w2 to w3 (m),
t_1 = passage time from w1 to w2 (sec), and
t_2 = passage time from w2 to w3 (sec).

The other terms are as defined for Equation 1. These parameters are shown in Figure 6. Compare these parameters with Equation 1 and note that $V_1 = L/t_1$, $v_2 = L/t_2$, and $(V_1 + V_2)/2 = 2L/(t_1 + t_2)$. Substituting them into Equation 7 produces

$$\begin{aligned} R &= G - (2L/g)\,[(V_2 + V_1)/2]\,[(V_2 - V_1)/L]\,(1/2L * 10^{-3}) \\ &= [G - (V_2^2 - V_1^2)]/2g\,L * 10^{-3} \end{aligned}$$

which is exactly the same as Equation 1. Therefore, Equation 3 also holds for this approach. In the Sotteville Yard, G = 0 and L = 10 m. From Equation 3

$$\Delta R = 20V^2 \delta V \qquad (8)$$

Suppose that $V \doteq 4$ m/sec and $\Delta L = 0$; then from Equation 5, $\delta V = \delta t$, and thus $\Delta R = 320\delta t$.

In order to reach an accuracy of $\Delta R = 0.1$ kg/ton, $\delta t \leq 0.031$ percent is required; i.e., $\Delta t \leq 0.78$ msec. It is difficult to achieve such accuracy in passage-time measurement in classification yard environments. This problem will be discussed in the next section.

Error in Passage Time

In order to obtain an R of acceptable accuracy, it is critical to decrease errors in the time it takes cars to pass through pairs of wheel sensors. Passage time is measured as shown in Figure 7. An external clock sends pulses of high enough frequency to the counter. After wheel sensor pulses w1 and w2 have been shaped, shaped pulses p1 and p2 are obtained. Counting starts at p1 and stops at p2. The number of pulses counted corresponds to the passage time from w1 to w2. Much attention has been given to the clock frequency for improving the accuracy of the passage time (t). The clock frequency was even taken to be as high as 1 or 10 MHz. Unfortunately, this is not in the focus of the problem.

As is known, a wheel sensor sets up a magnetic field in a section of rail. When a wheel passes, it changes the field, including a current in a nearby coil, which produces a wheel sensor pulse that is sent to a shaper. Figure 8 shows the wheel sensor pulses (w1 and w2) and the shaped pulses. Shaped pulses p1 or p2 correspond to large wheel sensor pulses, and shaped pulses p1' or p2' correspond to small wheel sensor pulses. Wheel sensor pulse heights are different because of the physical in-

Figure 7. Measuring passage time.

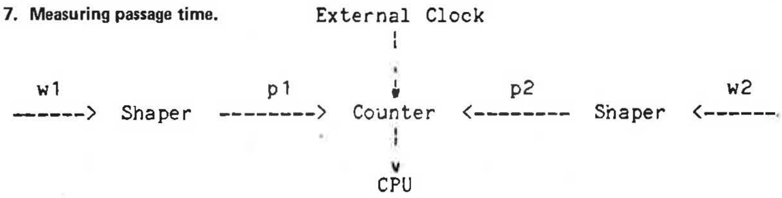
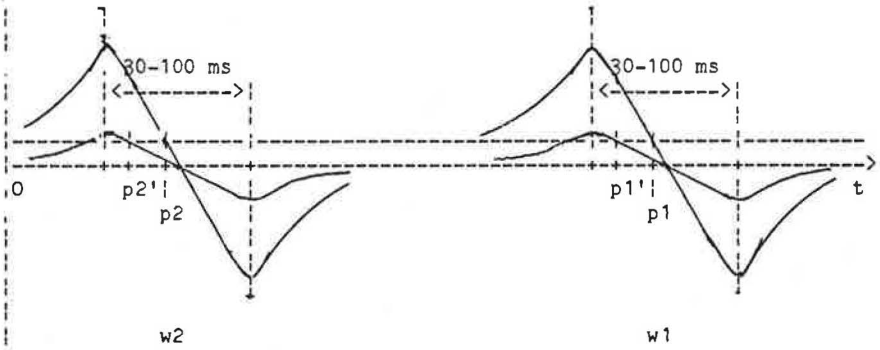


Figure 8. Wheel sensor pulses.



stallation positions and features of the wheel sensors. Experiments show that the difference can be so large that the height of a large pulse can be three to four times that of a small one. If w1 and w2 are large, the passage time (p1, p2) is obtained; if w1 and w2 are small, the passage time (p1', p2'), which has almost the same length as (p1, p2), is obtained. But if w1 is large and w2 is small, the passage time (p1, p2') is obtained, resulting in an error $\Delta t = p2 - p2'$. If w1 is small and w2 is large, the time error $\Delta t = p1' - p1$, which is negative. Analysis indicates that $\Delta t = 6.8$ msec is common. This is the main reason for errors in rollability measurement. Therefore, the problem is how to make shaped pulses p1 and p2 correspond to fixed physical positions on the track. To solve this problem a zero cross-switch circuit instead of a magnitude-discriminator circuit is applied to get the shaped pulses at the moment the wheel sensor pulses go through zero. But the zero cross-switch circuit should be carefully designed to suppress noise (8, pp. 145-150).

For on-line rollability measurement, the same problem exists. In addition, if the CPU receives shaped wheel sensor pulses by an interrupt mode, the interrupt waiting time and response time have to be considered. No more than 3 to 5 msec of interruption-masked time of the CPU is allowed. This is an additional requirement for CYCCS software and the RTOS. Unfortunately, this requirement is not generally satisfied and efforts to achieve it have to be made in the software. In a CYCCS in China, after hardware and software had been carefully designed and coordinated, the rollabilities of the same car measured by its four pairs of wheels were only approximate. The difference among them was about 0.1 kg/ton, which was the error in rollability measurement [see paper by Min (5)].

Remarks on Rollability Measurement

The preceding analysis allows us to suspect the precision of existing data on car rollability because of unreliable measurement techniques. The data were employed to come to many conclusions that did not agree with practice. For instance, the range of rollability variety was said to be 0.5 to 5 kg/ton, even 10 kg/ton, which would mean a hump height of 5 m or so. Too high a hump causes problems and waste. Actually the range of rollability variety is not so large as the preceding estimate. Many cars continue to run at a speed of 3 to 5 m/sec until the ends of bowl tracks if no control is taken. It was occasionally found that some cars run freely down the hump and stop at a point about 100 m from the tangent retarders. This, however, is often due to improper positioning of car bleed brakes or other trouble with the cars. Therefore, this is a yard operation problem and should be solved by the servicing crew. It should not be taken into account in designs of hump height and CYCCS.

By applying Equation 3, some ways can be found to improve the accuracy in rollability measurement as discussed previously. On the other hand, the obtainable accuracy is limited because of the randomness in the car speed-decreasing rate. However, it is not necessary to pursue excessive accuracy of rollability for the purpose of yard control and design.

MATHEMATICAL MODEL FOR CONTROL

As mentioned earlier, suppose that a preceding car is located after IV R, and a rolling car is approaching. Before the rolling car enters a IV R, the CYCCS has to compute a correct exit speed from the retarder IV R according to the measured and given parameters, such as rollability, distance to couple, and so on. This is why a mathematical model for control is needed.

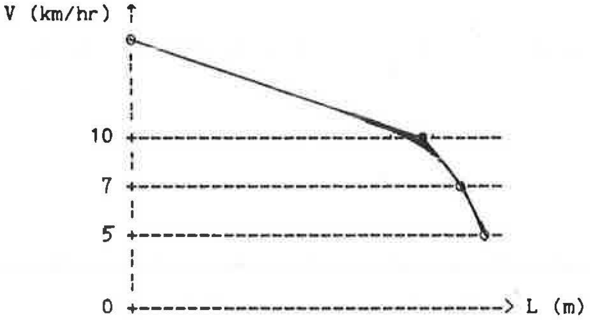
At the beginning of the research, the motion of a freight car rolling down a grade was analyzed and described by the concepts of classical mechanics. The exit speed from a retarder is calculated by the following equation:

$$V_e^2 = V_c^2 + 2\underline{g}L(R - G) * 10^{-3} \qquad (9)$$

where

V_e = exit speed from the retarder (m/sec),
V_c = allowed coupling speed (m/sec),
$\underline{g}$ = conversion acceleration of gravity (m/sec^2),
L = distance to couple (m),

Figure 9. V-L curves.



R = rollability (kg/ton), and
G = grade (%).

Experiments show that V_e computed by Equation 9 in general is too large, which means that when a rolling car leaves the retarder at speed V_e, it will couple with the preceding car at a speed higher than V_C. On the other hand, theoretical analysis indicates that Equation 9 is equivalent to the proposition that R is a constant. Hence, as has been widely noted recently, R is not a constant. A strong relationship exists between rollability and velocity of rolling cars. In order to find the relationship, a series of field experiments was performed. In some 800-m-long bowl tracks, many wheel sensors were installed to measure velocity of rolling cars at many different points. Many velocity-distance curves were then obtained. The shape of these curves is shown in Figure 9, where L = 0 corresponds to the exit point of tangent retarder III R.

A piecewise-linear function is a good approximation of the V-L curves. It can be separated into the following components:

1. When V > 10 km/hr (for a free-rolling car, V cannot be higher than about 25 km/hr), the curve is close to a straight line with slope a. Therefore we have

$$\delta V/dL = a = \text{constant} \tag{10}$$

The acceleration of cars (A) is

$$A = dV/dt = (dV/dL) * (dL/dt) = aV$$

On the other hand, the following formula can be found in a report by Wong and others (7):

$$R = G - (A/g) \tag{11}$$

Hence, we have

$$R = G - (a/g)V \tag{12}$$

which reveals the relationship between R and V. Note that slope a is usually negative, so R increases with V. Also note that slope a has its physical meaning, that is, the decrease of velocity in distance passed of unit length. Parameter a plays an important role in this mathematical model and is called the speed-decreasing rate.

2. When 7 km/hr < V $\leq$ 10 km/hr, the V-L curve is close to a straight line with slope k_1a. Experience shows that k_1 = 1.3.

3. When 5 km/hr < V $\leq$ 7 km/hr, the V-L curve can be approximated by a straight line with slope k_2a, where k_2 = 2. But the lower the car speed, the greater the randomness in the speed-decreasing rate (a).

4. When V $\leq$ 5 km/hr, the randomness in the speed-decreasing rate (a) is dominant. How far a rolling car can go is uncertain when its speed is less than 5 km/hr.

Based on the V-L curves, the ideal exit speed from a retarder can be determined as follows:

$$V_e = \begin{cases} 1.11 + 2aL & \text{when } L \leqslant (0.83/2a) \\ 1.94 + 1.3a\,[L - (0.83/2a)] & \text{when } 0.83/2a < L \leqslant 0.84/1.3a \\ 2.78 + a\,[L - (0.83/2a) - (0.84/1.3a)] & \text{when } L > (0.83/2a) \\ & \quad + (0.84/1.3a) \end{cases} \tag{13}$$

Note that 1.11 m/sec $\doteq$ 4 km/hr, 1.94 m/sec $\doteq$ 7 km/hr, 2.78 m/sec $\doteq$ 10 km/hr, and V_C = 4 km/hr.

For example, suppose that the preceding car is located some 400 m after the exit from a retarder; i.e., L = 400 m. The grade of the bowl track is zero. Before the retarder, the speed-decreasing rate has been measured as 0.5 km/hr per 100 m; i.e., a = 1.39 * 10^{-3} (m/sec)/m. According to Equation 10 and with 0.83/2a = 0.299 * 10^{-3} = 29.9 m and 0.84/1.3a = 0.469 * 10^{-3} = 46.9 m,

$$\begin{aligned} V_e &= 2.78 + 1.39 * 10^{-3}\,(400 - 29.9 - 46.9) = 3.23 \text{ (m/sec)} \\ &= 11.6 \text{ (km/hr)} \end{aligned} \tag{c}$$

The uncertainty in rolling-car rollability becomes evident when the car speed decreases. Therefore, correction factors k_1 and k_2 should be modified in different situations.

REMARKS AND CONCLUSIONS

The railway classification yard is considered the bottleneck in railway operations. CYCCS has significant benefits. Now that some work has been done on CYCCS, the problem of controllability has been posed. If the coupling rate is regarded as the ratio between coupling time at the allowed coupling speed and the total number of couplings, it appears difficult to realize the requirement of a 100 percent coupling rate. Even though it is possible to reach such a rate, the CYCCS would be prohibitively expensive. Cost and performance should be balanced. The cost increases exponentially with the coupling rate, especially when the coupling rate is higher than 90 percent.

A target-shooting control-system scheme for the CYCCS is presented in this paper. There are two fundamental problems in the system--one is rollability measurement and the other is a mathematical model. For rollability measurement, the accuracy of some existing rollability data is suspect. In this paper the primary error sources are analyzed and approaches to improving the accuracy are given. As a result, the error in rollability measurement has been found to be 0.1 kg/ton. In this paper a piecewise-linear mathematical model based on many V-L curves obtained from a series of experiments is proposed. Experiments showed that a coupling rate of 90 percent can be achieved with a CYCCS.

ACKNOWLEDGMENT

We would like to thank Edward J. McCluskey, director of the Center of Reliable Computing, for his advice and support during the preparation of this paper. We would also like to thank Peter J. Wong, Robert L. Kiang, and William A. Stock of SRI International for their proofreading of early drafts.

We wish to extend our deep appreciation to Shouheng Li and other participating members of the Classification Yard Automation Laboratory, Signalling and Communication Institute, China Academy of

Railway Sciences, for their contributions to this project.

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Effect of Measurement Errors on Car Rollability Distribution in a Yard

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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:

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

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:

$$R = G - (1/2gL)(V_b^2 - V_a^2) \tag{2}$$

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:

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

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:

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

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

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

$$t_b \approx (J_4 - J_3)/g(G - R) \tag{5}$$

where

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

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:

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

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

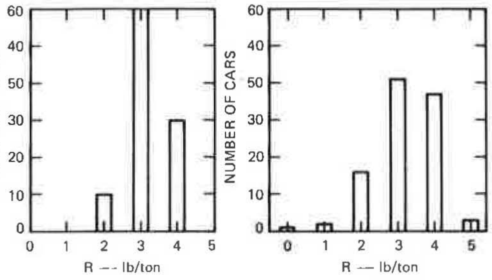
$$\Delta R = m - nR \tag{8}$$

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.



(a) TRUE R HISTOGRAM (b) APPARENT R 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.

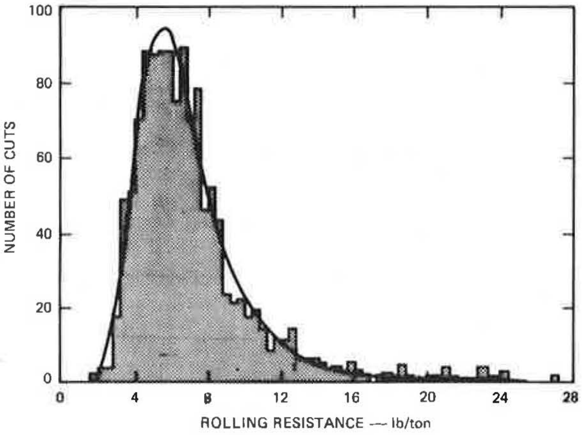


Figure 3. Measured rolling-resistance distribution.

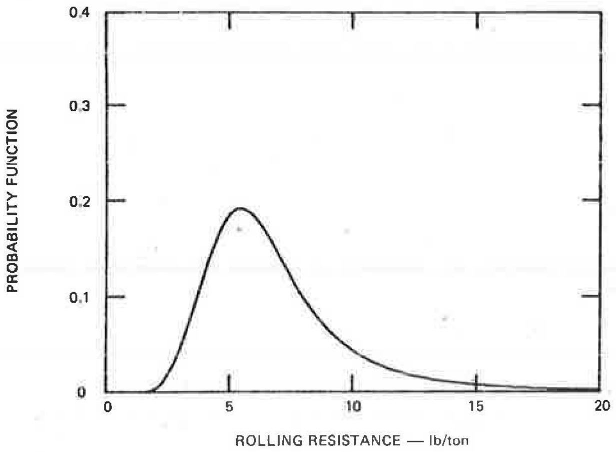
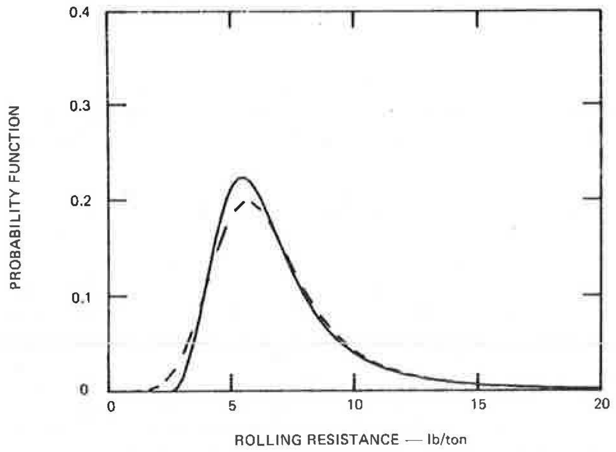


Figure 4. True (solid curve) versus apparent (dashed curve) distribution: $\Delta \ell = 0.4$ ft.



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:

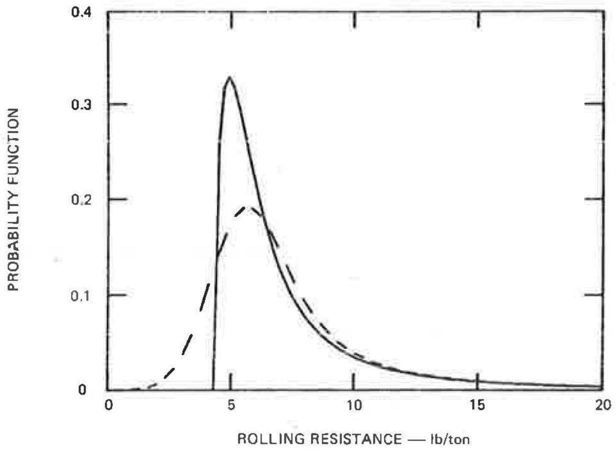
$$f_e(|R'-R|) = [1/\sigma(2\pi)^{1/2}] \exp\left\{-\tfrac{1}{2}[(R'-R)/\sigma]^2\right\} \quad (14)$$

with

$$\sigma = m - nR \quad (15)$$

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

I am indebted to Phillip R. Jeuck III for his programming help in obtaining the numerical solutions of the convolution integral. Private discussions with William Stock are greatly appreciated.

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Semiautomatic Operation for Upgrading Intermediate-Sized Hump Yards

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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 displayed for cut 2, he must push the CUT CANCEL button three times, cancelling in turn cuts 4, 3, and 2. He then reenters the numbers, beginning with cut 2. As each cut enters the master retarder, its number is dropped from the CUT 1 display and all following cuts advance one position, allowing a new number to be entered for cut 4. Any numbers entered while all cut displays are filled will be disregarded.

As a cut enters the master retarder, its destination track in the CUT 1 display can no longer be changed, and all switches leading from the crest to the destination track are positioned, unless any of the required switches are awaiting an earlier cut. Progress of the cut is tracked by the computer by using both retarder-wheel detectors and switch-presence detectors (PDs). The computer always attempts to position as many switches as possible ahead of each cut without affecting earlier cuts. If a switch fails to achieve the requested position within approximately 0.9 sec after the request, it will be restored to its previous position (unless its PD has been occupied), and a switch-failure alarm will be issued.

MANUAL SWITCH OPERATION

On the console there is a control level for each switch with three rotary positions: left, right, and automatic. In the automatic position, the switch is controlled by the computer as described previously. In the left or right position, the computer will not attempt to control the switch but still monitors its position. In the left or right position, the switch will remain in the requested position and the position will be displayed continuously by the appropriate white light on the console and the test panel. Cuts can be routed automatically through a switch in manual mode as long as a change of position is not required. If a destination-track number is entered for a track and it cannot be reached because of a switch manually positioned for other than the required route, the track number will not be accepted, and a ROUTE BLOCKED alarm will be issued. If a track is to be protected or "blue flagged," the switch-control lever is placed in the protecting manual position and pulled up; a blocking collar is slipped under the knob to hold it in the up position. This provides the additional protection of opening the circuit to the control relays and lighting the blue light alongside the switch on the control panel to indicate that the switch is blocked. Automatic operation makes no distinction between a blocked switch and one that is simply in manual operation; it cannot control it in either case. As in automatic operation, if a switch fails to achieve the requested position within approximately 0.9 sec after the request, it will return to its previous position.

Pushing of the TRIM button deactivates data input from the keyboard and weigh-rail PD to prevent default track selection by the automatic routing when manual switching is used. The TRIM pushbutton is lighted to indicate that the system is in the trim mode. Routes stored in the computer before the trim mode is selected are unaffected and continue to be processed by the computer. Manual route selection can be performed by manual operation of the switches in each selected route. The trim mode is cancelled by pushing the lighted TRIM button.

SPEED CONTROL

The speed-control portion of the system begins with a weight measurement on each cut. The weight of each cut being humped is classified on a weigh rail installed just below the crest of the hump. The weigh rail uses microswitches to transfer contacts based on rail-head deflection. Weight categories represented by the contacts are light, medium, heavy, and extra heavy. Actual weights applying to each category are adjustable within limits at the time of installation. Because rail-head deflection occurs only when a wheel is centered over the deflection point, a separate reading is made for each wheel. These momentary outputs from the microswitches are stored during the time that the PD at the weigh rail is occupied. The measurement is progressive in that the greatest weight recorded for any one wheel during passage of a cut is stored and used as the weight for that cut. Cut weight and track circuit occupancy are indicated in lights on the console and on the test panel while the weighing takes place. The finally determined weight is delivered to the computer for transfer to the retarders when the PD becomes vacant. If for any reason no weight is obtained, the system will default to the category of heavy.

Actual speed of each cut as it moves through each retarder is measured by the Doppler radar unit. The radar antenna is enclosed in a heavy sheet-metal housing with a nonmetallic front panel. The antenna assembly is mounted on a foundation consisting of two rectangles made up of galvanized steel angle stock. Light-duty bolts are used to mount the antenna to provide break-away protection in the event that an antenna is struck by dragging equipment. The antenna unit is mounted approximately 15 ft upstream from the top of the retarder and just outside the ends of the ties. A light cable from each antenna unit will terminate in a bootleg junction box adjacent to the antenna, which is also mounted with the break-away principle.

A card cage in the control bungalow contains a logic card for each antenna unit. A rack-mounted power supply provides the power for the radar. Inputs to the logic card are the audio signal from the antenna, with frequency proportional to measured speed; track occupancy taken from the wheel detectors in each retarder; and requested speed from the computer. Outputs from the logic card are analog voltages to drive meters on the test panel that indicate actual speed, target speed, and deviation from target speed as well as contact closures that represent radio-frequency (RF) failure (to operate warning lights on both the console and the test panel), close retarder (when speed is above target), and open retarder (when speed is at or below target). Each of these outputs will be displayed in lights on both the console and the test panel. These contact closures drive relays in a network that also uses weight data from the computer and provides for manual override from the console. In automatic operation, the selection of which pressure to apply to the retarder is based on weight, and the decision to close or open is based on radar output. The resting position of all retarders in this mode is the weight category of heavy. For the master and intermediate retarders, target speed input to the logic card is an analog voltage from a speed-selection potentiometer. For all group retarders, a 6-bit digital signal is supplied from the computer.

To assure that the retarder units are only operating when a car is in the retarder, a wheel-detector count-in, count-out scheme is used in each retarder. Some types of retarders could be used with track circuits, but the wheel-detector approach is adaptable to any retarder. Wheel detectors are bolted to the base of the rail, one at the upper end and one at the lower end of each retarder. A separate count is maintained for each retarder; all counting is done in a microprocessor control unit.

Each time the upper detector is actuated, the count is increased by 1. Each time the lower detector is actuated, the count is decreased by 1. Any count greater than zero is interpreted as an occupied retarder. A count of less than zero, for whatever reason, is ignored. When occupancy is detected in this way, the counter control unit drives a relay the contacts of which key on the radar antenna, operate lights on the console and the test panel, and notify the computer when the retarder is occupied by a car so that the proper weight and speed information may be obtained. The computer relays the appropriate weight information continuously as long as the occupancy is indicated. A time-out feature is used to recover from the possibility of a miscount on one of the wheel detectors.

Exit speed from the master and intermediate retarders is selected by rotary potentiometers for each retarder on the operator's console and is the same for all cuts regardless of their destination. Markings on the panel, along with a pointer on the speed-select knob, indicate the approximate speed chosen within the range of 5 to 12 mph. Exit speeds from the group retarders will vary with destination track, and the operator will assign a specific retarder exit speed to each of the classification yard tracks. Once assigned, the exit speed will apply to all cuts destined for that track until changed by the operator. A small cathode-ray tube (CRT) is provided to continuously display a list of all destination tracks in the yard and the exit speeds assigned to each track. This is a ready reference for the operator that allows him to easily check the current speed assignments at any time.

To change a speed assignment or enter a new one, the operator pushes the SPEED-SELECT button. This takes the system out of the track-select or default-select mode, whichever it was in previously. While the system is in the speed-select mode, the SPEED SELECT pushbutton is lighted. In the speed-select mode, the operator uses his number keyboard on the console to select track numbers and make the speed assignments. For each speed entry, he must first enter the two-digit track number in the same manner as for track selection; leading zeros are required for tracks 0 through 9. If an invalid track number is entered, an invalid-track alarm will be issued. If the two digits entered represent a valid track number, the system will then accept the next two digits entered as the new exit speed for that track, in integral miles per hour. Speeds under 10 mph must be entered with leading zeros in the same way as the single-digit track numbers. As the new speed is entered, it will replace the previously stored speed, if any, both in the computer storage and on the CRT display. Speeds selected must be within a permissible range that is set from the terminal device adjacent to the computer, inaccessible to the operator. The range of permissible speeds would typically be 3 to 12 mph. If speeds are being entered for more than one track, the operator will continue to use the number keyboard; after a speed has been entered, the next two digits represent the next track number, followed by two digits for its speed assignment, and so on until all speed assignments have been made. When speed assignments are complete, the operator returns to either the default-select or the track-select mode by using the appropriate pushbutton. Any track for which no exit speed has been assigned will use a default speed of 6 mph. Default speed may also be changed from the computer maintenance terminal. In place of making rolling-resistance measurements, a speed offset of 0.6 mph for medium-weight cars and 1.2 mph for lightweight cars is automatically added to the selected track speeds to compensate for the inherent poorer rollability of the lighter-weight cars. Changing of speed offset for lighter-weight cars is done from the computer maintenance terminal. An additional offset is provided via the summer/winter switch, which adds a fixed speed differential in the winter position only.

The console is equipped with a linear-motion lever for each independent retarder section. Most retarders have independent upper and lower sections. Because there is only one radar per retarder, both sections operate together in automatic, but either section can be taken out of automatic and operated manually, independent of the other section. The retarder levers have five positions: open, light, medium, heavy, and automatic. A pushbutton is provided adjacent to each pair of levers, which may be used when either lever of the pair is in the heavy position to increase the pressure to extra heavy (XH). The XH pressure will be applied only as long as the XH button is held down. When it is released, the pressure will revert to heavy.

Because of the relatively short distance from the weigh rail to the master retarder and because weight information on each cut must be determined before the lead wheel reaches the master retarder, weight is generally based on measurement of the first two trucks of a cut. On longer cuts, the weight of the first car is generally used as the weight of the cut, and retardation pressure will be applied accordingly. For this reason, multiple-car cuts of mixed weights may require manual retardation control.

Additional functions provided on the operator's console are various operational alarms, a hump signal stop control, indications of actual hump signal aspect, control of the warning siren, a dimmer control for the console indication lamp, a switch-status control that causes the positions of all switches to be displayed on the console, and an indicator showing when the test panel is operating in either the monitor or the control mode.

The test panel, located in the remote bungalow or equipment room, presents a track diagram of the hump area containing various controls and indicators. These include switches for simulating occupancy of all track circuits, PDs, and wheel detectors; indications of switch positions, retarder positions, track circuit and PD occupancy, and hump signal aspects; and speed meters indicating actual speed, target speed, and variance from target speed with a selector switch allowing the meter set to be used on any selected radar unit. Also on the test panel are a set of data entry pushbuttons allowing the entry of destination tracks for test purposes and a set of lighted pushbuttons duplicating the alarm indications presented on the operator's console. A keylock switch on the test panel selects one of three modes for the test panel. These are the off mode; the monitor mode, in which all indications are presented on the test panel but control and simulation inputs are disabled; and the control mode, in which control is taken away from the operator console and transferred to the test panel. Indications and alarms are presented on the operator's console at all times, regardless of the status of the test panel.

ALARMS

An assortment of different alarms is provided. In each case the alarm is indicated by flashing a lighted pushbutton bearing a legend to identify the alarm and requiring the operator to push the button to acknowledge the alarm. Where a function needs further identification, such as a switch number or track number, this number will appear in a digital display in the alarm window.

The alarm for invalid track entry is produced when the operator inputs a two-digit number for either a destination-track or default-track assignment that is not an existing track number accessible to the automatic switching. When an invalid number is detected, the INVALID TRACK light goes on, the invalid number is posted in the alarm display window, and a single-stroke bell is sounded. The INVALID TRACK light and track-number display will remain on until acknowledged.

The switch-fail alarm is generated when a switch in automatic mode fails to achieve the requested position within approximately 0.9 sec. With this alarm the SWITCH FAIL light goes on, the number of the failed switch is displayed in the alarm window, and the single-stroke bell is sounded. The light and number display will remain on until acknowledged.

The route-blocked alarm is generated when the operator enters a destination track that cannot be reached because one or more switches in the route to that track are in the manual mode, positioned for other than the required route. The alarm consists of the ROUTE BLOCKED light, display of the requested track number in the alarm window, and the single-stroke bell. The light and number display will remain on until acknowledged.

The power-off alarm responds to contacts on a power-off relay provided by the railroad and contacts of two power-off relays in the control bungalow. The power-off indication will be a steady light that uses battery energy.

The radar-fail alarm is generated when the antenna of one of the radar units is not transmitting properly. The alarm consists of a flashing RADAR FAIL light, the single-stroke bell, and the red warning light adjacent to the appropriate retarder on the console and test panel track diagrams. The operator is required to acknowledge by pressing the RADAR FAIL light. The light on the track diagram will remain on as long as the condition exists.

The overspeed alarm is generated when a cut passes through a retarder without having been brought down to the desired exit speed. If at any time during retardation the cut reaches the desired speed and the retarder is opened, the alarm is preempted for that cut. The alarm consists of a flashing OVERSPEED light, a flashing red warning light adjacent to the retarder involved on the operator's console and test panel track diagrams, and the single-stroke bell. The lights will go out when the operator acknowledges the alarm with the OVERSPEED button. The alarm is operative only when the retarder control lever is in the automatic position.

Any alarm described in the preceding list may be logged in coded form on the maintenance terminal adjacent to the computer for reference by maintenance people.

OPTIONS

Several enhancements are available as options to this system that are not part of the existing installations. One of these is an automatic speed compensation for track fullness. The operator assigns a clear-track speed for each track, which applies to the first cuts entering when the track is empty. The system then counts the number of cuts it switches into each track and reduces the entrance speed automatically as the number of cars increases. A typical value of compensation might be 1 mph for each eight cars, but this would be selectable individually for each track. The operator has the ability to override the calculated speed with a manually entered speed at any time, and future reductions for fullness will then start from the manually entered value. When a track has been pulled clear, the operator reports this information and the speed automatically reverts to clear-track speed.

Another available option is direct entry of switch lists from a host computer rather than manual entry as defined earlier. In this configuration the system can store up to 30 trains of 200 cars each, with a car initial and number and a classification code for each car. Lists may be called up for editing on a CRT before humping. During humping the system permits operator corrections to add a car, delete a car, or reverse the order of a block of cars. It also provides for track swings as needed. When a given list is complete, the operator is asked to make any corrections for cars that did not go as intended, and the as-switched information is then added to a classification yard inventory. This inventory is subject to manual adjustments as necessary to account for errors or trimming. When classification tracks are pulled to make up outbound trains, the appropriate inventories are then combined into an outbound file for transmission back to the host computer.

New technology and the elimination of many high-level refinements makes it possible to install a system such as this in a moderate-sized yard for a fraction of the cost of a fully automatic system. It is unsuitable for a major terminal handling 3,000 cars a day, but there are many yards that could benefit from this straightforward, no-frills concept.

A Computer for Your Old Hump Yard?

JOSEPH A. RICE

In 1977 Southern Railway decided to replace an old and hard-to-maintain hump control computer with a new control computer system. The new system was developed entirely by Southern Railway employees. Functions of the new system exceeded those of the old, allowing Southern to eliminate two 24-hr positions. System installation was done in phases at Brosnan Yard, Macon, Georgia; the final phase was completed in September 1980.

In late 1976 Southern Railway was faced with the necessity of replacing an old computer system used for master-retarder control at Brosnan Yard, Macon, Georgia. This computer system had been installed in 1966 as a complete retarder-control system but had been only marginally successful because of multiple tuning difficulties.

The system design required a hump conductor at the hump crest; a scale clerk to produce weigh tickets on the 5 percent of traffic that needed weighing; and a car retarder operator for overriding computer control, making trim moves with the hump engines, and blocking tracks.

Brosnan Yard was handling as many as 3,000 cars per day over its single hump. Management had information that damage claims were high on traffic passing through this yard. The decision to replace the old computer system with newer equipment programmed by Southern Railway employees was reached in the late spring of 1977.

PREPROJECT HISTORY

In 1965-1966 Southern Railway built a new hump yard at Macon, Georgia, on the site of an old flat yard and a swamp. Into this yard went one of the first modern minicomputers, a Digital Equipment PDP-8. The PDP-8 and its input-output hardware were used for controlling both master and group retarders; both system design and implementation were provided by General Railway Signal Company (GRS).

Although the system controlled all required equipment, coupling speeds remained erratic throughout the life of the PDP-8 system except during concentrated tuning efforts. Furthermore, group retarder control in full manual by the car retarder operators was the rule, not the exception, from 1973 on.

Meanwhile, in 1973 Southern had built another hump yard at Sheffield, Alabama, also using a GRS control system, Data General computers, and an information link to the first prototype of Southern's Terminal Information Processing System (TIPS). No scale clerk or car retarder operator was required at Sheffield. The yard was considered the most modern in North America at the time and was an unqualified success.

Therefore, when Digital Equipment informed Southern in 1976 that they could no longer maintain the Brosnan PDP-8 after mid-1978, Southern management was inclined toward replacing the PDP-8 with Data General computers and linking these computers to the TIPS already installed at Brosnan Yard. In addition management decided that in-house development would be desirable; that work was assigned to the Management Information Services (MIS) Department.

COMMITTEE APPROACH

The control of the computer replacement project proceeded through a number of committees. At the top of this structure was the Committee on Computer Usage (CCU). The CCU was a permanent part of Southern Railway structure that determined all major applications of computer technology for the railroad. The CCU was made up of all company vice presidents and those above them. Below the CCU was a group from middle management called Management Information Services--Rail Operations (MIS-OP). The job of MIS-OP was to coordinate efforts of MIS and operations on joint activities. Because MIS would be developing the system for Brosnan Yard, the project was subject to MIS-OP review.

Initially a programming group was assigned to evaluate the project's needs in terms of hardware, software, and development time. The results of this evaluation were a hardware-software plan, a performance specification, and a phased implementation schedule.

Because the system would have to be placed in service in the yard while the yard handled normal traffic, a temporary committee of middle and lower-level management was established to oversee the system installation. This technical monitoring committee was composed of members from Transportation; Communications and Signals (C&S); MIS; Maintenance of Way; and Freight Claims Services. This group was responsible for resolving interdepartmental conflicts and for deciding on solutions to various problems that appeared in the original plan. It was from this committee that the implementing team took its direction.

IMPLEMENTING TEAM

Working under the technical monitoring committee was the actual implementing team. The only full-time employees assigned to this work were from MIS: three programmers and one programming manager. Part-time members were one C&S operations specialist, two C&S supervisors, one superintendent of terminals, and one track supervisor.

Because the programming manager was the senior full-time person on the project, he became the de facto project leader. But because the technical committee was in place, only relatively minor tactical decisions were made without committee direction.

The amount of time spent on the project by the programming team was December 1977 through September 1980. A major interruption occurred between March 1979 and October 1979 as the team was shifted to Linwood, North Carolina, to assist GRS in installing another new hump yard at that location. Of the original group of four, only two remained on the project for the full duration. Of the other two jobs, one turned over twice during the project.

A total of nine programmer years was spent through the final phase of installation in September 1980. The total becomes 12 years if the programming manager's time is included.

An interesting aside on the programming team: No more than two who had technical educations were ever assigned at one time. No one assigned had an engineering degree.

PHASES OF THE PROJECT

The project as a single task was clearly beyond the ability of a relatively inexperienced programming team. This was particularly so because of a July 1, 1978, cutoff of maintenance on the PDP-8. Considering this situation, the only reasonable alternative was to phase in the replacement computer.

Four major project phases were defined. In the first, the control of the PDP-8 was paralleled on the master retarder only. In the second, the master retarder was controlled and the car retarder operators were provided with a cathode-ray tube (CRT) display of information needed to manually retard cars in the groups. At the end of this second phase, independence of the PDP-8 had been accomplished. Third, actual control of the group retarders was taken over. Fourth and most important, lists from TIPS including tracking of cars to destination and automatic weighing of weigh cars were processed. With completion of the fourth phase the positions of scale clerk and car retarder operator were eliminated.

The first three phases constituted the job that had been originally defined for the PDP-8. An important requirement in the third phase was to minimize the amount of tuning done by local yard personnel. This was accomplished by using a high-level programming language (FORTRAN) and by introducing the concept of multiple yard factors sensitive to weather changes rather than a completely different set of values by temperature class.

The fourth phase presented major opportunities because the original equipment design did not anticipate any list capability. Furthermore, only a limited budget was available to upgrade field hardware for this purpose. Cost-effectiveness dictated the budget limitations.

Phase 1 was completed in April 1978. Phase 2 was completed in July 1978, 18 days after the maintenance contract on PDP-8 had expired. Phase 3 was completed in January 1979 just before the need to devote full time to the new Linwood, North Carolina, yard project. Finally, on the day after Labor Day 1980 the fourth phase was completed.

A major project-extending factor between phases 3 and 4 was the decision to replace the first Data General computers (Nova 840s that had been recycled from an early TIPS development) for development of phase 4. The Nova computers were replaced by the then-latest Data General computers (Eclipse S/130s), which incidentally provided additional mutual on-site parts backup with TIPS.

Through all phases of the project much time was spent in the hurry-up-and-wait mode. Especially in phases 3 and 4, test set-up time and test type (tests that used revenue traffic) caused potential conflicts with yard operation. Careful coordination with the local Transportation Department was required to do adequate testing without affecting yard service. Essentially this meant that test time was minimal, project development was slowed, and expenses of the implementing team were high.

MAJOR ACCOMPLISHMENTS OF THE SYSTEM

The three major accomplishments of the system were as follows:

1. Introducing a new computer to an old yard, including an old computer's inputs and outputs, retarders, grades, and basic yard layout. By not having to lay in cable and new field hardware devices (like wheel detectors) major costs were avoided. Adapting some of the old interfacing gear minimized the new engineering effort required, thus saving money and simplifying parts of the system.
2. Providing a new system that was easier to maintain and one that more consistently achieved the coupling-speed goals established by management.
3. Developing system features that allow one employee to do the work of the three previously required. Even though the hump conductor now sits in the seat formerly occupied by the car retarder operator, where his field of vision must exceed 180 degrees, closed-circuit TV and well-conceived inputs and displays give him good system monitoring capabilities for a minimum dollar expenditure. This human engineering performance was particularly important to system success.

HOW SUCCESS IS MEASURED IN HUMP YARDS

A basic criterion used to measure success or failure in a hump yard is coupling speed. Norfolk Southern has a simple method of measuring whether a yard is doing an adequate job on couplings. Coupling speeds are measured by hand-held radar according to a sampling scheme developed by Freight Claims Services. Of observed couplings to cars that have stopped, 94 percent or more must be at or below a nominal 6-mph coupling rate.

Stalls are not counted as an explicit part of the coupling speeds, although notes on stalls are kept. A track kickoff rate of six tracks per shift is acceptable, regardless of cause.

Coupling speed tests are performed on at least a quarterly basis. They serve both as a scorecard on performance and as a tuning tool. Results are widely published so that everyone is getting the same information without undue interpretation. Other criteria of importance are hump throughput, classification accuracy, and correct handling of TIPS interface.

RESPONSIBILITY

During the development of the system phases all the departments were expected to cooperate to see that they supported each other's activities. This mechanism was enforced via the technical committee when conflicts or other problems arose. The departments' activities were in addition to any of the normal responsibilities they variously had toward normal yard operation during system testing and implementation.

Now that phase 4 has been completed, day-to-day responsibility for system operation falls principally on two departments. Transportation is responsible for enforcing discipline on the hump conductors as in any other non-system-related activity that the hump conductors perform.

C&S is responsible for maintaining computer inputs and outputs as well as all field hardware associated with the system. Any tuning changes in the yard description data are also the responsibility of C&S.

On other than a day-to-day basis, MIS provides for computer hardware maintenance by Data General and software upgrades as necessary. MIS also assists C&S with tuning on request and system troubleshooting on an on-call basis. No MIS personnel are permanently assigned to Brosnan or any other yard.

PROS, CONS, AND COSTS OF DEVELOPMENT STRATEGY

There was an overall plan and phase sequence from the project's outset, although many specific details were not settled until well into the project cycle. This approach caused the goals to remain clear even as the problems were muddled through.

Pros

Recycled computers were used to extend the useful life of these systems until prices for the newer equipment fell and software on the newer computers was improved. The phased approach to system function upgrades combined easily with the computer hardware recycling.

The phased approach minimized the negative impact of change on yard operation. Each phase evolved from the previous one, which almost led the user ahead. Major retraining of personnel was not required.

Most of the code was developed on site and was tested as developed. Some of the code, particularly that for handling exceptions, was better tested in the field than in any laboratory that could have been economically created.

The implementing team gained by direct exposure to the experts, the car retarder operators. Much of their experience was eventually translated into program refinements.

Cons

The large amount of out-of-town work contributed directly to the high personnel turnover experienced during the project. Developing the experience of the implementing team took more time than hiring a new team of experts. Out-of-pocket expenses were relatively high simply because of the implementing team's expense accounts.

An individual railroad cannot afford the overhead of a large development staff such as the signal companies possess. This tends to concentrate too much specialized information in too few hands.

Old field hardware and cables caused the use of inputs that were less than ideally located and more error prone. Eventually several had to be replaced and relocated. Some had to be enhanced by backup devices.

The lack of a central development and test facility forced some work into the field that could have been done without incurring travel.

Costs

A definite trade-off exists between the expense of keeping a team in the field and the capital costs of a central laboratory.

Control systems involve a specialized type of programming. Railroad control systems are even more specialized. Hiring or training personnel with such specialized skills is costly.

For an automatic system to work well a high degree of maintenance of facilities and equipment is required. This includes such mundane items as working rail greasers and well-maintained track grades, all of which is costly.

PRACTICAL SYSTEM LIMITS

The master and group retarder configuration is becoming ever more inconsistent now that longer cars and constant-contact side bearings make up a large percentage of the car fleet. At older yards that have tight curves in the bowl tracks this problem is becoming severe. Some measure of curve resistance is needed to reduce the inconsistency. The obvious alternative to this is tangent-point retarders.

Human factors must be carefully considered. An ill-defined approach to how the hump conductor is to relate to the system can make the job appear impossible.

Simple-looking but hard-to-achieve changes to yard layout can improve performance. For instance, having some accelerating grade through the group retarders can add to the system's recovery capability for cars that are controlled to below their target speed.

SUMMARY

Puting a computer in an old yard is not a panacea. A successful project to do this requires a strong commitment from management to that goal, particularly if jobs are to be cut off as a result of computer installation.

A computer by itself will probably help in freight claims by lessening damage, but this may slow the humping rate. A slower hump rate may not affect the number of cars per day over the hump, but less hump-engine time is available for duties other than hump activities.

Maintenance costs are higher than in a manual yard because of a larger array of equipment to be maintained. If the yard is adequately configured, a computerized master and group retarder scheme will reduce damage, labor costs, and misroutes. Without a good yard layout, installing a computer will probably be no help in reducing damage claims.

The VR-IV Retarder Control System

DAVID C. CONWAY

A system for controlling the speed of freight cars coming out of car retarders in classification yards is described. The key element of the VR-IV system is the use of an acceleration servo to cause cars to decelerate at a constant rate and achieve the proper exit speed just as they leave the retarder. This is in contrast to the velocity servo used in earlier systems. With a microprocessor, the VR-IV system continuously repeats the computation of deceleration that will produce the desired exit speed; then it operates the compressed-air application or exhaust valves to produce the proper air pressure in the retarder cylinders.

In this paper a car retarder speed-control system is described that was designed to cause cars to decelerate uniformly throughout the entire length of the retarder. This is a desirable feature for several reasons. First it distributes the wear evenly throughout the retarder instead of causing the work and the wear to occur at the front end. Second it allows cars to maintain a higher average speed through the retarder, which increases the production rate or throughput. And third, in the case of electropneumatic retarders, it produces a substantial savings in compressed air by maintaining a relatively constant air pressure for any given weight of car.

OVERALL YARD CONCEPT

Before the Union Switch and Signal Company (US&S)

VR-IV retarder speed-control system is discussed, brief mention will be made of the overall yard concept from the point of view of a classification yard systems engineer.

Fundamentally, in a modern railroad terminal incoming trains must be disassembled and then reassembled into outgoing trains. The classification yard is the key element in this process.

Because virtually all of the traffic handled by a terminal must pass through the classification yard, it is vital that this operation be performed as smoothly and as quickly as possible, lest the yard become the bottleneck of the terminal.

The classification yard allows free-rolling cars to accelerate to a reasonable speed, pass through the switching area, and then proceed along a bowl track to a safe coupling with a previously humped car on that particular track.

Normally the crest of the hump is made high enough to provide most cars with sufficient speed to roll to coupling. Nevertheless, easily rolling cars would attain higher speeds than poor rollers. With no intervention, good rollers would overtake poor rollers and be routed to the wrong track. To prevent this, car retarders are placed along the route between the crest and the entrance to the bowl track to control the speed of the cars. The more retarders along the route, the better the separation between cars can be maintained and the faster the train can be classified or humped. Retarders, however, cost money and placement is an important factor in the design of hump yards. The most popular yard configuration has master and group retarders. However, when high hump rates are desired, retarders are required at the tangent point of each track. Tangent-point retarders allow speeds through the last switch area to be higher, thus reducing the likelihood that cars will catch up to each other.

RETARDER SYSTEMS

There are a wide variety of retarder configurations and control devices. US&S uses pneumatic retarders with solenoid-controlled pilot operator valves. These components were chosen because they are clean, respond quickly to control commands, and provide unlimited selection of control pressures up to the system line pressure. Also, US&S classification yard switch machines are pneumatically operated, so one compressor system can operate the whole yard.

Retarder control schemes range from simple manual control by a lever on a retarder operator's console to highly sophisticated automatic control like the VR-IV system.

With manual control a retarder operator uses his own judgment to select a suitable pressure that will not squeeze the wheels out of the retarder. He has only a four-position lever to select retarder pressures. He must be aware of the bowl track to which the car is assigned, and he must presume a proper exit speed for the car. Then he must open the retarder at just the proper time to allow the car to maintain that speed. Obviously, the whole operation requires the undivided attention of an experienced operator.

With automatic control, a weigh rail, radar, and electronic hardware assume many of the retarder operator's decisions. A weigh rail ahead of the master retarder measures the weight of each car and classifies it in one of four categories: light, medium, heavy, or extra heavy. Maximum retarder pressure limits are set according to these categories. Doppler radar monitors the car's speed while the car passes through the retarder. The retarder operator must still be aware of the destination of the car so that he can select a suitable retarder exit speed. The selection is made by turning a dial on the retarder control console to the desired exit speed.

In more modern yards where process-control (PC) computers are used, the retarder operator is relieved of the task of deciding what the proper speed should be. An algorithm based on the formula for conservation of energy computes the optimum exit speed by using electronically determined space available on the destination track and a rolling-resistance measurement for the car that is determined by the PC computer.

The rolling-resistance measurement is used to predict how much energy a car will lose after it leaves the last retarder and while it is traveling through the curves of the switching area and along the tangent bowl track to the coupling point. The purpose of the algorithm is to determine the amount of energy that is required to overcome these losses and to cause the car to couple at an acceptable speed. The total energy is then converted to group retarder desired exit speed.

Before use of the VR-IV the proper exit speed was achieved by electronic hardware in the configuration of a velocity servo. The role of the velocity servo was simply to reduce the speed error to zero somewhere along the retarder and then to maintain that condition until the car left the retarder. In the velocity servo the actual speed is compared with the selected speed and the difference, or speed error, then controls the air application and exhaust valves accordingly. In this type of control system the entering end of the retarder does most of the work and sustains most of the wear.

VR-IV SYSTEM

Rather than attack the speed error as the velocity servo does, the VR-IV focuses on deceleration, or the rate of change of velocity, as the car passes through the retarder. The objective of the VR-IV is to determine the proper deceleration and then to control the car's actual deceleration to produce the desired exit speed just as the car's last axle leaves the retarder. The entire available length of the retarder is used in this computation. The actual deceleration of the car is derived from the radar Doppler signal. The acceleration servo adjusts retarder pressure to make the actual deceleration equal to the desired deceleration. When the difference is zero, the car leaves the retarder; when it is not zero, the system increases or decreases pressure to make it zero. The VR-IV does not stop there. The desired deceleration is computed continually as the car passes through the retarder. For each 1 1/8 in. of progress through the retarder, or every other Doppler pulse, a new computation is made. This allows the pressure, which is initially set to a nominal value, to be adjusted continually. Ideally, once the proper deceleration is achieved, no further changes in pressure should be needed.

The system responds automatically to car wheels with varying coefficients of friction. When a car has wheels contaminated with grease or other lubricating substance, the retarder pressure is allowed to build up to a higher level than normal. Then when the contaminant wears or burns off and deceleration increases, the pressure is adjusted accordingly. Thus with the VR-IV some cars are controlled properly that with other control systems may have left the retarder at too high a speed. This flexibility of control pressures and the continually updated computations of desired deceleration provide accurate control of exit speed.

The VR-IV achieves a new level in the status of retarder speed control, and new electronic hardware was required to accomplish it. An additional radar unit at each master and group retarder was required in order to be certain that a good Doppler signal was available regardless of the car's position in the retarder.

A new radar Doppler signal processor was developed. The circuit is called a hole filler, and it does just that by supplying pulses that are missing in the Doppler signal. Because of reflected radar energy from various parts of the car, some Doppler pulses are cancelled out and some extra pulses occur. These phenomena are called dropout and multipathing, respectively, and the hole filler overcomes their effect, providing a much smoother and more accurate signal that represents the actual velocity of the car.

A microprocessor unit was designed into the VR-IV system for executive control of the many modes of operation and decision tasks required. The microprocessor selects the proper control valves and air-pressure limits for the system. It also enables system control of the valves through acceleration-mode logic or velocity-mode logic. If a situation occurs in which two cuts catch up to each other, the microprocessor takes appropriate action to provide the best control of both cuts in the retarder. It selects the entering-end radar or leaving-end radar based on the position of the car in the retarder, and when no car is present, it initiates a system reset and self-test.

The microprocessor monitors the failure status of the VR-IV subsystems. It also receives information on each cut from the PC computer. By using all of this information, it determines and enables the appropriate mode of operation. A watchdog timer monitors the microprocessor to detect its ability to complete its scan; if it cannot, the timer takes appropriate action to place the system in a back-up mode.

A complete new retarder air-pressure measurement and control system was also developed by which a pressure transducer converts retarder air manifold pressure to an analog signal proportional to that pressure. This signal is compared with the analog value of the desired pressure, and the retarder pressure is adjusted to match. Pressures can be selected in this manner, or they can be raised and lowered on demand from the acceleration servo.

A system for tracking a car through the retarder was also developed. By using a wheel detector at the entrance end of the retarder to count axles in and a wheel detector at the exit end to count axles out, a running count of the number of axles in the retarder can be maintained. This is necessary to determine the amount of deceleration available at any moment.

Many parameters must come together in the computation of desired deceleration. The PC computer passes the number of axles in each cut of cars to the VR-IV system. Then the number of axles multiplied by the length of the retarder is a measure of the total amount of the retardation available. Because the reception of each Doppler pulse indicates progress of about 9/16 in. through the retarder, the total length of retarder available is diminished by 9/16 in. multiplied by the number of axles in the retarder at that particular time. Also, to determine the desired deceleration, the difference between the actual velocity squared and the desired exit velocity squared must be calculated and then divided by the remaining available retarder length. The result is the desired deceleration and it is computed over and over again every 1 1/8 in. through the retarder.

Another circuit compares this desired deceleration with the actual deceleration to produce the deceleration error. The sign of the error signal indicates whether the pressure should be increased or decreased. The deceleration error signal pulse width modulates the control commands to the air application and exhaust values to reduce the possibility of overcontrol. This allows more precise control of deceleration and thereby produces a high degree of accuracy in speed control.

In conclusion, even though the VR-IV retarder control system is somewhat more complex than earlier systems, the benefits are also greater.

Compared with the earlier velocity servo systems, lower preset pressures are used for each weight category, and the pressure increases only to the extent required. This means that the air volume used is reduced and the air compressor plant size can be reduced significantly.

Because the retarder air pressure is made only as high as it needs to be to cause the desired deceleration, pressures will generally be lower and more uniform than in earlier systems. This reduces stresses at the entering end of the retarder and distributes work and wear more evenly along its length. It also reduces the frequency of brakeshoe replacement.

Increased retarder pressure limits increase the retarder effectiveness for light, medium, and heavy cars with low coefficients of friction.

When the whole retarder is used to achieve the desired exit speed, the average speed through the retarder is higher; therefore less time is spent in the retarder. This allows cars to follow more closely and allows throughput to be higher.

Finally better accuracy in the control of exit speeds means a better chance to get good coupling speeds in the bowl tracks. In other words, the VR-IV can improve the effectiveness of the classification yard, which will improve the efficiency of the terminal.

Notice: The Transportation Research Board does not endorse products or manufacturers. Trade and manufacturers' names appear in this paper because they are considered essential to its object.

Developments in the Application of the Dowty Continuous-Control Method

ARTHUR W. MELHUISH

The Dowty system for the continuous control of freight car speeds in classification yards is based on hydraulic retarders and pneumatic booster-retarder units. Dowty retarders adopt the retard mode only for cars traveling faster than the preset control velocity; the booster-retarder units are adjusted to monitor speed and accelerate or retard as appropriate. Five examples of recent application developments are given: (a) Sentrarand Yard in South Africa, in which both retarders and booster-retarder units provide continuous speed control; (b) Trondheim Yard in Norway, in which the continuous speed-control system has been modified to facilitate clearing snow; (c) Nürnberg Yard in West Germany, in which the retarder system is a combination of existing clasp retarders and a modernized control system; (d) an electrohydraulic latch to hold the retarder capsule in the down position to permit high-speed train withdrawals toward the hump; and (e) use of hydraulic retarders to provide end-of-track arrester zones.

The principles of operation of the Dowty hydraulic retarder and the booster-retarder unit are widely appreciated by engineers involved with classification yards in North America. Therefore detailed descriptions of these two units are not incorporated within this paper; it is sufficient to explain that both units are speed sensitive.

The retarder (Figure 1) adopts the retard mode only for cars traveling faster than the preset control velocity; booster-retarder units (Figure 2) are adjusted to monitor car speed and to accelerate or retard cars as appropriate.

In application a continuous speed-control system may be made up of retarders only (i.e., where the running gradients are adequate to maintain the motion of cars with high rollability values) or of a combination of retarders and booster-retarder units to accelerate the cars with low rollability and retard the cars with high rollability to maintain constant car speed.

To study recent application developments five examples have been chosen to present a variety of facets:

1. Sentrarand Yard, South Africa: The overall design aspects for this South African yard are presented. This is an excellent example of a large, high-throughput yard equipped with both retarders and booster-retarder units to form the continuous speed-control system.
2. Trondheim Yard, Norway: Although small and with only a low throughput, this yard has been economically automated with a continuous speed-control system. The parameters and design features for this project are reviewed with a look at the method adopted for clearing snow, an important feature in this northern region.
3. Upgrading existing yards with classification-track control: The Dowty retarder installation in Nürnberg Yard, West Germany, is reviewed as a practical example of the adaptability of the Dowty system.
4. Equipment development: An electrohydraulic hold-down latch has been designed and developed for attachment to the Dowty retarder. The design, principles of operation, and application of the latch for retarder on-off operation are explained.
5. End-of-track control: A design study for economic end-of-track arrester zones based on practical North American parameters is reviewed.

SENTRARAND YARD

General Aspects

It has been planned to develop three complete yards in the Sentrarand complex; land is available for a provisional fourth module if it is required in the future. The first of these yards was completed and commissioned in autumn 1982 (Figure 3).

The module layout includes an arrival yard, two departure yards, and a main switching yard with two secondary hump yards appended (Figure 4). There is a dual-lead track over the primary hump to promote 5,000 cars per day switched into the 64 classification tracks. The designed humping velocity is 2.25 mph. Both secondary hump yards are arranged to include a herringbone track formation for the purpose of building block trains.

Figure 1. Dowty hydraulic retarders.

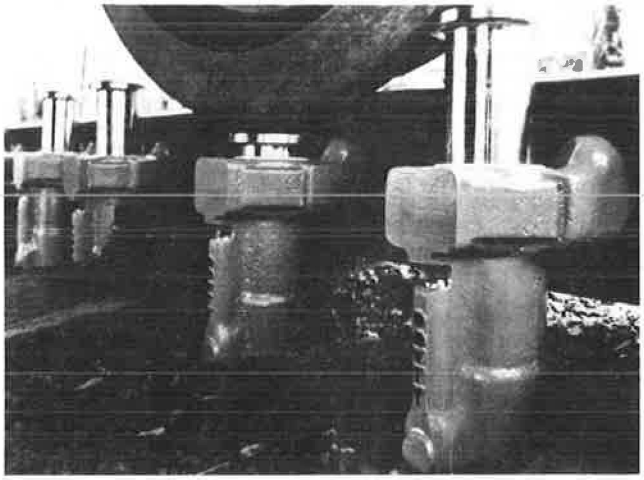


Figure 2. Dowty pneumatic booster-retarder units.

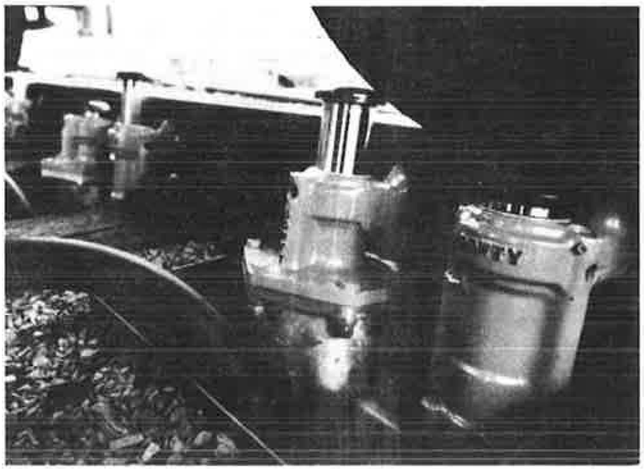


Figure 3. Sentrarand Yard.

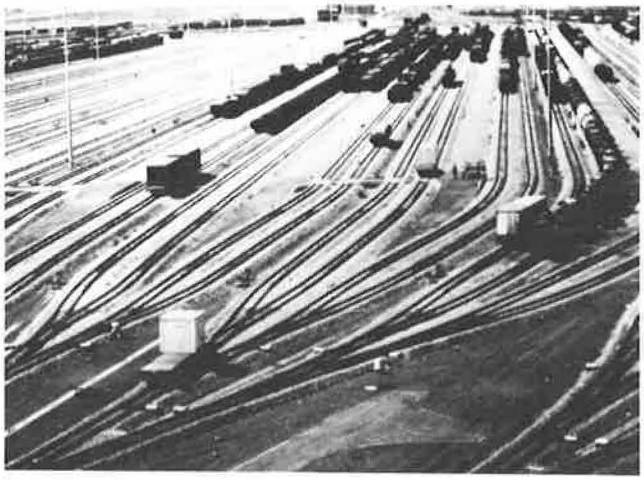


Figure 4. Layout of Sentrarand Yard.

Continuous Speed-Control System

The Dowty system for the continuous control of car speed is used throughout the main and secondary yards.

The speed-control system design was based on the following parameters:

Parameter	Amount
Axle loading	18.2 tons maximum, 3.6 tons minimum
Basic rollability bandwidth	0.001-0.018
Humping velocity (main yard)	2.25 mph
Car length	40 ft avg
Separation (main yard)	50 ft
Crest-to-clearance distance (main yard)	984 ft maximum

In the early design stages of the yard it was recognized by the engineers that particular problems were imposed by the need to cater to light cars combined with the wide rollability bandwidth specified. They also recognized that the ideal control system is one in which all cars, regardless of weight or rollability, are sustained at appropriate continuous velocities in the switching area to maintain separation and in the classification tracks to control the coupling speed.

To employ a control system based on retarder units alone would have imposed the need for unacceptable hump and gradient requirements. It was therefore determined, by using computer-aided design methods, that the optimum solution lay in the use of both retarders and booster-retarder units to supplement the gradients. In the final design of the main yard the hump height and vertical radius are equivalent to an accelerating gradient of 6.25 percent; boosters are added at a density of 0.88 unit/ft to accelerate all cars to the switching-area velocity of 11.2 mph.

In the switching area a gradient of 2.5 percent is used to keep the cars with high rollability in motion, and retarders are installed to hold the heavy cars with low rollability at 11.2 mph. The retarder densities vary between a maximum of 1.71 units/ft on tangent tracks to 0.4 unit/ft on curves and turnouts.

Deceleration zones are installed at the heads of the classification tracks to reduce the speed of the cars from the switching-area velocity of 11.2 mph to the classification-track control speed of 2.25 mph. These zones are equipped with a mixture of retarders and booster-retarder units; the retarders control the heaviest cars and the boosters and ensure that light cars with low rollability rapidly penetrate and clear the zone.

To achieve the optimum performance in the zone, in which the heavy cars are fully decelerated and yet light cars and cuts clear the zone as quickly as possible, the deceleration in the zone is in stages, i.e., 11.2 to 10.0 mph, 10 to 7.8 mph, 7.8 to 4.5 mph, and 4.5 to 2.25 mph. A variety of unit densities is needed to provide this type of control for the full range of cars.

The classification tracks, which have a gradient of 0.4 percent, are equipped with retarders installed at 0.003 unit/ft and booster retarders at 0.2 unit/ft; both are set to a control speed of 2.25 mph. With this arrangement all cars fully couple in the classification tracks at a controlled maximum velocity of 2.25 mph.

Secondary Yards

Both secondary yards employ humped switching over an accelerating grade equivalent to 4.0 percent. Each of the yards includes five tracks built to a 0.75 percent gradient and equipped with retarders and booster-retarder equipment to continuously monitor and control the car speed. The center track is the hump lead and feeder line into the two flanking herringbone tracks and to the outer pair of parallel reserve storage lines; all these tracks are on a 0.75 percent gradient throughout.

The cars are continuously controlled to 9.0 mph while they are traveling down the center feeder line. When traversing the turnouts and switches, they are decelerated in stages (i.e., 9 to 7.8 to 6.7 to 5.6 to 2.25 mph) before they arrive in the herringbone tracks. Cars running in the outer tracks are controlled to a velocity of 2.25 mph. Operable skate retarders are installed at 330-ft intervals along the herringbone tracks to form five blocks in each track; these retarders are also installed in the outer tracks, dividing each of them into two long blocks. The operations of the yard are enhanced by this design of the secondary yards; formation of block trains and the preparation of short local trains are rendered simple and expedient.

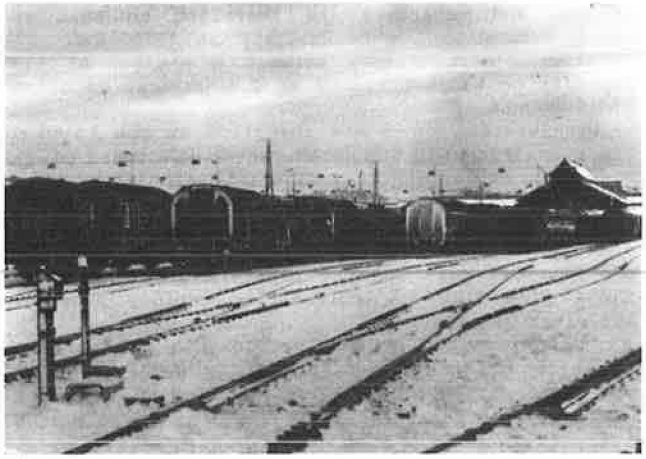
The specification for this type of operation is to sustain car separation down to the last switch, a distance of 1,880 ft in this case, and accommodate a wide rollability bandwidth. The cars must also run down to the end-of-block retarders and completely finish coupling in order to fill the blocks.

These parameters can only be met by using a speed-control system such as the Dowty system, in which retarders and booster-retarder units operate to continuously monitor speed and to adjust the motion of the cars by absorbing or dispensing energy as required.

Developments and Installations

It was the advent of this modern automated yard that promoted the design and development of the Dowty

Figure 5. Trondheim Yard.



booster-retarder unit. As mentioned previously, it was recognized early in the design stages that to achieve the maximum performance in car speed control and to avoid impractical gradients it would be necessary to employ mechanical feed equipment to impart energy to the cars with high rollability.

In the early 1970s trial systems of Dowty retarders were installed in the New Kaserne Yard for testing and evaluation. It was during this period that the head of the retarder capsule evolved into a mushroom shape to improve operation on tight horizontal curves.

These trials were extended in the mid-1970s to include the booster-retarder unit for equipment and system assessment. Cooperation among South African Transport Services, Telkor, and Dowty in the final development of the unit during this stage culminated in the production of approximately 18,000 units, to be installed with approximately 42,000 retarders to form the most extensive and complete continuous speed-control system ever derived.

Final costs quoted for the completed development of the yard are approximately $202,500,000 (1), of which $35,250,000 (2) was the approximate escalated cost for the speed-control system, including associated compressor plant and compressed-air reticulation.

TRONDHEIM YARD

General Aspects

Trondheim Yard is located in Norway 180 km south of the Artic Circle. Snow in this locality is a problem to be contended with each winter, and it was necessary during the planning stages to ensure that the retarder equipment selected and the snow-clearing methods adopted would be compatible. This yard, which was remodeled and commissioned in the autumn of 1982, is an example of how a low-throughput mini-yard can be economically equipped with a complete speed-control system to provide all the operating advantages of an automated yard.

There are 16 dead-end classification tracks to accommodate 1,200 cars per day over the hump. The specified humping velocity is 2.0 mph. All trains have to be withdrawn from the classification tracks via the switching area and hump bypass tracks (Figure 5).

Continuous Speed-Control System

The Dowty system for the continuous control of car speed is used throughout the yard. The speed-control system design was based on the following parameters:

Parameter	Amount
Axle loading	18.2 tons maximum, 3.7 tons minimum
Rollability bandwidth	0.001-0.007
Humping velocity	2.0 mph
Car length	42.6 ft
Separation	49.2 ft
Crest-to-clearance distance	675 ft avg

All cars are accelerated off the hump to a speed of 6.7 mph and this velocity is maintained throughout the switching area, which is graded to 1.2 percent.

The deceleration zones, situated at the head of each classification track, slow the cars from 6.7 mph to a coupling velocity of 3.4 mph. These zones commence 16 ft past the clearance markers and are installed across two gradients, 0.8 and 1.2 percent nominal. The location and gradients have been chosen to ensure that cars and cuts with low rollability move away from the clearance markers as quickly as possible. In the classification-track control area the speed is maintained at 3.4 mph on a 0.3 percent gradient.

The continuous speed-control system has been applied to this remodeled yard for less than $1 million, including spares, maintenance tooling, and commissioning. A gang of skatesmen has been released from their arduous and dangerous duty, and the car throughput has been greatly improved.

Snow-Clearing Operations

Before the final selection of the retarder system for use at Trondheim, snow-clearing trials were conducted at the existing Alnabru Yard near Oslo. The purpose of the trials was to evaluate the compatibility of the retarders and a suitable snow-clearing method.

During the trials snow-clearing machines with rotary brushes (Figure 6) were operated over the Dowty retarders. The rotating brushes were fitted with nylon-coated wire flails. This method was found effective in removing the snow and in no way affected the retarders mounted on the track.

The Dowty retarders and the brush method of snow clearing were adopted for use in Trondheim Yard; Figure 7 shows clearing operations in progress in the yard in February 1983.

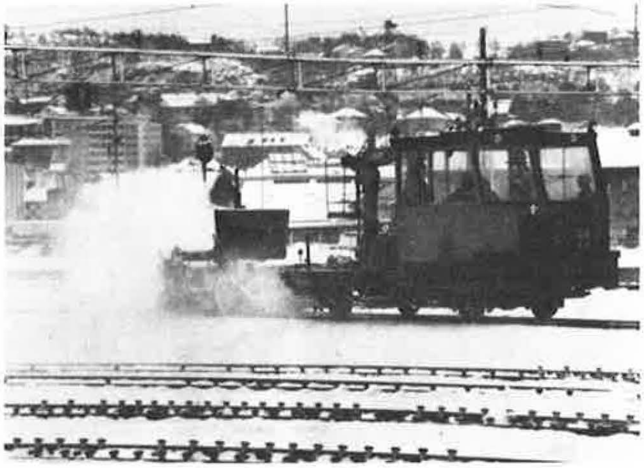
NÜRNBERG YARD: UPGRADING EXISTING YARDS

In many older yards the existing track gradients and speed-control system are not fully compatible with modern traffic and operations. A common problem in these yards is poor performance in the classification tracks because of excessive car speed. These conditions give rise to expensive freight and car damage, diminished safety due to high car speeds, and runouts at the trim end.

Nürnberg Yard in West Germany was built at the beginning of this century. In recent years plans were instigated for the remodeling of this important large yard. Work is already proceeding to produce a main yard with 72 classification tracks. After renovation the existing clasp retarders are to be retained in the switching area and operated via a fully modernized control system. A secondary hump yard is being designed for inclusion in the main

Figure 6. Snow-clearing machines, Alnabru Yard.

Figure 7. Snow-clearing machine at work, Trondheim Yard.



body of the yard. There are two further secondary switching yards located separately and to the north of the main yard.

Because of existing services, bridges, and so forth that have developed around the yard during 70 years of use, it has not been practical in the remodeling to greatly improve the gradients in many of the classification tracks. These classification-track gradients were constructed in the days when car rollability values were, on the average, much higher than those today, and therefore they present unacceptable accelerating grades to the majority of contemporary traffic.

In 1976, 300 Dowty retarders were installed in one of the classification tracks for test and evaluation of their control capabilities. Following this satisfactory trial, 4,800 retarders were installed in six classification tracks during May 1979 to form continuous classification-track control systems developed from the original trial applications. At the head of track 22, one of six so equipped, an 81-ft-long deceleration zone made up of 148 retarders at a density of 1.83 units/ft was installed on a gradient of 0.66 percent. Three different speed settings (6.7, 4.5, and 2.25 mph) were used for staged deceleration in the zone to ensure that light cars and cuts with low rollability pass through as quickly as possible.

After leaving the deceleration zone, the cars are continuously controlled down the track at a maximum speed of 2.25 mph to finally stop on preset rail skates (Figure 8).

On track 22 the gradients and distances equate to a velocity head value of 9-10 ft for a car with high rollability; without continuous speed control it would not be feasible to switch into such a track and utilize its full length.

As the reshaping of this yard progresses during the next few years, more classification tracks will be equipped with continuous-control systems to meet development and operational needs.

ELECTROHYDRAULIC LATCH

To permit high-speed train withdrawals toward the hump, an electrohydraulic hold-down latch has been designed to hold the retarder capsule in the down (i.e., off) position during the passing of a train.

The latch assembly is a self-contained unit bolted onto the side of the retarder pot. It is retained against a positive location face on the pot by 2x10-mm H.T. steel bolts (Figure 9). The mechanism is actuated by a 12-W electrosolenoid, which can be remotely signaled to control the operating position.

With the solenoid energized, the first passing wheel flange depresses the capsule and the latch engages with the mushroom head to lock the retarder in the off mode for the duration of the train's withdrawal. The solenoid is deenergized to release the capsule, which then returns to the normal retarder on mode.

Operation

Solenoid Energized and Retarder Off

With the solenoid (2 in Figure 9) energized, the armature extends, pushing the ball valve (3) onto its seat, and closes the vent line from the piston chamber. On the downward stroke of the capsule, the latch tongue rotates against the torsion spring (8), allowing the capsule head to pass by. On the return or upward movement of the capsule, the head contacts the latch tongue but is prevented from pushing it away because the subsequent downward movement of the piston (5) creates a hydraulic lock when the ball valve (6) is forced onto its seat.

The capsule is therefore prevented from extending and will remain down, so that all subsequent wheels pass without significant engagement with the capsule as long as the solenoid valve remains energized.

Solenoid Normal and Retarder On

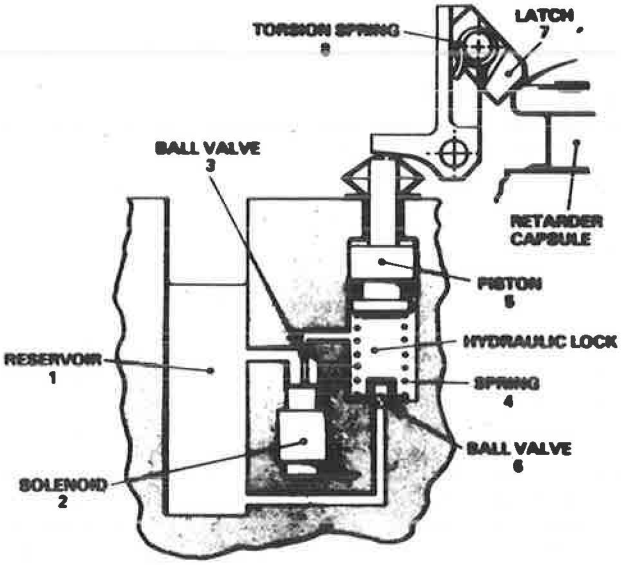
In the deenergized condition (Figure 10), the plunger of the solenoid (2) is retracted, allowing free flow of oil from the main piston chamber to the reservoir (1) via the ball valve (3).

Downward travel of the attendant capsule brings the mushroom head in contact with the latch (7), rotating its tongue against the torsion spring (8). This allows the capsule to complete its downward stroke.

Once the capsule head has passed the latch, the torsion spring (8) rotates and extends the latch tongue back into position above the capsule head. The return stroke of the capsule then brings it into contact with the latch tongue, causing the latch (7) to rotate about its fulcrum. This depresses the piston (5) into its chamber against the spring (4). At the same time, the ball valve (6) closes and oil from the chamber is vented to the reservoir (1).

Figure 8. Rail skates, Nürnberg Yard.

Figure 9. Electrohydraulic hold-down latch: solenoid energized.



As the capsule's upward travel continues, its head disengages from the latch, allowing the spring (4) to extend and drawing oil into the chamber from the reservoir via the ball valve (6).

The cycle is repeated for each following capsule stroke as long as the solenoid valve remains deenergized.

Development

The general design for the hold-down latch was conceived in 1982, and during that year prototype units were produced and tested to prove the principles of operation.

Six prototype latch units were installed on a track in Seinajoki Yard in Finland in January 1983 to commence a 4-month winter test period (Figure 11). The objectives of the trial were to evaluate the operational integrity of the unit in a field environment when it was subjected to low temperatures and snow conditions.

During the trial period the ambient temperatures ranged from 10°C to 25°C and there were many snowfalls when the units were subjected to snow-clearing operations in which a high-speed rotary brush was used.

Figure 10. Electrohydraulic hold-down latch: solenoid normal.

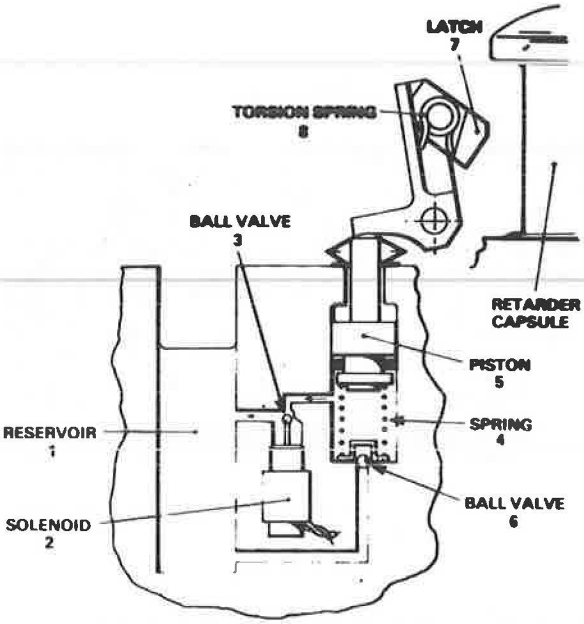
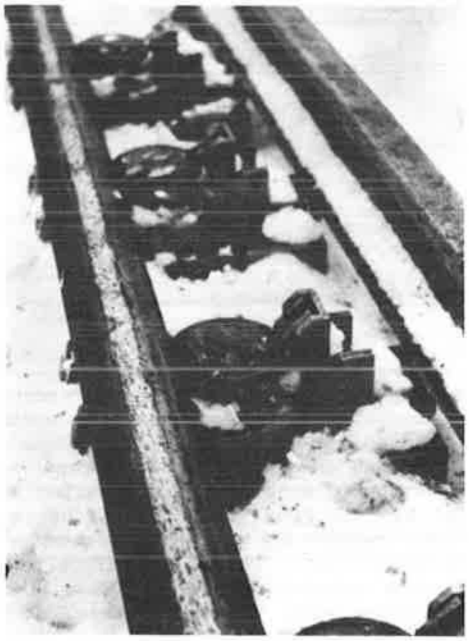


Figure 11. Prototype hold-down latches, Seinajoki Yard.



To test the effectiveness of the latch, test trains were driven at various approach and maximum velocities over the units; these speeds ranged from 9 to 21 mph. Low-voltage tests revealed that the solenoid could be effectively energized and held at 30 percent full DC potential.

At the end of April 1983, the latches were removed from the track, having successfully completed all trials. During the test period 15,400 axles had operated the retarders and the solenoids had electrically cycled on or off for 1,841 hr with a period of 12 min/cycle.

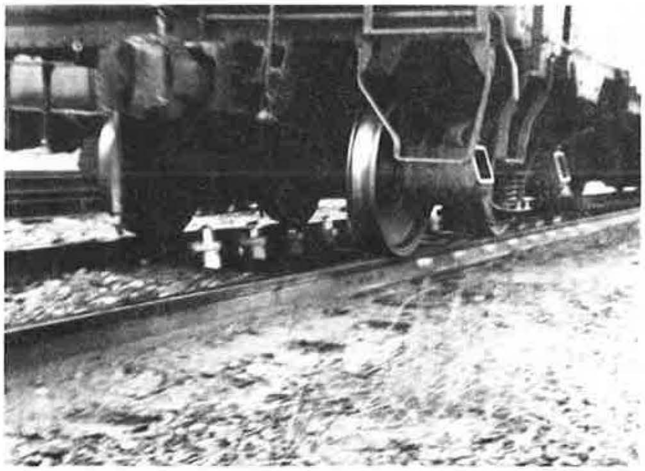
All six of these prototype units operated without failure under conditions of both snow and ice throughout the test period. They have since been completely dismantled and all components have been examined. From this investigation the only details calling for attention during the stage of making production drawings are to change the ball-valve seating material, improve the piston gaiter against a small leakage of moisture, and improve the method of excluding air from the piston seal during the assembly of the unit.

In parallel with the track trials a prototype latch was subjected to 1.0 million cycles of operation on a cycling test rig. A complete retarder was loaded into the rig so that the capsule could be stroked vertically in the normal operating method. During the 1.0 million cycles the solenoid was energized for one-sixth of the time and deenergized for five-sixths of the time to approximately simulate operating conditions.

Future

Following these most satisfactory test results, production drawings and specifications are being prepared for the manufacture of latches. The six prototype units are being rebuilt and are destined for a further trial period in the Alnabru Yard in Norway, where on-site trials will be conducted with a view to future applications. Trials with the latch in Finland will of course continue until the time that the application of hold-down latches in new yards will be required.

Figure 12. Arrester zone, De Butts Yard.



With the advent of the hold-down latch, an operable Dowty retarder can now be offered for special applications where there is an operational need for unrestricted train withdrawal speeds.

The hold-down latch could advantageously be applied to Dowty arresters to form an operable unit. It would then be possible to turn the arresters off when trains are being pulled or in trimming movements to permit unrestricted speed coupled with an extensive working-life expectancy for the arresters.

END-OF-CLASSIFICATION-TRACK CONTROL

Efficient Design of Arrester Zones

Dowty arresters, i.e., hydraulic retarders in which the speed-sensitive valves are set to zero during manufacture, are installed in yards to provide end-of-track arrester zones.

In the past the arresters have been installed to form a dense bank of units situated on the change of grade, i.e., at the start of the end-of-track reverse gradient. Figure 12 shows an arrester zone in the De Butts Yard.

Because these zones, with their ease and rapidity of installation, lack of retarder squeal, immunity to wheel contamination, economic maintenance needs, and ability to operate without controls, offer an attractive alternative to skate retarders, a design study has been made of this type of application.

It was determined that an efficient and economic arrester zone can be achieved by distributing the arresters along the reverse gradient track so as to take advantage of the energy absorbed from the cars moving through a distance and the track elevation. In this manner, the kinetic energy of the car will be absorbed by

1. The rolling-resistance value times distance traveled,
2. The elevation gained by the car, and
3. The activation of the arresters by each axle of the car.

In adopting this method it is necessary to determine first the density of the arresters needed to prevent the cars from accelerating down the gradient in the reverse running direction (Figure 13).

The arrester density can be calculated from

$$d = (G - R)/E_A \quad (1)$$

where

d = arrester density (units/ft),

Figure 13. Arrester-zone diagram.

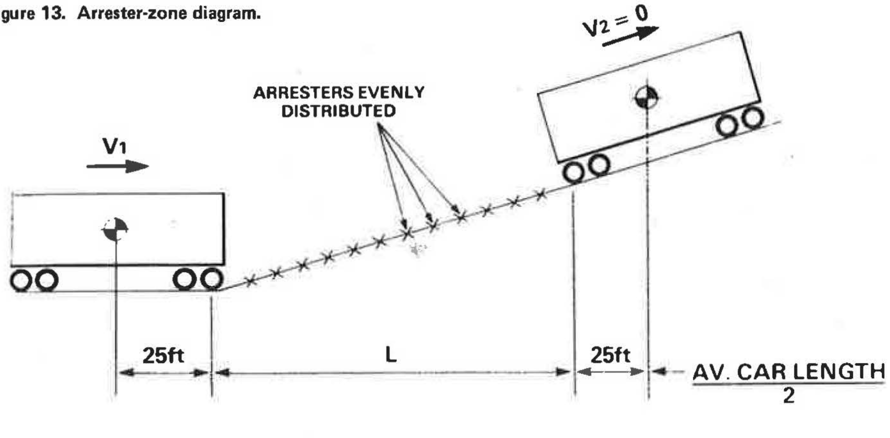
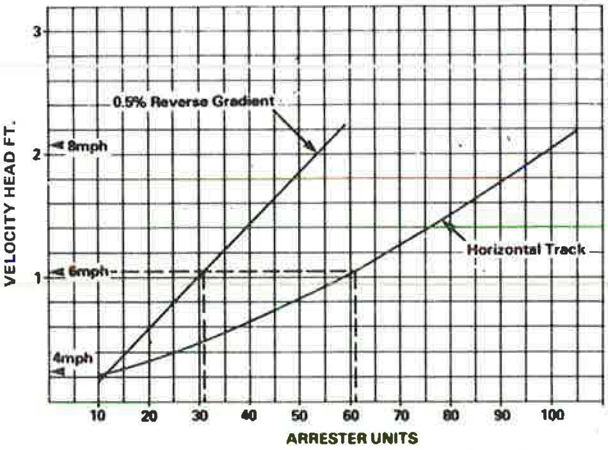


Figure 14. Velocity head versus arrester quantity for 135-ton car.



G = gradient coefficient,
R = rollability coefficient, and
E_A = arrester energy head value (ft).

Once the unit density has been determined, it is then possible to calculate the distance (L) by using Equation 2, and from this the length of the arrester zone and the minimum quantity of units can be found:

$$VH1 = VH2 + (E_A \times d \times L) + G(L + 25) + R(L + 50) \tag{2}$$

where

VH1 = initial velocity head (ft),
VH2 = final velocity head = 0, and
L = distance traveled (ft).

The value of E_A used in determining the arrester density is not the same as the E_A value used in the final equation. In the first case the energy value is appropriate to a low-speed car, and in the second case it is appropriate to the mean velocity-head value, which is dependent on the initial car velocity; the unit energy value increases with car speed.

Arrester-Zone Example

In the graph shown in Figure 14 a typical curve of velocity head versus arrester quantity has been plotted for a gradient of 0.5 percent. For this example the following parameters were used:

Parameter	Amount
Car weight	135 tons
Rollability	2 lb/ton
Arrester density	0.31 unit/ft
Car length	50 ft

For comparison purposes the curve of velocity head versus arrester quantity for horizontal track has been included to illustrate the effectiveness of the up grade. When this type of arrester zone is designed, it is necessary in some cases to temper the mathematical solution slightly by considering the desired ultimate stopping point for the car, i.e., at the top of the grade or a specified distance before.

This consideration is most pertinent where gradients are shallow or initial car velocities are high; e.g., an 8.0-mph car requires an arrester zone of 258 ft on a 0.30 percent gradient; in some cases this could bring the car close to the top of the gradient with little margin of safety. It is possible, by applying some small adjustment to the unit density value, to restrict the final length of the arrester zone and achieve a compromise quantity of units.

CONCLUSION

The developments mentioned in this paper have in the main taken place outside the North American continent. They are, however, applicable to possible projects in the United States and Canada.

Sentrarand Yard is equal in magnitude to the scale of yard developments still planned on the American continent. Its design and equipment present an excellent model of engineering for a high-throughput yard needing accurate separation in the switching area with precisely controlled speed and coupling in the classification tracks.

The method of clearing snow adopted with the Dowty retarder installation in Trondheim must, because of the nature of North American winters, be of interest. The design for Trondheim Yard illustrates how it is possible to bring the benefits of automation to miniyards, and there are those within the American railroad industry who think that there may be more of these in the future. To expand on this view, one might ask what the operating possibilities are in a miniyard that includes some herringbone track arrangements. Surely a formula should be considered for reducing the switching operations and the time spent by cars in yards.

With about 120 automated hump yards in North America, of which about 45 percent are more than 20 year old, there could exist opportunities for updating them with the Dowty classification-track control system.

The electrohydraulic hold-down latch, although designed to meet a specific yard-operating requirement, will find a wider range of uses in the future. For some installations there could be advantages in using operable arresters in order to comply with the required operating needs; retarders that can be signaled on or off could enhance the control capabilities of the Dowty systems employed in industrial terminals, where low car speeds and accurate spotting are often needed.

Arrester zones have already been installed in American yards, and engineering design proposals for planned installations are currently being considered by a number of railroad companies. These zones can also be profitably merged with classification-track control zones when yard improvements are made.

REFERENCES

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Canadian National Railways' Terminal Interactive Model (TRIM)

GEORGE P. ENGELBERG

Historically, Canadian National Railways (CN) had analyzed operating and design changes to classification yards by using manual simulation. This approach was costly and time consuming, permitting the examination of only one or two alternatives. Recognizing the need for a better approach, CN embarked on the development of a computerized terminal interactive model (TRIM) to replace the tedious and costly manual simulation. The objective of TRIM is to retain the benefits provided by a manual simulation (applicability to both hump yards and flat yards of any configuration, maintenance of a high degree of accuracy and level of detail, use of skills of experienced yardmasters) and add the benefits of computer simulation (faster execution, lower labor intensity, greater detail, rapid analysis of simulation results,, flexibility of specification). TRIM is an event-based simulation in that it moves forward through time from one activity to the next. More than one yard analyst at a time can participate in the simulation. A typical scheme would parallel the sphere of control by a yardmaster in a tower. TRIM has been used to study two important yards in western Canada—Kamloops and Thornton (Vancouver), British Columbia.

In the 1980s Canadian National Railways (CN) must expand or redesign most of its yards in western Canada in response to anticipated major growth and changes in demand for service. Because of the magnitude of the investment required, it is necessary for CN to rigorously evaluate its approach to improving and expanding yards. The objective is not only to expand yards to cope with projected traffic volumes but to make terminals more efficient in the process.

Historically, CN had analyzed operating and design changes by using manual simulation. This approach was costly and time consuming; only one or two alternatives could be examined. Recognizing the need for a better approach to analyzing yard changes, CN, working with Peat, Marwick, Mitchell and Company, embarked on the development of a computerized terminal interactive model (TRIM) to replace the tedious and costly manual simulation approach.

The objective of TRIM was to retain the benefits provided by manual simulation (applicability to both hump yards and flat yards of any configuration, maintenance of a high degree of accuracy and level of detail, and use of skills of experienced yardmasters) and incorporate the benefits of computer simulation (faster execution, lower labor intensity, greater detail, rapid analysis of simulation results, and flexibility of specification). The result was a tool that combined the best of both approaches through an on-line interactive computer model.

TRIM enables CN to evaluate capital investment alternatives in greater detail than was previously possible with manual techniques. Because the time required to evaluate a proposed design modification is drastically reduced, CN is able to examine a broader range of alternatives than was possible before the development of TRIM. That capability translates into designs more precisely tailored to the demands expected to be placed on the yards. In turn, CN will achieve more effective application of its capital investments, because the minimum investment necessary to meet demand can be more easily identified through extensive analysis of alternatives.

Before embarking on the development of TRIM, CN first surveyed the industry to determine whether an existing modeling technique met the company's needs. Several attempts have been made over the past 15 years to create fully automated models of yard operations to supplement the manual techniques most commonly used in the industry. But none of these replicated actual yard operations as successfully as manual simulations, and therefore none was in extensive use. The shortcomings of most previous attempts at computer simulation of yard operations were fourfold:

1. Attempts at mathematical model formulations were either too simplistic (assuming away most of the problem being tested) or overly complex (because of an inability to select an appropriate number of parameters for inclusion in the model);
2. Attempts at logic-based simulations were limited in their flexibility by the requirements of the computer representation used, frequently ignoring important elements of the yard's resources;
3. Data requirements for many simulations were prohibitively large and required some computer knowledge on the part of the analyst; and
4. Many simulations were highly location specific; they worked well for the yard under study but would require almost a total redesign or rewrite for use in a different yard.

In addition, most models are oriented toward hump yards and permit little or no flexibility in the simulation of various kinds of yards. The dynamic interaction of the various components of a yard is lost in these models because of the difficulties in simulating this kind of interaction. Thus, CN determined that existing models would not meet its criteria for accurate replication of both flat- and hump-yard operations, including all of the flexibility and critical yard and terminal dynamics that a detailed simulation requires.

One of the main features of TRIM is that it is designed to be used by railroad personnel. A knowledge of computers and scientific modeling is not required. The system converses with the analyst entirely in railroad terms. A familiarization period of a few weeks is required for the analyst to become comfortable in the use of the model and aware of its numerous features. In performing the simulation, the analyst or analysts simultaneously play more than one role. Part of their function is to be a yardmaster, determining the overall strategy of operating their portion of the yard. In addition, they are also switching foremen and inspection crew foremen as they carry out the more detailed work of the yard.

HOW TRIM WORKS

General Objectives

Because the objective was to design a model that could be used to study a yard in great detail, TRIM has the ability to handle all major operations that occur in a yard. The study team is free to choose the amount of detail that is appropriate to the objectives of the yard under study. For example, in evaluating a particular yard design, it may be suspected that insufficient departure tracks result in frequent congestion in the classification yard as trains are made up. In this case, the specific track geometry of these parts of the yard would be represented in the model. In other cases, the track geometry could simply be approximated, combining or ignoring certain tracks that were not expected to have any significant impact on yard performance. A second example of optional detail would be crew management and utilization. TRIM can specifically model the detailed work carried out by inspection crews. If there are too few crews, the result will be trains waiting for inspection; too many crews would later result in low crew utilization. Should these human resources not be a constraint (or of interest) in a particular evaluation, they could be ignored completely. TRIM also allows the time window for yard activities to be adjusted. For many types of simulation, specifying the duration time of any activity to be a minimum of 1 min (or more) results in no significant loss of accuracy.

In the discussion that follows, the detailed operations that TRIM can handle will be presented. It is important to remember that much of the detail is optional if the study objective is not compromised by its omission.

Resources

TRIM requires the analysts to manage four major kinds of yard resources.

Structural Resources

Tracks and their connection pattern define the yard under study. Track length is the only other required parameter. If desired, TRIM can also model the foul-point locations from either end and the location of inert retarders. Unless the analysts want to specifically model throwing switches by hand, these can be ignored and the model will infer the switch characteristics from the permissible track transitions specified.

Passive Resources

The cars on inbound trains and those cars initially in the yard are the only passive resources. No other information need be provided about cars other than an average car length and the number of cars and their sequence on each inbound train. Nevertheless, the user will typically want to include additional information about each car because it is this information that implicitly defines the work to be done. The most important optional items are

1. Car initial and number,
2. Car length,
3. Car weight,
4. System destination,
5. Local destination,
6. Special handling instructions,
7. Contents (commodity), and
8. Bad-order information.

Because TRIM allows the user to examine these items (typically by examining all cars on a specified track), the decision on how to handle a car will be based on the system destination, whether a car is bad ordered (in need of repair), and so forth.

Active Resources

Work in a yard is done by locomotives and crews. Typically, road engines bring trains into and out of the yard and switching engines perform the work in the yard. Crews are used to operate the locomotives and to perform switching and inspections. Therefore, it is these two resources--crews and locomotives--with which the analyst is most actively concerned. For example, TRIM does not allow car movement unless an engine is associated with it. Nor will it allow a train to be inspected if an inspection crew is not available at the appropriate track.

Information Resources

TRIM simulates the major information documents on the basis of which a yardmaster would run the yard. Detailed knowledge about inbound trains is from an advance consist. Switch-hump lists must be prepared by making use of predefined (and modifiable) switching tables. Also, as described later, a major yard inquiry subsystem is available to the yardmaster.

Simulation Concept

The major consideration in using the TRIM model is that it does only what it is specifically instructed to do. More than one yard analyst at a time can participate in the simulation. The active resources--locomotives and crews--are assigned to the specific analysts, and they then issue commands to accomplish specific functions. An analyst can issue commands controlling only his own assigned resources. Those resources can be reassigned, if desired. A typical scheme would parallel the sphere of control by a yardmaster in a tower. For example, one analyst may be in control of the receiving yard, another the departure yard, and a third the hump operation. It is by proceeding in this deterministic manner that the plant and operating rationale is evaluated.

The TRIM commands that control the yard operations fall into four main categories.

Movement Commands

Movement commands advance locomotives (with or without coupled cars) along a route specified by the analyst. As part of the command, the analyst specifies the destination and duration of the move. Optionally, the analyst can kick or set off cars. Other commands permit the analyst to switch cars or hump a train. To support these latter activities, TRIM maintains switching tables, which are automatically referenced when an analyst prepares a switch list. Of major interest is the detection and handling of conflicts in the yard. Should a track already be occupied along a route, for example, the system warns the analyst. If so instructed, the simulation will advance the locomotive to the blockage, wait until it has been cleared, and then resume the balance of the move.

Crew-Movement Commands

Crew-movement commands affect control of the crew resources. Included is the ability to call or relieve crews, assign them throughout the yard to tracks or to locomotives, and issue commands for them to inspect trains. As with car and locomotive movement, the analyst specifies the duration of the foregoing activities.

Coordination Commands

Commands that allow the analyst to control yard environment but that are not specifically associated with movement are coordination commands. Such commands as requesting notification when specified yard conditions arise, waiting for specified periods of time, performing switching-table maintenance and preparing switch lists, and setting and removing blue flags on tracks would be included.

Inquiries

Because it is not possible to control yard resources without a detailed knowledge of where they are, a comprehensive inquiry system has been incorporated into TRIM. It is based on CN's computer-based Yard Inventory System (YIS) now in use at CN hump and flat yards. Car lists for specified tracks can be obtained, for example, that show not only the detailed car data but also the specific car locations on the track. Other inquiries allow information to be summarized by system destinations, advance consists of trains due in the yard, and so forth.

Numerous additional capabilities will be added to TRIM over the years. The most important ones will be those that automatically handle certain basic decisions, removing these burdens from the analyst. One example is the incorporation of standards into the model. Based on locomotive dynamics, number of cars, and total length, the time for a move could be determined automatically. Similarly, the time to switch a set of cars could be determined from the sequence of system destinations in a switch list. Eventually, certain sequences of commands could be generated automatically. For example, a train could be automatically made up for departure, trains automatically switched in sequence, and so forth.

Evaluating the Results

Although the study team will have developed a certain feel for the performance of a tested yard alternative at the conclusion of a simulation run, this must be backed up by more-detailed statistics.

It is in this area that TRIM exhibits a distinct advantage over manual techniques. TRIM records in a log file all activities as they occur in the yard. With the data recorded in this form, it is possible to create any type of analysis report. When done manually, preparation of analysis reports could take months. Thus, not only does TRIM speed up the simulation of a yard, it also permits a more timely analysis of the simulation results. The following report types are produced:

1. Graphical representations of track population over time for specified track groups; percent utilization and cars handled are also maintained;
2. Statistics about crew utilization--time working, time in transit, time idle;
3. Statistics about locomotive utilization--total miles loaded, total miles light, time working, and time idle; and
4. Statistics about conflicts and delays in the yard.

DETAILS OF TRIM'S OPERATION

TRIM is applied in three distinct phases: preprocessing, or preparing and validating the input data; simulation, or performing the simulation; and postprocessing, or producing and analyzing the results. Figure 1 shows the relationships among the phases.

Preprocessing

Input data for the model are collected in the first phase and subsequently validated by TRIM for correctness and consistency. Considerable effort must go into creating the input files if realistic yard activities are to be produced by the analysts. Up to five input files may be prepared.

Tracks

The track file is mandatory and would most likely take an analyst from 1 to 4 weeks to prepare depending on yard size. A large yard may have approximately 1,000 track sections. All tracks are assigned unique names and the legal movements between tracks must be specified. TRIM validates this file when constructing the network and informs the user of errors and inconsistencies.

Switches

Although the user can specifically name the switches that connect tracks, this file would usually be omitted. During a simulation, the analyst would probably never have to be concerned with switch names.

Initial Population

The initial-population file is optional. If it is omitted, however, an extra day or two of simulation may have to be performed to reach a stable car population in the yard. The data contained in the file are the yard's locomotives, cars, and crews and the specific track locations.

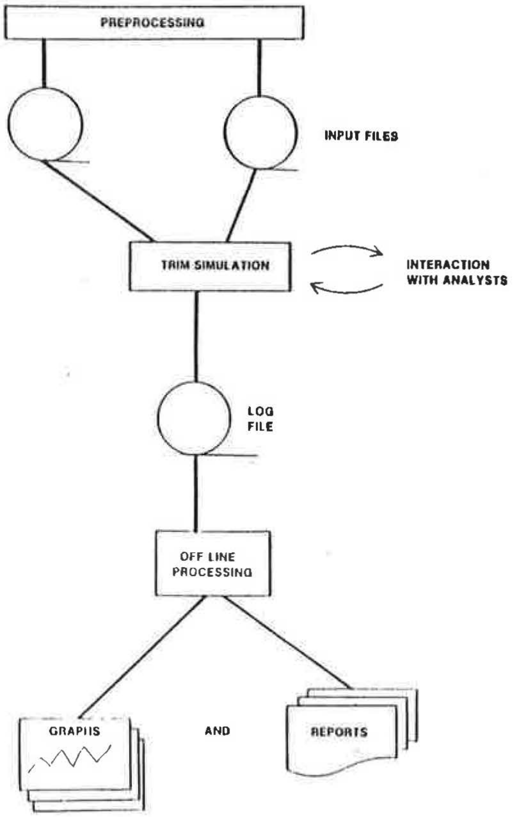
Crew Schedule

The crew-schedule file is optional. If it is included, the model will call crews automatically at the specified time.

Inbound Trains

Although it is optional, the inbound-train file is usually a key file as is the track configuration.

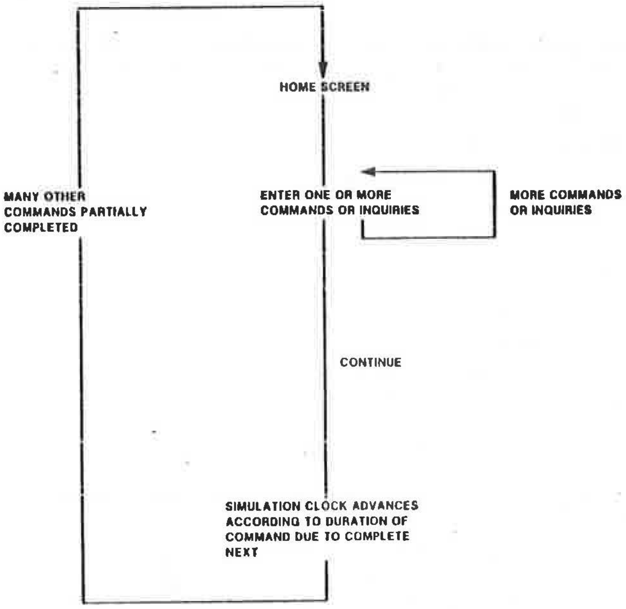
Figure 1. Relationships among phases.



For each train, the file contains the time of arrival and the arrival track, the number and type of locomotives, and the sequence and detailed information for each car. Each element is important. For example, incorrectly specifying the number or type of locomotives would make it difficult to dispatch trains later because of a lack of power in the yard. Unrealistic marshalling of cars on inbound trains would significantly change the work to be done in the yard. CN uses its computer-assisted network analysis tool (CANAT) forecasting system to generate inbound trains. A realistic workload can be obtained for up to 10 years in advance. This forecast is then scrutinized and, if necessary, edited manually so that any changes can be made before it is used for TRIM. The value of a computerized forecasting system is apparent when it is considered that up to 15,000 cars can enter a large hump yard during the course of a 3-day simulation. Nevertheless, numerous shortcuts are possible if the study does not require that all the detail be included.

Although not strictly part of the input files or preprocessing, the determination of a realistic train service design for outbound trains is an important activity before simulation. This sets the goal for the work to be carried out.

Figure 2. Simulation sequence.



Simulation

TRIM is an event-based simulation in that it moves forward through time from one activity to the next. The model examines the jobs it has to do (based on the commands that have been entered), selects the one that will be completed first, and moves the simulation clock ahead by that amount of time. It then adjusts all yard resources to their new position. As a result, certain resources will have reached their destination, others will have advanced only partially, and still others will remain where they were initially because no specific command was given to move them. Figure 2 shows the patterns when only one analyst is working.

As an example, suppose that two commands are given before the analyst instructs the simulation to continue:

1. Assign a crew to a track (traveling time is 5 min) and
2. Move a locomotive along a specified three-track route (traveling time is 7 min).

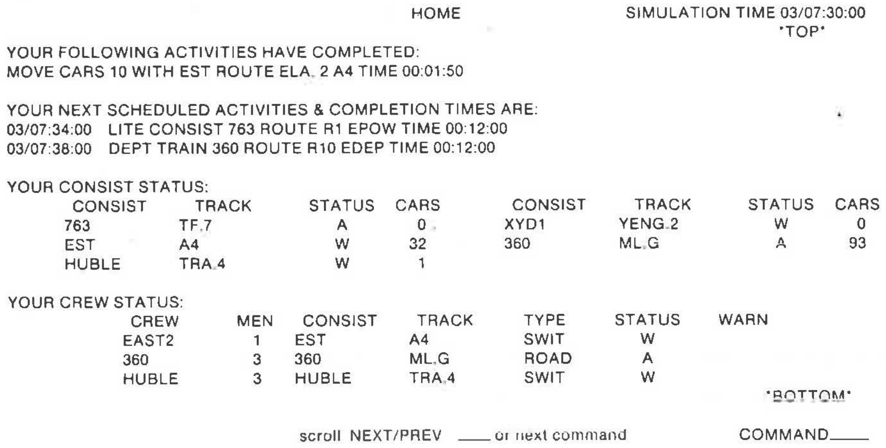
When the analyst gives the command to continue simulation, the simulation time would move forward 5 min. The crew would be located at the new track, and the locomotive would be on an intermediate track between its origin and destination.

In a large simulation, numerous commands could be only partially complete after the clock has advanced and control has returned to the analyst. When control returns, the analyst would be presented with a home screen (Figure 3). The home screen would inform him what the new simulation time was, describe what activity had just been completed, and provide a list of all other pending activities and their expected completion times. It would also indicate the current location and status of crews and locomotives, the resources that were capable of performing further work. Based on the home screen, the analyst could

1. Request a more-detailed yard status report to assist in determining what commands to enter,
2. Request a formatted screen so a new command could be entered, and
3. Instruct the simulation to continue without more commands.

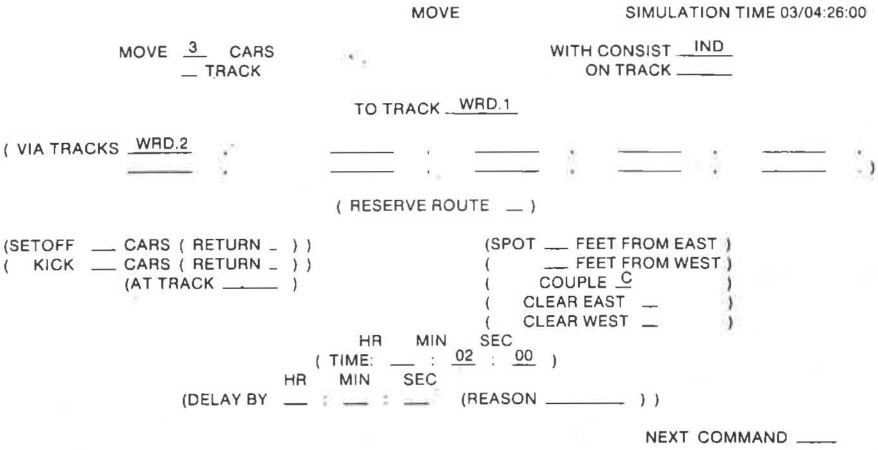
Figure 4 shows a screen that an analyst has

Figure 3. Home screen.



```
                              HOME                         SIMULATION TIME 03/07:30:00
                                                                         'TOP'
YOUR FOLLOWING ACTIVITIES HAVE COMPLETED:
MOVE CARS 10 WITH EST ROUTE ELA. 2 A4 TIME 00:01:50

YOUR NEXT SCHEDULED ACTIVITIES & COMPLETION TIMES ARE:
03/07:34:00   LITE CONSIST 763 ROUTE R1 EPOW TIME 00:12:00
03/07:38:00   DEPT TRAIN 360 ROUTE R10 EDEP TIME 00:12:00

YOUR CONSIST STATUS:
      CONSIST      TRACK        STATUS  CARS      CONSIST     TRACK       STATUS   CARS
      763          TF.7           A       0       XYD1        YENG.2        W        0
      EST          A4             W      32       360         ML.G          A       93
      HUBLE        TRA.4          W       1

YOUR CREW STATUS:
             CREW        MEN   CONSIST    TRACK     TYPE     STATUS     WARN
             EAST2        1    EST        A4        SWIT       W
             360          3    360        ML.G      ROAD       A
             HUBLE        3    HUBLE      TRA.4     SWIT       W
                                                                         'BOTTOM'

                  scroll NEXT/PREV ____ or next command          COMMAND____
```

Figure 4. Move command.



```
                                  MOVE                    SIMULATION TIME 03/04:26:00

          MOVE _3_ CARS                                  WITH CONSIST _IND_
               _ TRACK                                     ON TRACK _____

                               TO TRACK _WRD.1_

( VIA TRACKS _WRD.2_      _____  _____  _____  _____ )
             _____        _____  _____  _____  _____ )

                            ( RESERVE ROUTE _ )

(SETOFF  __ CARS ( RETURN _ ) )              (SPOT __ FEET FROM EAST )
(  KICK  __ CARS ( RETURN _ ) )              (     __ FEET FROM WEST )
         (AT TRACK _____ )                   (      COUPLE _C_       )
                                             (   CLEAR EAST  _       )
                                             (   CLEAR WEST  _       )
                                 HR    MIN    SEC
                          ( TIME: __ : _02_ : _00_ )
                      HR     MIN    SEC
          (DELAY BY __  :  __  :  __     (REASON ______ ) )

                                                   NEXT COMMAND ___
```

filled out to specify a sample move command. Because most commands follow a fill-in-the-blank approach, they relieve the analyst from memorizing complex computer commands. The move command also offers the analyst a choice of how to specify the move. For example, he can specify the locomotive consist or the track that the cars are on. In this case, the consist was specified. Items on the screen directly underneath each other represent a choice. Furthermore, certain items are optional; these are indicated by parentheses. If time were not specified, the simulation would calculate it based on total distance to travel plus certain default track speeds. It can be specified that cars be spotted (aimed at a certain point) or the system can choose to default. In the latter case, cars are spotted clear of the switch foul point. In the next-command item, the analyst can name another command screen he wants next, continue the simulation, or take any of a number of other actions. TRIM performs numerous validation checks before a command is actually accepted into the queue for processing. Resource names must be correct and the resources available, routes must not be blocked, and so on. Appropriate errors and warnings are issued.

When more than one analyst is working on the yard, the simulation must, by its nature, stop when an activity has been completed by any one of them. Only one analyst, therefore, may be in a position to enter new commands. It would not be appropriate for other analysts whose commands are only partially complete to enter new ones. Nevertheless, they could perform inquiries into yard status as an aid to planning future commands. TRIM is currently designed to handle up to 10 analysts working at one time. It is estimated that two analysts would be required for a medium-sized flat yard; four or five analysts would be needed for a major hump yard.

An important feature built into TRIM is the ability to check the yard status at a particular time. If this is done on a regular basis, work already accomplished will not be lost in the event of computer malfunction or power failures. Such a check also allows different yard-operating strategies to be evaluated from a common base condition. For example, if the yard status at 1,400 hr is deemed unsatisfactory, it is possible to continue simulation from an earlier checkpoint and operate the yard under a different strategy.

Postprocessing

As the simulation proceeds, TRIM performs extensive data logging. The purpose is to record what happened during the simulation. Therefore, each car movement on and off each track is logged, along with the corresponding detailed locomotive and crew movements. The log tapes are then processed through a comprehensive reporting system, separate from TRIM itself. It is not necessary to wait until a simulation has concluded; analysis reports can be produced at any time. If different strategies have been followed from a common based checkpoint condition, the data from either path can be selected for the postprocessing. The log file captures virtually all the yard activity that transpired and is independent of any specific report. By further splitting the log file into subfiles, however, almost any type of report can be developed. At this time, the following reports are available:

1. Track population (graphical),
2. Receiving and departure (R&D) occupancy (graphical),
3. Lead occupancy (graphical),
4. System destination population (graphical),
5. Track throughput,
6. Throughput by car type,
7. Crew utilization (switching or inspection),
8. Locomotive utilization (switching or road), and
9. Conflict and delay.

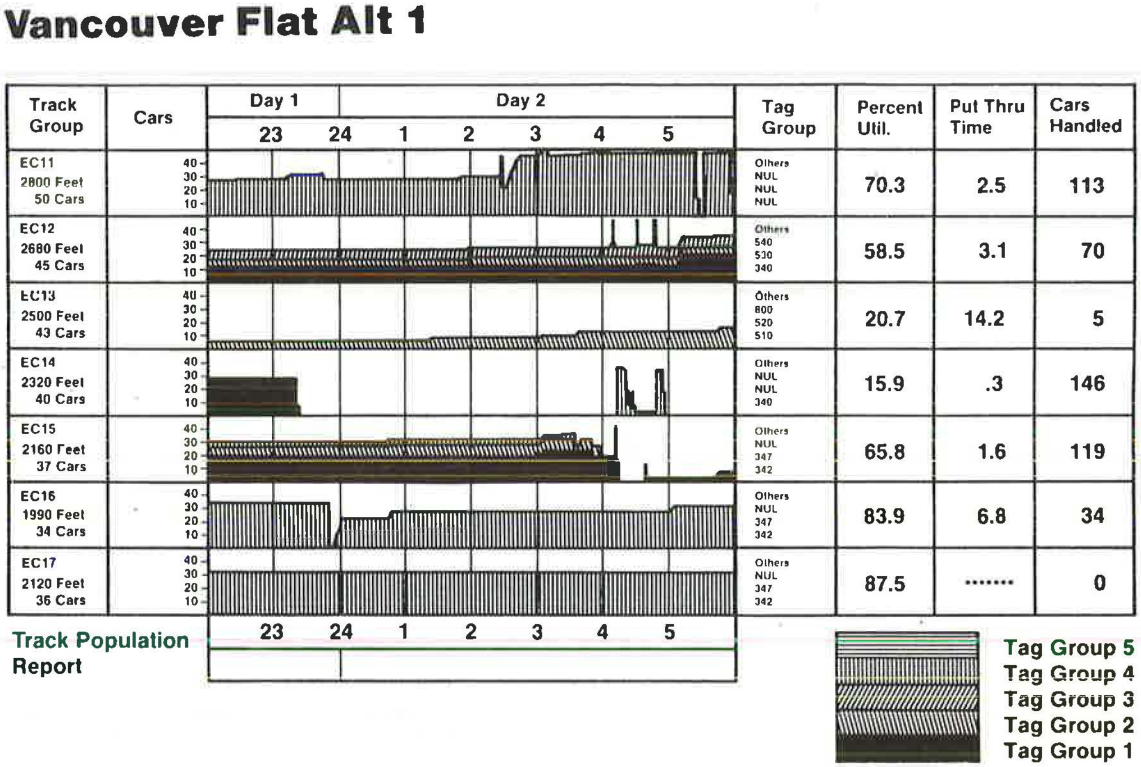
Each report allows the analyst a great degree of flexibility. The analyst can choose to extract and consolidate only those operations in which he is interested. For example, the analyst may specify a time window to use for reporting results so that the activities performed in generating an initial population do not distort the overall statistics. Track population can be examined on an individual track basis or specified tracks may be grouped together to form an aggregate population. Individual reports are tailored to an analyst's requirements by preparation of a control table that governs the selection and consolidation of the associated reporting program.

Two report types are illustrated. Figure 5 shows a graphical report of track population. It may be noted that the population is further broken down into its constituent system destination groups. Figure 6 shows a report on locomotive utilization that indicates how much time was spent in various working and idle categories plus total miles traveled in the yard.

COMPUTER CONSIDERATIONS

The nature of the TRIM simulation made it desirable

Figure 5. Track population graph.



for CN to acquire a separate computer to run the model. The primary reason was the intended heavy use of TRIM. In anticipation of extensive traffic growth in western Canada, virtually every yard in that part of the country will be analyzed by using the model. Because the model is to be used on a continuing basis, it was more cost effective to dedicate a computer to it than to pay recurring charges on CN's central computers. Another advantage of a dedicated computer is that for interactive simulations minicomputers offer many features that are more flexible and easier to use than do main-frame computers.

There were certain technical requirements that the computer system had to meet:

1. The programming language desired was PL1. Although it would have been possible to write the simulation with FORTRAN, PL1 offers much more flexibility in defining data structures, an important consideration in light of the complex relationship of yard resources.
2. The system had to have virtual memory--the ability to run a program larger than the capacity of main memory. This was important because yard data (tracks, cars, and so on) can, in a large simulation, require substantial storage.
3. The computer had to support multiprogramming.
4. The computer had to be upgradable in place to significantly higher capacity to be able to support more than one concurrent TRIM study as well as other transportation planning simulation models.

All the preceding requirements served to narrow down considerably the list of candidate computers. CN determined that a PRIME 550 system was the most cost-effective computer. The current configuration is as follows:

1. PRIME 550 central-processing unit,
2. A 2.25-MB main memory,
3. One 300-MB disk drive,
4. One tape drive,
5. One 300-line/min printer,
6. Six terminals, and
7. Communication capability with CN's main-frame computers.

A color-graphics terminal has been acquired and will be used to provide a bird's-eye view of yard status.

In the design of TRIM applications software, certain important features were considered:

1. All commands are entered via CRT terminals in a fill-in-the-blanks mode;
2. The model handles a varying number of analysts, who can attach to and leave the simulation as desired; and
3. TRIM is designed so that it is not permanently tied to any one computer system. For example, TRIM could in a relatively straightforward manner be changed to run on an IBM main-frame computer.

EXPERIENCES WITH THE MODEL

Three yards were studied with TRIM in 1982. Kamloops and Prince George are medium-sized flat yards, and Thornton is a major flat yard; all are in British Columbia.

In the case of Thornton, two flat and one hump configuration were simulated. The hump alternative had 11 departure and 12 receiving tracks, 48 tracks in the classification yard, and a surge yard with 12 tracks. The total number of tracks, including connecting tracks and crossovers, was more than 600. The overall goal of the simulation exercise was to evaluate several yards expanded to handle projected 1991 traffic volumes and requiring the handling of approximately 3,600 cars daily. The strategy employed was to use yardmasters experienced in Thornton operations, plus up to three yard analysts who

Figure 6. Locomotive utilization report.

LOCOMOTIVE REPORT

VANCOUVER - FLAT ALTERNATIVE I

			HOURS			MILE		CARS	
CONSIST	SHIFT	CREW	WORK	BLOCK	IDLE	LOADED	LITE	HANDLINGS	AVG/MOVE
East 1	01/2200-02/0600	East 1A	3.68	0.16	4.16	48.3	14.6	607	17.1
	02/0600-02/1400	East 1B	3.96	0.05	3.99	35.8	16.8	473	10.0
	02/1400-02/2200	East 1C	4.26	0.13	3.61	23.8	13.3	243	3.4
	02/2200-03/0000	East 1A	1.29	0.07	0.64	5.7	4.4	87	6.4
Sub Total			13.19	0.41	12.40	113.6	49.1	1410	
East 2	01/2200-02/0000	East 2C	0.10	0.08	1.82	0.1	1.0	1	-
	02/0000-02/0800	East 2A	3.87	0.27	3.86	32.0	15.3	400	6.7
	02/0800-02/1600	East 2B	3.81	0.05	4.14	25.4	15.5	348	6.3
	02/1600-03/0000	East 2C	4.20	0.01	3.79	32.7	7.1	569	19.0
Sub Total			11.98	0.41	13.61	90.2	38.9	1318	
West 1	01/2200-01/2300	West 1C	-	-	1.0	-	-	-	-
	01/2300-02/0700	West 1A	3.52	0.56	3.92	25.3	13.1	492	11.6
	02/0700-02/1500	West 1B	4.10	0.21	3.69	23.9	15.8	409	12.7
	02/1500-02/2300	West 1C	3.63	0.31	4.06	31.0	10.2	335	8.7
	02/2300-03/0000	West 1A	0.56	0.03	0.41	3.7	3.1	45	5.9
Sub Total			11.81	1.11	13.08	83.9	42.2	1281	
West 2	01/2200-02/0600	West 2A	3.52	0.15	4.33	40.9	15.7	445	11.7
	02/0600-02/1400	West 2B	4.19	0.19	3.62	29.2	24.4	453	7.1
	02/1400-02/2200	West 2C	4.16	0.24	3.60	34.5	16.6	264	6.6
	02/2200-03/0000	West 2A	0.92	0.19	0.89	5.2	3.3	58	7.1
Sub Total			12.79	0.77	12.44	109.8	60.0	1220	
Unit 1	01/2200-01/2300	Unit 1C	-	-	1.0	-	-	-	-
	01/2300-02/0700	Unit 1A	4.10	0.36	3.54	37.3	22.8	283	10.3
	02/0700-02/1500	Unit 1B	4.02	0.26	3.72	45.9	14.7	281	13.5
	02/1500-02/2300	Unit 1C	3.50	0.12	4.38	30.1	16.7	231	11.7
	02/2300-03/0000	Unit 1A	0.53	0.01	0.46	4.60	2.5	61	11.0
Sub Total			12.15	0.75	13.10	117.9	56.7	856	
Total			61.92	3.45	64.63	515.4	246.9	6085	

actually used the CRT screens to translate the yardmasters' general directives into more specific yard commands. Two analysts tended to handle most of the locomotive and car movement commands, whereas the other handled crew assignments and inspections.

Several lessons have been learned from the simulations carried out so far:

1. Each analyst should have about 2 or 3 weeks of training with TRIM before participating in a full-scale simulation. Although each individual TRIM command is straightforward, the training period is necessary because of the number of commands available and their options and the requirement to be able to develop a good overall familiarity with the current yard status.
2. The simulation team will require about a week of working together before a teamwork relationship develops fully. The team members will develop their own sharing of responsibilities, methods, and shortcuts to perform an efficient and well-coordinated simulation.
3. The amount of detail included in the simulation must be traded off with the time to complete the study. In the case of Thornton, certain track sections were consolidated (tracks going up a switching ladder, for example) in order to simplify route specification. Some crew-related activities were simplified as well.
4. The time window for activities should be specified as being at least 2 or 3 min. Setting the value too small can cause the simulation time jumps to frequently be only several seconds long. It is more efficient to force the simulation to handle all activities up to the longer time-window mark. In this case, some resources would remain unnecessarily idle until the end of the window, when new commands could be entered. Nevertheless, little accuracy is lost with this scheme, and the increased opportunity for analyst coordination is a major benefit. This is especially important in the simulation of larger yards with more than two analysts at computer terminals.
5. The simulation rate achieved for Thornton was approximately 2 hr of yard simulation during each working day of the simulation or about one full yard day each 2.5 weeks of simulating. Intermediate and final graphical and tabular reports were available on request. A large flat yard such as Thornton takes longer to simulate because of the requirement for a large number of yard analysts. The hump alternative simulation proceeded significantly faster, as did that of the smaller flat yards. Inclusion of graphics and automatic time standards is expected to further increase the simulation rate substantially.

TRIM Simulation of Canadian National Railways' Thornton Yard

J.L. ZADEL

The Canadian National Railways terminal interactive model (TRIM) was used to simulate five selected design alternatives to choose the best design for Thornton Yard. Cost estimates were developed for each design, ecological and property impacts were assessed, and interference with existing operations during construction was determined. The first set of simulations reduced the five alternatives to three—two flat-yard designs and one hump-yard design. Further simulation resulted in the selection of one of the flat-yard designs. Additional simulations were run to fine tune the design selected.

Vancouver, British Columbia, is Canada's largest West Coast port. Major export commodities include coal, grain, potash, and sulfur with lesser volumes of forest products, chemicals, mineral concentrates, and general cargo. Imports include phosphate rock, automobiles, and various other containerized and general commodities for both Canadian and U.S. markets. In addition to the international movements, greater Vancouver (approximate population 1.5 million) generates a considerable volume of inbound and outbound local traffic.

Canadian National Railways (CN), which is the larger of Canada's two transcontinental carriers, captures a significant share of rail traffic to and from Vancouver. In addition to export and local volumes, CN interchanges traffic with Burlington Northern Railroad, British Columbia Railway, Canadian Pacific Railway, and British Columbia Hydro Railway.

Thornton Yard, located in suburban Surrey, is the hub of CN's operation in greater Vancouver. It is the classification, distribution, surging, and inspection point for all Vancouver traffic as well as the servicing and repair point for most rolling stock moving through the region.

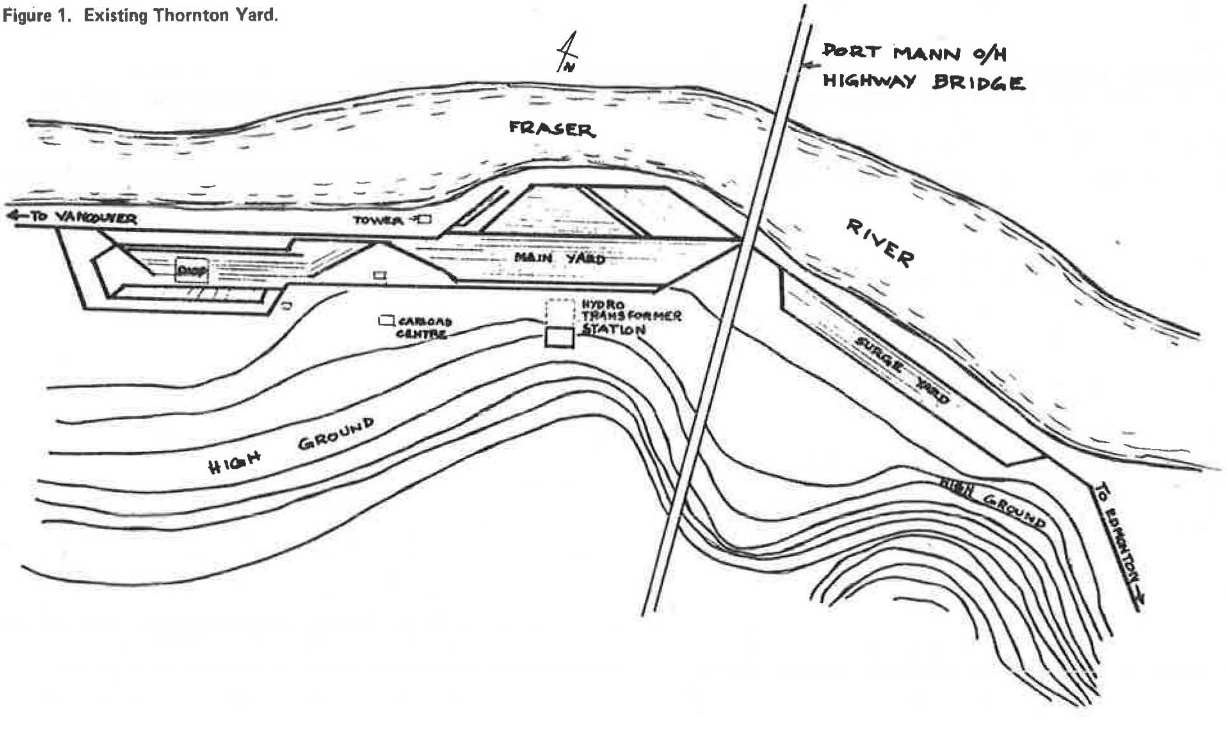
Thornton, a flat yard with a standing capacity of 4,700 cars, now dispatches some 650,000 cars per year. This is forecast to increase by more than 50 percent during the next 10 years. Current operating conditions clearly indicate that Thornton, like many other CN yards in western Canada, will be unable to cope with this level of growth. It was therefore decided to design an expanded plant that would be capable of handling traffic growth projected for the next 10 to 15 years.

DESIGN CONSTRAINTS

As shown in Figure 1, Thornton Yard is located on a narrow strip of relatively unstable land, bounded by the Fraser River on the north and rapidly rising topography to the south. Other constraints include a large electric utility station and the Port Mann Bridge, a major four-lane structure. In addition, railway facilities such as the carload center (yard office), car and diesel shop, and the yardmasters' tower are located throughout the west end of the property.

Despite these constraints to plant expansion, a preliminary analysis ruled out relocation of Thornton Yard facilities to another site on economic and operational grounds. Therefore, it was decided to expand the existing Thornton Yard. The high cost of grading and structure relocation and the ecological impact of expanding into the river dictated a judicious use of all available property.

Figure 1. Existing Thornton Yard.



STUDY METHODOLOGY

The optimum design for a system as complex as a major freight yard is difficult, if not impossible, to define. Nevertheless, the best design can be selected from a range of alternatives by using simulation techniques. Selected alternatives can be further refined through analysis of simulation data and additional simulations.

CN's terminal interactive model (TRIM) is probably the most powerful yard simulator available today. It was clear that a series of TRIM simulations would produce a design that would make the most effective use of available property and satisfy most other design criteria while providing a balance between capital and operating costs.

The general study methodology using TRIM involved six basic steps:

1. Development of design-day workload,
2. Identification of alternatives,
3. Input of simulation data,
4. Simulation process,
5. Analysis and evaluation of simulation results and selection of best alternative, and
6. Fine tuning of selected alternative.

Note that data and methodology are similar to those of a yard study using manual simulation techniques. The major difference is level of detail.

Workload Development

Before the design-day workload could be developed, a thorough understanding of current Thornton traffic patterns was necessary. Export coal, potash, and sulfur move in 98-car unit trains that require no switching as they pass through Thornton on the way to the tidewater bulk terminals. On the return (eastbound) move, bad-order cars are switched out of the empty unit trains and replaced with serviceable equipment. Unit trains make up about 55 percent of Thornton traffic. Most grain arrives in 100-car solid trains that require substantial switching at Thornton, because some grain must be delivered to specific elevators. Solid grain trains make up 15 percent of total traffic.

An additional 10 percent of the traffic moves in 15- to 30-car blocks because of specific origin-destination patterns. This includes cars carrying wood chips, chemicals, copper concentrates, alfalfa pellets, and some grain and potash. These blocks stay intact when switched at Thornton Yard. The remaining 20 percent is general carload traffic that requires car-for-car switching.

Future yard workloads for various traffic segments are determined on the basis of 10-year forecasts provided by CN's Marketing Department. CN's computer-assisted network analysis tool (CANAT) is used to translate these forecasts (which are expressed in tonnages) into a design-week train service pattern. Data generated by CANAT for non-unit-train traffic are further refined by CN's CANATerm model, which marshals and blocks cars on arriving trains in line with historic performance, future service design specifications, and projected customer demands. Minor manual modifications to the CANAT and CANATerm data were required to account for some Thornton Yard idiosyncrasies and to develop the internal yard workload for such operations as weighing cars, repairing bad-order cars, releasing cars being held, and handling dangerous commodities.

In line with current CN practice, the day of the design week with the second highest workload was selected as the design day. The design-day workload thus exhibits a peak about 30 percent higher than the annual daily average.

With the inbound and internal yard workloads defined, the final step in workload development was defining the initial yard population. This was one of the most difficult aspects: Historic samples were not adequate because the traffic levels and the plant were unlike those experienced in the past. The procedure used was to first develop a preliminary estimate of an initial yard population by using manual approximation methods. This population level was used as the basis for a preliminary simulation of a 24-hr period. The yard inventory at the end of this preliminary simulation was then used as the initial population for the simulations of the design-day operation.

The outbound workload is, of course, primarily a function of the simulated performance of the yard. Outbound train patterns and marshalling for nonunit trains were based on projected service design specifications. Outbound unit-train service depended on the arrival time of the corresponding inbound trains, which in turn was based on a random historic pattern.

Identification of Alternatives

Plant

At the outset, 11 alternative plant design concepts were defined through discussions between system and local planning and operating personnel. By a process of elimination and further discussion, this number was reduced to five designs that broadly satisfied all design parameters. Each of the five alternatives was sized for future workload by using projected throughput and occupancy calculations. Leads were designed on the basis of current design standards and crossovers were placed in locations dictated by discussions of various operating moves. This facilitated drawing of each alternative to scale. It was now possible to develop detailed cost estimates for each design, assess ecological and property impact, and determine interference with existing operations during construction.

The result of this process was the elimination of two more alternatives; this left two flat designs and one hump design for further analysis. These designs, which are shown in schematic form in Figures 2, 3, and 4, were further assessed for cost, interference with operations during construction, and ecological ramifications. These assessments resulted in additional design refinements. Once the necessary changes had been made, the three alternative plant designs were ready to code for TRIM input.

Operation

A variety of operating options was developed as an integral part of discussing each design alternative. Leads, crossovers, and various yard segments of each alternative were actually designed on the basis of specific operating parameters.

These operating parameters were reassessed and organized to satisfy the layout of each yard. Features such as arrival and departure routes, receiving and departure yard segments, and classification and train make-up patterns were defined. Internal flow of bad-order cars and cars to be weighed, distribution of empty cars, and storage of cars being held and dangerous cars were also ascertained and incorporated into the total operating package for each alternative. These operating strategies then served as the basic rules of operation during each simulation. To put the basic operating differences

Figure 2. Thornton Yard: flat plan 1.

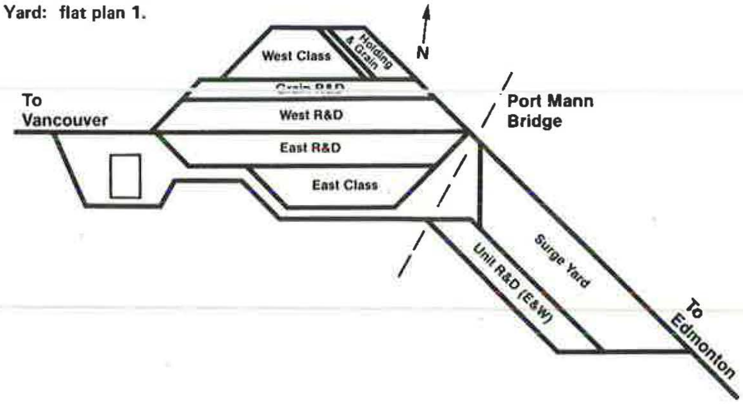


Figure 3. Thornton Yard: flat plan 2.

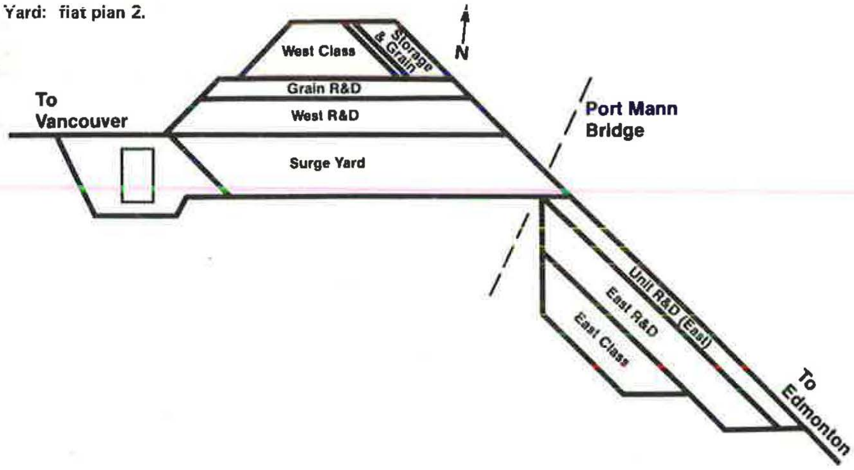
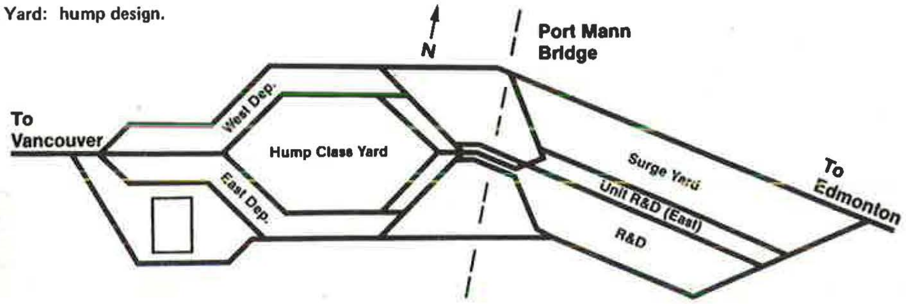


Figure 4. Thornton Yard: hump design.



into perspective, a brief description of the operating rationale for each alternative follows.

Operating Alternatives

Flat Plan 1

In flat plan 1 traffic flow through the yard is separated into three segments. All unit-train traffic in both directions is handled in the unit receiving and departure (R&D) yard and surge yard located east of Port Mann Bridge. Loaded westbound unit trains bypass the surge yard and main Thornton Yard (located west of Port Mann Bridge) on their way to the unloading terminals. If a unit train cannot proceed directly to the unloading point, it is held in the surge yard until required by the bulk terminals for unloading. In the eastward direction empty unit trains again bypass main Thornton Yard along the south side and are held in the unit R&D tracks. Inspection, servicing, and bad-order replacement take place in this yard; switching activity is confined to dedicated leads.

Non-unit-train traffic flows through the main body of Thornton Yard bidirectionally. Westbound trains bypass the unit-train yard and arrive at the west R&D yard. Classification of this traffic takes place at the west end of the west R&D and west classification yards. Westbound transfers are then made up from the west classification yard to west R&D tracks by pulling in a westerly direction on dedicated switching leads.

Westbound grain trains are held in the grain R&D tracks and are switched from the grain R&D yard to grain classification and storage tracks at the east end. Once again this takes place on separate leads. In this entire process eastbound movements and unit-train movements are not affected by the westbound flow.

Eastbound transfers are held in the east R&D yard. All classifying takes place at the east end of this yard on separate leads. Train makeup from the east classification yard to east R&D tracks can be performed on either end, independent of westbound and unit-train movements.

Flat Plan 2

Flat plan 2 separates the traffic flow by direction. All westbound traffic, unit and nonunit alike, is held in the west R&D yard, grain R&D yard, or the surge yard. West classification and grain classification processes are identical to those for flat plan 1. All switching and train makeup takes place on separate leads. The surging function is performed in the surge yard when required.

All eastbound movements bypass the west yard (i.e., trackage west of Port Mann Bridge) along the south side and arrive into R&D tracks in the east yard. Unit-train bad-order switching takes place on dedicated leads at either end of the unit R&D yard. Classification of non-unit-train traffic is done on separate leads at the west end of east R&D and east classification yards. As in flat plan 1, train makeup can be done from either end.

Hump Operation

In this design the surge yard, unit-train R&D yard for eastbound trains, and receiving yard for non-unit-train traffic were located east of Port Mann Bridge. Classification took place in a westerly direction by shoving from the receiving tracks and humping into the classification tracks west of the bridge. Train makeup was performed by pulling from the classification tracks in a westerly direction and making up east and west departure trains in their respective departure yards. Loaded unit trains moving in the westerly direction had the option of bypassing the entire plant along the north side or being held in the surge yard. One of the major problems with the hump design was the conflict between eastbound trains arriving into the receiving yard and the westward humping process.

Simulation Data Input

Workload

Design-day traffic flow generated by CANATerm is produced in TRIM format. Consequently, the train file (i.e., arriving traffic during the simulation) was constructed by simple electronic transfer of data from CANATerm to TRIM.

Plant

A scale drawing of each alternative was translated into a schematic showing all necessary track data, such as track identification code (track name), track length, switch clearance points, crossover connections, and leads. Figure 5 shows a portion of flat plan 1 schematically coded for TRIM input. Data from these schematics were organized on a code sheet and entered into TRIM via a keyboard to create the track file.

Yard Resources

Discussions dealing with yard design and operating options produced an approximation of yard-engine requirements for each alternative. These requirements were refined by examining future workload and design of each plant in detail, which culminated in a rigid definition of number of assignments, their respective starting times, and work areas for each yard assignment.

With respect to train inspection crews, standard times were developed for inspection and servicing. These standards were applied to the projected workload to produce an estimated number of inspection crews required. This number was used as the available number of inspection crews throughout the simulations.

Initial Inventory

As discussed earlier, the initial yard population for the projected workload and new plant was produced by a 24-hr simulation of each alternative. The volume and location of traffic produced by this preliminary simulation constituted the yard status at time zero of the design day. These data were defined as the initial population file in TRIM.

Simulation Process

TRIM Simulation Room

The TRIM simulation room, located at CN System Headquarters, is equipped with two rows of desks, a number of CRTs, and a printer as shown in Figure 6. For Thornton Yard simulations the three CRTs located

Figure 5. Flat plan 1 coded for TRIM input.

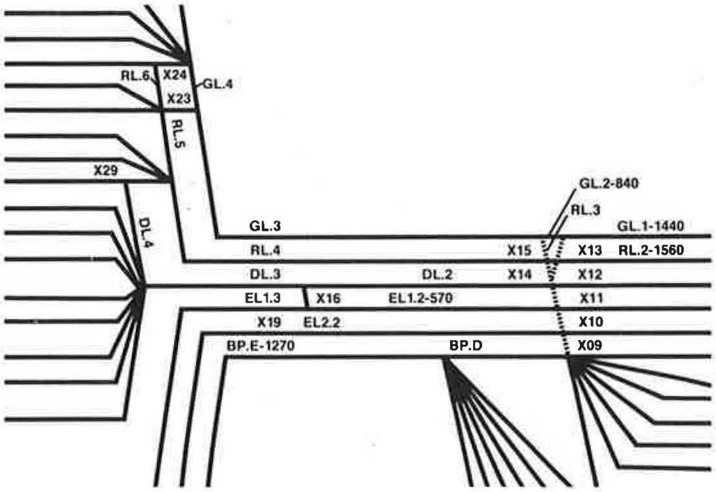


Figure 6. Simulation room layout.

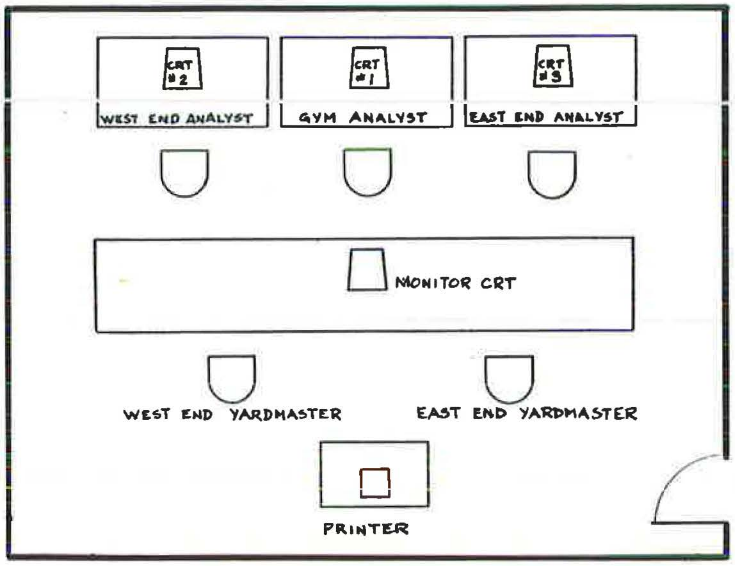
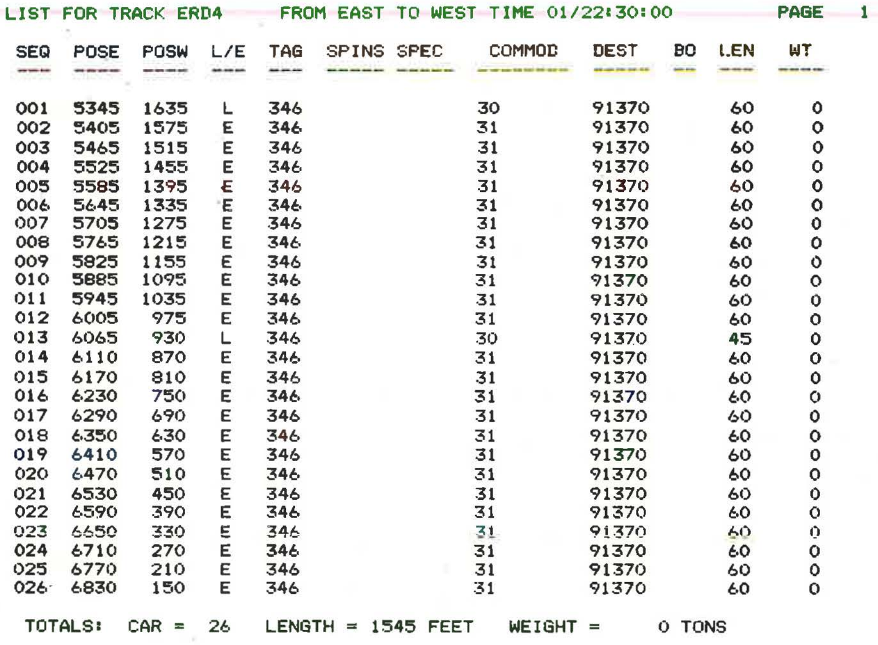


Figure 7. Sample track list.



```
LIST FOR TRACK ERD4      FROM EAST TO WEST TIME 01/22:30:00            PAGE    1

 SEQ  POSE  POSW  L/E  TAG  SPINS SPEC  COMMOD    DEST   BO  LEN   WT
 ---  ----  ----  ---  ---  ----- ----  --------  -----  --  ---  ----

 001  5345  1635   L   346              30        91370        60    0
 002  5405  1575   E   346              31        91370        60    0
 003  5465  1515   E   346              31        91370        60    0
 004  5525  1455   E   346              31        91370        60    0
 005  5585  1395   E   346              31        91370        60    0
 006  5645  1335   E   346              31        91370        60    0
 007  5705  1275   E   346              31        91370        60    0
 008  5765  1215   E   346              31        91370        60    0
 009  5825  1155   E   346              31        91370        60    0
 010  5885  1095   E   346              31        91370        60    0
 011  5945  1035   E   346              31        91370        60    0
 012  6005   975   E   346              31        91370        60    0
 013  6065   930   L   346              30        91370        45    0
 014  6110   870   E   346              31        91370        60    0
 015  6170   810   E   346              31        91370        60    0
 016  6230   750   E   346              31        91370        60    0
 017  6290   690   E   346              31        91370        60    0
 018  6350   630   E   346              31        91370        60    0
 019  6410   570   E   346              31        91370        60    0
 020  6470   510   E   346              31        91370        60    0
 021  6530   450   E   346              31        91370        60    0
 022  6590   390   E   346              31        91370        60    0
 023  6650   330   E   346              31        91370        60    0
 024  6710   270   E   346              31        91370        60    0
 025  6770   210   E   346              31        91370        60    0
 026  6830   150   E   346              31        91370        60    0

  TOTALS:  CAR =  26   LENGTH = 1545 FEET   WEIGHT =      0 TONS
```

at the front of the room were manned by three analysts.

The east-end analyst was responsible for switching work at the east end of the yard. The west-end analyst handled the work at the west end of the yard and movements of bad orders to or from the car shop plus other internal moves. The general yardmaster (GYM) analyst at the middle CRT was responsible for deploying inspection crews and yard crews and scheduling all arriving and departing trains.

The two yardmasters located behind the analysts were local operating officers experienced in Vancouver operations. Their role was that of decision makers throughout the simulation, as yardmasters are in a yard tower. The east yardmaster was responsible for work at the east end of the yard, whereas the west yardmaster controlled all the work at the west end and most of the internal moves. Located on the yardmaster's desk was a monitor CRT displaying a constantly updated condition of yard resources. At the rear of the room was a printer that produced hard copies of switch lists, train lists, and advance consists.

Simulation

Because the yardmasters (operating officers) were the decision makers, the simulation could not begin until the first element of yard work was defined.

At the outset the yardmasters were provided with information specifying the initial status of the yard in detail and a list of trains scheduled to arrive into the system in the ensuing 8 hr. The initial condition is defined on hard copies of track lists. A sample track list is shown in Figure 7. In these lists the track is identified, cars are listed in sequence, and the distance from the east and west ends of the track to the cars is given. In addition, classification code (tag number and spin number), commodity code, destination station number, and length in feet are specified. In the column headed BO, bad-order cars are identified and in the column headed SPEC special instructions such as dangerous cars, cars to be held, cars not to be humped, and so forth are given.

In the inbound-train list (Figure 8) trains projected to arrive into the system are specified. Information such as train number, expected time of arrival, and number of loads and empties is given. Also provided is total weight of the train, total length, and number of locomotives powering the train.

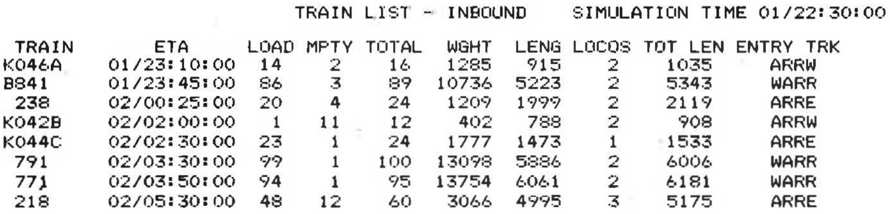
If desired, a car-by-car listing of each train's consist is also available. Figure 9 is a train consist for train K044C. These advance train consists provide such information as car sequence from the engine, loaded or empty status, and weight of each car.

Destination station number, commodity code, length in feet, and tag number (last column) are also specified for each car. In columns 8, 9, and 10 special instructions, bad orders, and cars to be cleaned are given. As an example W in the special instructions column indicates that the car is to be weighed, whereas HLD identifies a car destined to the hold track.

This information coupled with predefined service design specifications and operating plan are used by the yardmasters as the basis for planning and assigning yard work during the simulation. The process is similar to that experienced in yard towers during a typical shift. Having analyzed the preceding information, the yardmasters set the simulation process in motion by assigning work to yard assignments. Decisions about classifying, train makeup, available departure, and internal yard moves are also made. These decisions are passed on to the analysts for execution. Information regarding switching, train makeup, and internal yard moves is generally passed to the analysts by means of an annotated switch list, an example of which is shown in Figure 10. In addition to the switch lists, yardmasters verbally instruct the analysts what routes are to be used for specific moves and estimate the time for completion of each move.

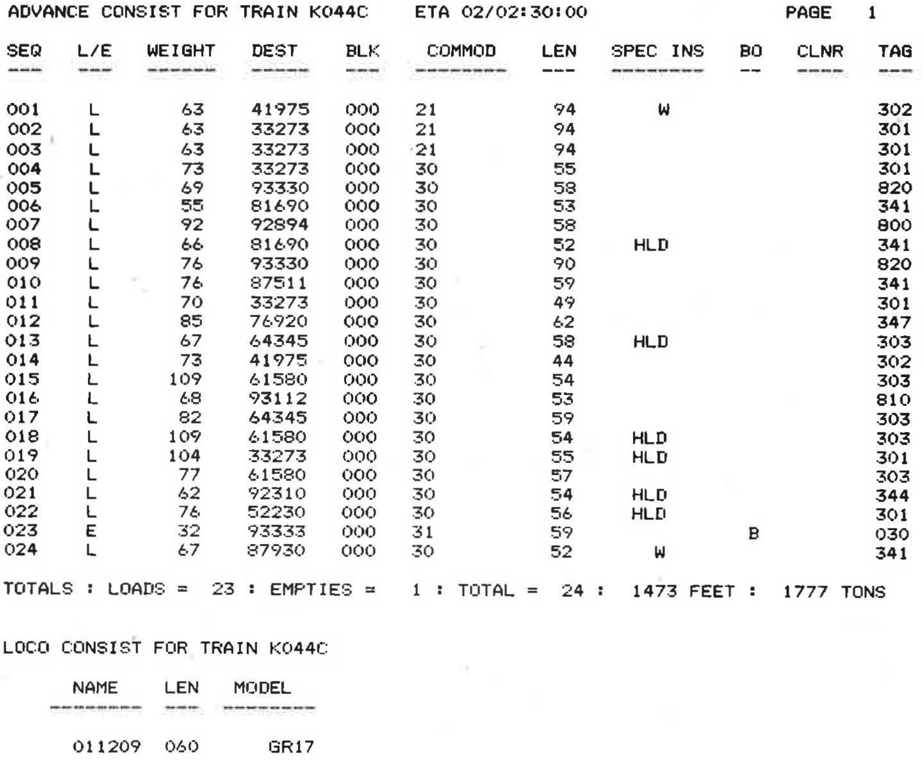
Having received the instructions, analysts instruct the computer to make the required move. These instructions (commands) are issued by filling in the blanks on a formatted screen. An example of a move command is shown in Figure 11. In this particular case the analyst instructed the model to move four cars with engine WEST 1 to track C5 via tracks L1, X10, and L2 and to couple the four cars to those al-

Figure 8. Inbound-train list.



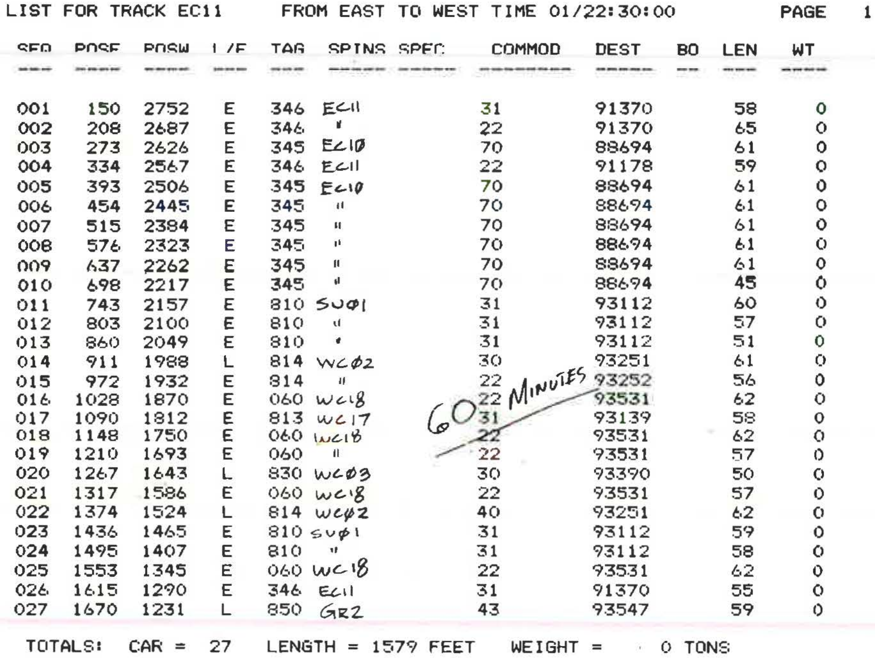
```
                         TRAIN LIST - INBOUND    SIMULATION TIME 01/22:30:00

 TRAIN        ETA        LOAD MPTY TOTAL   WGHT   LENG LOCOS TOT LEN ENTRY TRK
K046A    01/23:10:00   14    2     16    1285    915    2      1035      ARRW
B841     01/23:45:00   86    3     89   10736   5223    2      5343      WARR
 238     02/00:25:00   20    4     24    1209   1999    2      2119      ARRE
K042B    02/02:00:00    1   11     12     402    788    2       908      ARRW
K044C    02/02:30:00   23    1     24    1777   1473    1      1533      ARRE
 791     02/03:30:00   99    1    100   13098   5886    2      6006      WARR
 771     02/03:50:00   94    1     95   13754   6061    2      6181      WARR
 218     02/05:30:00   48   12     60    3066   4995    3      5175      ARRE
```

Figure 9. Advance consist for train K044C.



```
ADVANCE CONSIST FOR TRAIN K044C    ETA 02/02:30:00                PAGE   1

SEQ   L/E   WEIGHT   DEST    BLK    COMMOD     LEN   SPEC INS    BO   CLNR   TAG
---   ---   ------   -----   ---   ---------   ---   ---------   --   ----   ---

001    L       63    41975   000   21           94       W                   302
002    L       63    33273   000   21           94                           301
003    L       63    33273   000   21           94                           301
004    L       73    33273   000   30           55                           301
005    L       69    93330   000   30           58                           820
006    L       55    81690   000   30           53                           341
007    L       92    92894   000   30           58                           800
008    L       66    81690   000   30           52     HLD                     341
009    L       76    93330   000   30           90                           820
010    L       76    87511   000   30           59                           341
011    L       70    33273   000   30           49                           301
012    L       85    76920   000   30           62                           347
013    L       67    64345   000   30           58     HLD                     303
014    L       73    41975   000   30           44                           302
015    L      109    61580   000   30           54                           303
016    L       68    93112   000   30           53                           810
017    L       82    64345   000   30           59                           303
018    L      109    61580   000   30           54     HLD                     303
019    L      104    33273   000   30           55     HLD                     301
020    L       77    61580   000   30           57                           303
021    L       62    92310   000   30           54     HLD                     344
022    L       76    52230   000   30           56     HLD                     301
023    E       32    93333   000   31           59                B          030
024    L       67    87930   000   30           52       W                   341

TOTALS : LOADS =   23 : EMPTIES =   1 : TOTAL =   24 :   1473 FEET :   1777 TONS


LOCO CONSIST FOR TRAIN K044C

      NAME      LEN    MODEL
    --------    ---   --------

      011209    060       GR17
```

Figure 10. Annotated switch list.



```
LIST FOR TRACK EC11      FROM EAST TO WEST TIME 01/22:30:00          PAGE    1

 SEQ  POSE  POSW  L/E  TAG  SPINS SPEC   COMMOD    DEST   BO  LEN   WT
 ---  ----  ----  ---  ---  ----- ----  --------   -----  --  ---  ----

 001   150  2752   E   346  EC11            31     91370        58    0
 002   208  2687   E   346   "              22     91370        65    0
 003   273  2626   E   345  EC10            70     88694        61    0
 004   334  2567   E   346  EC11            22     91178        59    0
 005   393  2506   E   345  EC10            70     88694        61    0
 006   454  2445   E   345   "              70     88694        61    0
 007   515  2384   E   345   "              70     88694        61    0
 008   576  2323   E   345   "              70     88694        61    0
 009   637  2262   E   345   "              70     88694        61    0
 010   698  2217   E   345   "              70     88694        45    0
 011   743  2157   E   810  SU01            31     93112        60    0
 012   803  2100   E   810   "              31     93112        57    0
 013   860  2049   E   810   "              31     93112        51    0
 014   911  1988   L   814  WC02            30     93251        61    0
 015   972  1932   E   814   "              22     93252        56    0
 016  1028  1870   E   060  WC18            22     93531        62    0
 017  1090  1812   E   813  WC17            31     93139        58    0
 018  1148  1750   E   060  WC18            22     93531        62    0
 019  1210  1693   E   060   "              22     93531        57    0
 020  1267  1643   L   830  WC03            30     93390        50    0
 021  1317  1586   E   060  WC18            22     93531        57    0
 022  1374  1524   L   814  WC02            40     93251        62    0
 023  1436  1465   E   810  SU01            31     93112        59    0
 024  1495  1407   E   810   "              31     93112        58    0
 025  1553  1345   E   060  WC18            22     93531        62    0
 026  1615  1290   E   346  EC11            31     91370        55    0
 027  1670  1231   L   850  GR2             43     93547        59    0

  TOTALS:   CAR =   27    LENGTH = 1579 FEET    WEIGHT =      0 TONS
```

60 MINUTES

Figure 11. Simulation format for move command.

```
                                        MOVE            SIMULATION TIME

           MOVE   4..   CARS                       WITH CONSIST   WEST1...
                  TRACK   .                              ON TRACK   ........

                                     TO TRACK  C5......

( VIA TRACKS  L1.......   ,  X10.....   ,  L2......   ,  ........   ,  ........
              .........   ,  ........   ,  ........   ,  ........   ,  ........   ,
                                                                                  .)

                                   ( RESERVE ROUTE   .   )

(SETOFF   ...   CARS ( RETURN   .   ) )          (SPOT ....  FEET FROM EAST )
(  KICK   ...   CARS ( RETURN   .   ) )          (     ....  FEET FROM WEST )
             (AT TRACK  ........ )               (      COUPLE   X          )
                                                 (    CLEAR EAST    .       )
                                                 (    CLEAR WEST    .       )
                                        HR     MIN     SEC
                               ( TIME:  ..   :  04   :  00   )
                           HR     MIN      SEC
                   (DELAY BY  ..   :   ..   :   ..   (REASON  ................ ))

                                                              NEXT COMMAND   ...
```

ready on track C5. The estimated time for this move was 4 min. An X in the blank after the word "couple" is the instruction to couple. The instruction could as easily have been to spot (place) the four cars a certain distance from either end or to spot them in the clear. When the move has been completed, yard engine WEST 1 will be highlighted as ready for another task. This information is reflected on the analysts' CRTs and yardmaster's monitor screen.

As switching moves are carried out, trains are scheduled for arrival and departure, and other moves are completed, new track lists can be generated. These in turn end on the desks of yardmasters, who analyze and issue further instructions for continuing work. Throughout the simulations all pertinent data are logged for postsimulation production and analysis.

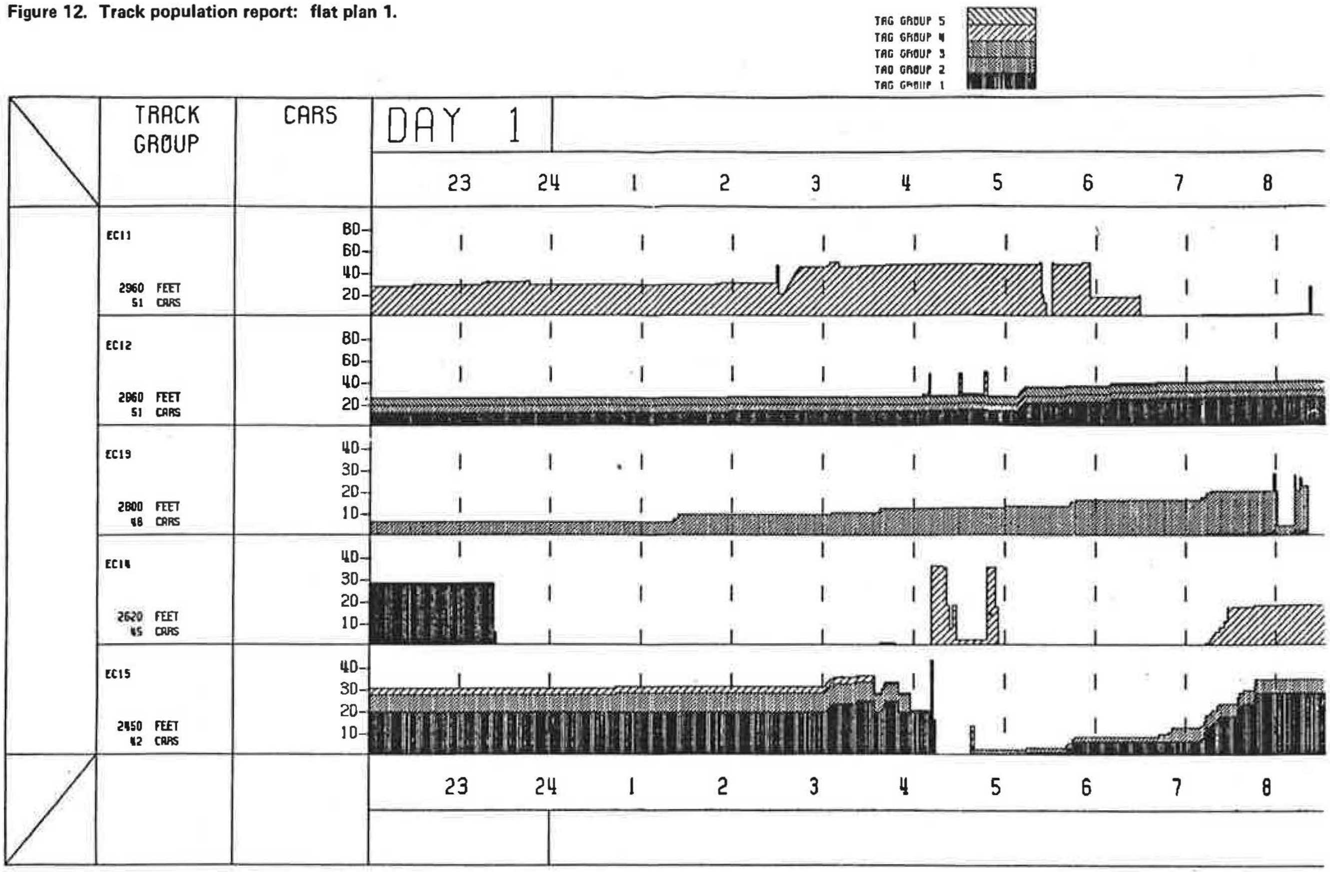
One of the most significant benefits of TRIM is its ability to highlight plant and operating deficiencies during the course of the simulation well before the results are plotted or tabulated and analyzed. For example, if a move was made to skirt a potential conflict but the plant was incapable of accommodating such a move, the problem would be highlighted immediately. It is possible to stop the simulation at that point, make the necessary track changes, and continue.

Classification-track capacity is another example in which TRIM immediately points out plant deficiencies. When a classification track is filled during a switching process, the program requests a swing track (an alternative track) for remaining cars of the same tag. A frequent swing request immediately indicates classification-track capacity shortfalls. From the operating viewpoint, a repeated conflict between yard assignments may indicate improper deployment of yard engines, whereas a yard assignment conflicting with a train movement may be indicative of poor operation or plant.

Evaluation

Plant and engine utilization data and crew produc-

Figure 12. Track population report: flat plan 1.



tivity data are generated by the postprocessing program. All plots and tables are computer generated, which requires limited manual organization before comparison and analysis. Examples of some of the plots and tables most frequently used in analysis are given in the following paragraphs.

Track utilization data generated in plot and tabular form are the most beneficial statistics in sizing the plant. Figure 12 shows 8 hr of occupancy for classification tracks EC11 to EC15. Usable track length in feet and car capacity for each track are indicated in the left-hand column. Occupancy plots reflect that the population of each track varies with time. Shading represents various tag groups. In addition the track utilization percentage is calculated. Classification-track occupancy is calculated on the basis of car hours, whereas R&D and lead calculations are made on a simple time-occupancy basis.

Figure 13 shows an example of lead occupancy plots. Engine activities are identified by the shaded coding defined at the bottom of the figure. In this case three segments of DL lead (DL.1, DL.2, and DL.3) are plotted individually, whereas total DL lead occupancy is shown by the fourth plot.

Figure 14 gives an example of R&D track occupancy. As in classification-track plots, track capacities are identified and percentage occupancies calculated. In addition trains that have recently arrived or are ready to depart are identified by number. (Note train K013G on track GR1 and train B841 on track GR2.)

In addition to plots, detailed tabular reports are produced for yard engine performance and crew utilization. Table 1 gives a summarized example of the inspection-crew report for flat plan 1 in shift format. For example, inspection crew INS 11 was on duty from 0800 to 1600 hr on day 2 and consisted of two workers. They worked 4.1 hr, were in transit for 1.2 hr, had 0.8 hr of personal time, and were idle waiting for instructions for a period of 1.7 hr. Inspection-crew productivity was examined by comparing various activity segments for the three alternative designs.

Table 2 shows a similar table for the switch-crew performance for flat plan 1. For example, the shift for yard crew West 2A started at 2200 hr on day 1 and terminated at 0600 hr on day 2. During these 8 hr the three-person crew worked for 3.23 hr, was in transit for 0.70 hr, used up 0.67 hr of personal time, was idle awaiting work for 1.72 hr, and was given 1.68 hr early quit. Individual and total times were compared for the three alternatives in determining productivity levels.

Analysis and Comparison

Track occupancy plots and cost played the most significant roles in alternative selection. Receiving, departure, and surge-track occupancies favored the flat-1 alternative as indicated in Table 3. These tracks were collectively occupied for 51.4 percent of available track time in flat 1 compared with 59.4 percent in flat 2. Flat 1 did, however, have one additional track (i.e., 4.2 percent more track capacity). The hump alternative exhibited a 54.3 percent occupancy of 30 available tracks. Occupancy of classification tracks and leads also favored flat 1 as did the crew productivity and engine utilization.

Total project cost favored flat 1 by a small margin when compared with flat 2, whereas the cost of the hump alternative turned out to be prohibitive. Flat 1 cost was estimated at $93 million; flat 2 was

$3 million higher. The cost of the hump alternative was estimated at $143 million.

Flat plan 1 performed best in each comparative category. Nonquantifiable operating features as perceived by the local operating officers favored this alternative as well. Consequently, simulation results, costs, and operating experience led to selection of flat plan 1 as the design for the expanded Thornton Yard.

Fine Tuning of Flat Plan 1

Once flat plan 1 had been selected as the best alternative, simulation results and simulation experience were used to refine the design. Track occupancies were used to size various yard segments more accurately. Lead occupancies, crossover occupancies, and movement conflicts were examined to refine the throat designs. Lead lengths and ladder designs

Figure 13. Lead occupancy report: flat plan 1.

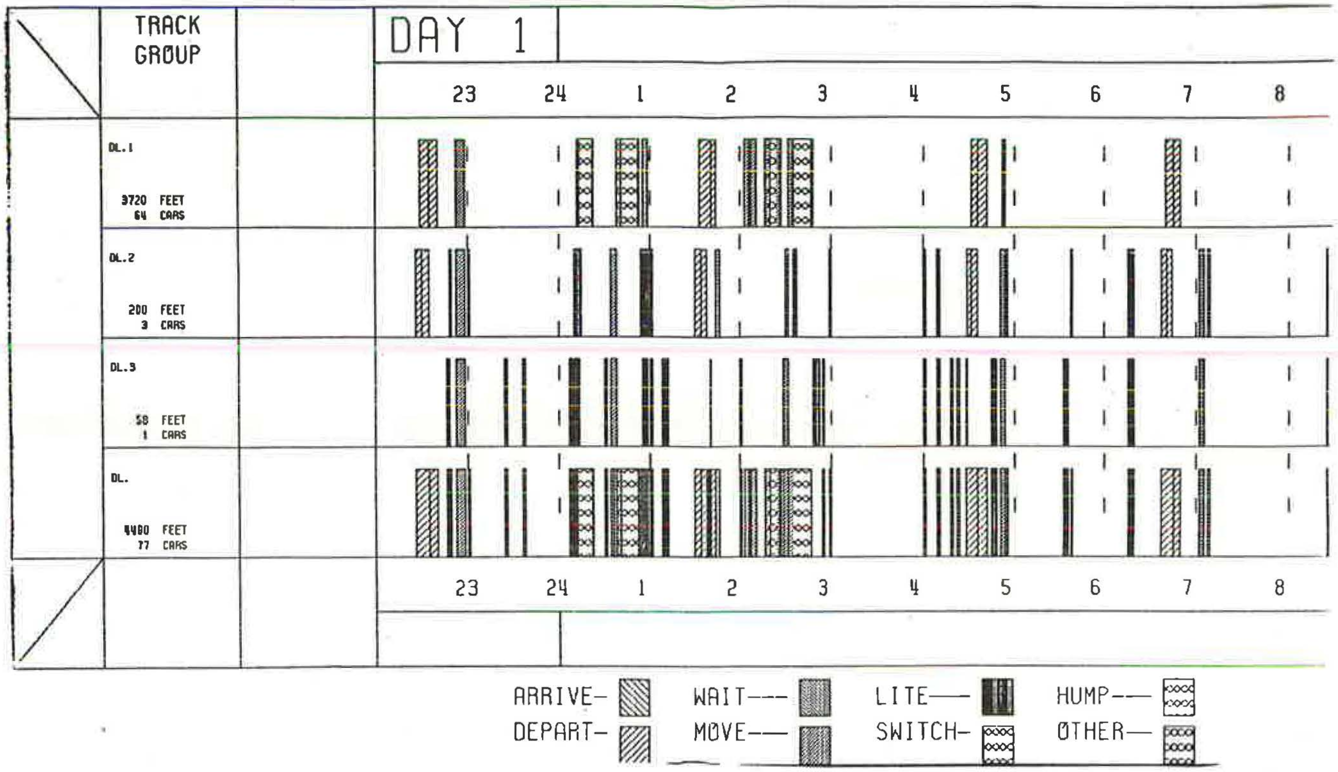
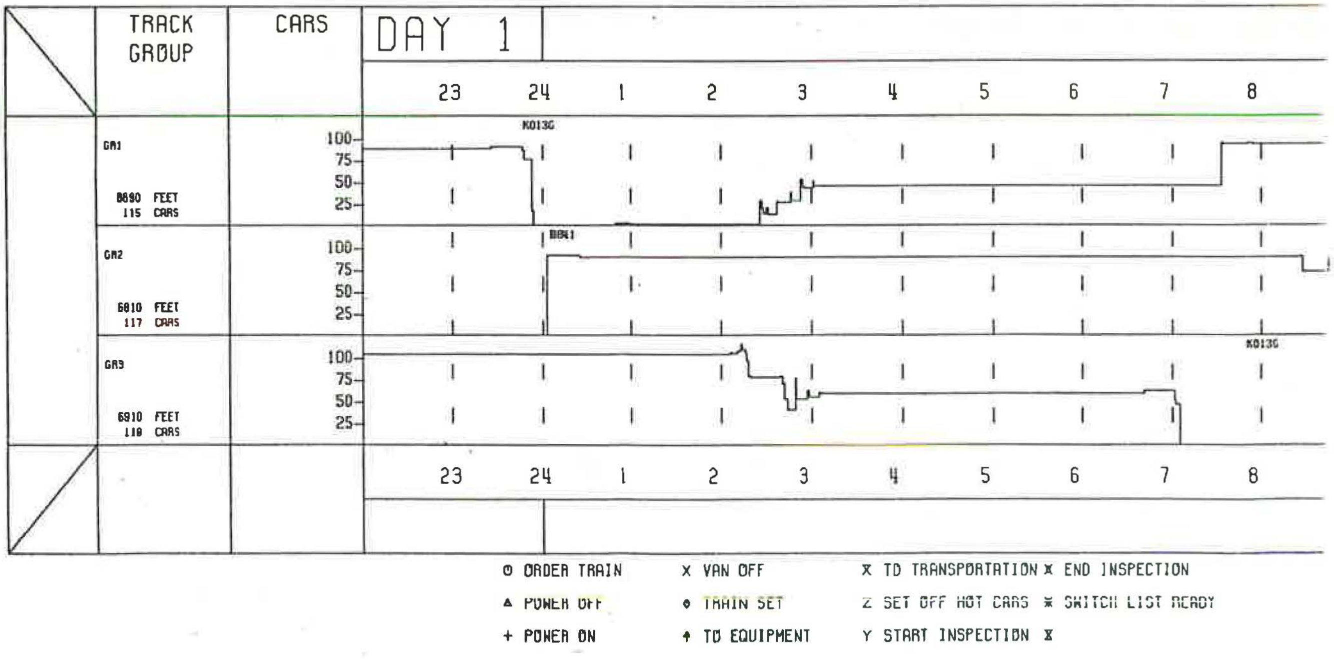


Figure 14. R&D occupancy report: flat plan 1.



were also modified on the basis of initial simulations. The refined flat plan 1 was then redrawn to scale.

Resimulation of Flat Plan 1

As in the initial case, the new flat plan 1 was translated into a schematic form and coded for TRIM input. Because of plant revisions, yard resources were adjusted in line with analysis of first simulation results. The operation was also marginally modified as necessitated by the plant revision.

On the basis of the new data flat plan 1 was resimulated. The results of this simulation were used to better gauge the true potential of the proposed yard and to make necessary final design changes. Thornton Yard master plan was produced on the basis of these final simulation results.

Table 1. Inspection crew report: flat plan 1.

			Time Allotment (hr)					
					Idle			
Crew Identification	Shift	No. of Workers	Work	Transit	Personal	Awaiting Instructions	Early Quit	Total
INS 7	01/2300-02/0700	2	2.4	1.0	0.8	3.5	0.4	16
INS 1	02/0000-02/0800	2	2.3	1.0	0.8	3.5	0.4	16
INS 2	02/0000-02/0800	2	2.5	1.2	0.8	3.2	0.4	16
INS 3	02/0000-02/0800	2	2.4	1.4	0.8	3.1	0.4	16
INS 4	02/0000-02/0800	2	2.5	1.4	0.8	3.0	0.4	16
INS 5	02/0000-02/0800	2	2.2	0.9	0.8	3.8	0.4	16
INS 6	02/0000-02/0800	2	2.3	0.8	0.8	3.7	0.4	16
INS 14	02/0700-02/1500	2	1.6	1.2	0.8	4.0	0.4	16
INS 10	02/0800-02/1600	2	2.0	0.8	0.8	4.0	0.4	16
INS 11	02/0800-02/1600	2	4.1	1.2	0.8	1.7	0.3	16
INS 12	02/0800-02/1600	2	3.1	1.4	0.8	2.3	0.5	16
INS 13	02/0800-02/1600	2	2.4	0.9	0.8	3.6	0.3	16
INS 8	02/0800-02/1600	2	1.4	0.8	0.8	4.8	0.3	16
INS 9	02/0800-02/1600	2	2.7	1.3	0.8	3.0	0.3	16
INS 21	02/1500-02/2300	2	1.7	0.9	0.8	4.4	0.3	16
Total		30	35.6	16.2	12.0	51.6	5.6	240

Table 2. Switch crew report: flat plan 1.

			Time Allotment (hr)						
					Idle				
Crew Identification	Shift	No. of Workers	Work	Transit	Personal	Awaiting Instructions	Early Quit	Total	Total No. of Moves
East 1A	01/2200-02/0600	3	2.80	0.87	0.75	2.15	1.43	24	62
West 2A	01/2200-02/0600	3	3.23	0.70	0.67	1.72	1.68	24	64
Unit 1A	01/2300-02/0700	3	2.75	1.42	0.75	1.36	1.72	24	48
West 1A	01/2300-02/0700	3	2.60	0.93	0.67	2.48	1.33	24	69
East 2A	02/0000-02/0800	3	3.15	0.81	0.75	3.21	1.53	24	36
East 1B	02/0600-02/1400	3	3.02	0.94	0.75	1.42	1.87	24	42
West 2B	02/0600-02/1400	3	2.98	1.36	0.75	1.22	1.70	24	42
Unit 1B	02/0700-02/1500	3	3.19	0.91	0.75	1.35	1.80	24	59
West 1B	02/0700-02/1500	3	3.24	0.93	0.75	1.02	1.80	24	31
East 2B	02/0800-02/1600	3	2.98	0.97	0.83	1.29	1.83	24	30
East 1C	02/1400-02/2200	3	2.91	1.10	0.75	1.34	1.90	24	25
West 2C	02/1400-02/2200	3	3.03	1.15	0.97	1.16	1.70	24	44
Unit 1C	02/1500-02/2300	3	2.48	1.17	0.75	1.29	2.30	24	38
West 1C	02/1500-02/2300	3	2.55	0.96	0.75	1.77	1.97	24	46
East 2C	02/1600-03/0000	3	3.85	0.60	0.83	0.51	2.20	24	49
Total		45	44.76	14.82	11.47	23.27	26.76	360	685

Table 3. Comparison of throughput for three alternatives.

	Flat Plan 1				Flat Plan 2				Hump Operation			
Yard	Percentage Used	Throughput	Cars Handled	No. of Tracks	Percentage Used	Throughput	Cars Handled	No. of Tracks	Percentage Used	Throughput	Cars Handled	No. of Tracks
East R&D	65.5	4.6	1,895	8	73.5	5.8	1,959	8	75.5	6.2	713	4
West R&D	45.3	6.3	1,232	9	45.5	4.6	1,791	9	30.0	2.7	1,469	7
Receiving	-	-	-	-	-	-	-	-	57.0	8.6	1,511	12
Unit R&D	49.6	6.1	1,588	6	74.4	8.0	834	4	70.4	6.2	1,073	4
Surge	27.4	10.1	141	2	43.7	8.0	389	3	50.6	8.2	487	3
Avg or total	51.4			25	59.4			24	54.3			30

CONCLUSIONS

Redevelopment of Thornton Yard presented many planning challenges. The need to greatly increase capacity contrasted sharply with the limited property available for expansion. This contrast heightened the need to investigate a wide range of plant and operating alternatives, select the one that best balanced capital and operating requirements, and further test and refine the chosen alternative. The TRIM simulation model was the only way of ensuring that these needs would be realistically met within a reasonable time frame. CN's Transportation Planning Department is confident that through the use of TRIM, an excellent yard design has been developed. This belief is shared by senior CN management and executives, who have approved the proposed flat plan 1 design as the basis for long-term expansion at Thornton Yard.

Engineering Design and Operational Study of Coyotepec Yard

SANTIAGO CARDOSO-CONTRERAS AND PETER J. WONG

Coyotepec Yard, near Mexico City, is being designed to handle 6,000 cars on a peak day. The basic design and the results of computer evaluation studies are presented. Topics addressed include trim-end design; capacity of the yard; humping rate; size of receiving, classification, and departure yards; and number of inspection and yard engine crews.

National Railways of Mexico has planned a large hump yard, Coyotepec Yard, with a capacity of 6,000 cars per day, the largest in the Western Hemisphere. Supplementing an existing, obsolete facility north of Mexico City, the new yard will become a key point for the country's rail network. The design of such a high-capacity facility required departures from conventional practice. In final form, the design represents a collaboration of the efforts of railroad representatives and consultants from Mexico, the United States, and Canada. When the yard has been completed, service will be improved and efficiency increased on the Mexican rail network.

Mexico has a large railway system in place today, which consists of 15,850 miles of track (1,000 miles under construction), 50,000 freight cars (plus 10,000 foreign cars on line at any given time), and 1,400 diesel-electric locomotives. This system handles 70 million tons of freight annually. Freight traffic is expected to grow at 6.8 percent annually through the year 2000.

A large percentage of the country's rail freight traffic must pass through Mexico City; not only do the routes of many cars terminate there, which serves the needs of the city's 16 million inhabitants (projected at 25 million by the year 2000), but all lines between northern and southern Mexico pass through the city as well. The burgeoning freight traffic threatens to overwhelm the existing Terminal Valle de Mexico (TVM) facility. Additional capacity is required, and it was decided not to expand the existing facility but to design a completely new yard to be located astride the new Mexico-Queretaro Main Line currently under construction. Several benefits will result from the new facility:

1. Reduction in transit time,
2. Reduction in operating costs,
3. Improvement in customer service,
4. Reduction in freight-car cycle time, and
5. Technology transfer.

Technology transfer has acquired great importance. The economic recession and tremendous inflation that have wracked Mexico recently have made it almost impossible to contract a large project such as Coyotepec to a foreign enterprise.

DESIGN PROCESS AND SPECIFICATIONS

The overall yard design was divided into the following categories:

1. Yard layout,
2. Yard data system,
3. Process-control system (PCS),
4. Trim-end design,
5. One-spot system and engine facilities,
6. Operating philosophy,
7. Operating management control points,
8. Key operating buildings,
9. Communication and signals (intrayard communication, interlocking design, and control of yard movements), and
10. TV monitoring system.

The purpose was not to complete a design in final detail but to develop each of the foregoing items in sufficient detail to know how these systems should work so that necessary performance specifications could be prepared for the invitation of bids. An exception was made for the critical crest and switching portions, for which a detailed design was made from the outset.

Yard Layout

The most important part of a yard project like Coyotepec is probably the yard layout, which consumes the most time in the conceptual phase of a large yard. Many days and weeks were spent on yard layout by the planning team for the Coyotepec Yard.

Three major constraints had to be considered in working on the yard layout. First, there were those imposed by the boundaries of the land site selected for the yard. Second, there was the division of the whole terminal into two phases, each of which would be able to handle 6,000 cars in the year 2000. The first is the North-South Phase (receiving yard, hump, classification yard, trim end, departure yard) and the second the South-North Phase. The third constraint was the preconceived notion of yard design imposed by the previous operating experience of National Railroads of Mexico personnel. Through many meetings and discussions some of the preconceived notions about yard design and operation were abandoned. This process consumed about 6 months. The main issue of discussion was the advantages and disadvantages of two basic yard layouts: an in-line yard in which cars are pulled from the classification yard to the departure yard and a shove-back yard in which cars are pulled from the classification yard and then shoved into the parallel departure yard.

The result of this long process was six possible layouts of both types of yard. The one selected was a compromise that had both in-line and shove-back departure yards operating through a single multitrack pulling throat that will be able to work five engines at the same time under ideal conditions. Subsequently, one of the advisors, Bill Williamson, submitted another design similar to the one selected but with three multitrack pulling throats that can work six engines under most conditions. This submission of a seventh layout raised considerable controversy with respect to how the yard would be operated.

The controversy led to a decision that simulation was the only way to make an evaluation of the two alternatives. Consequently, a contract was made with SRI International in August 1981 to undertake the simulation of these two alternatives with SRI's CAPACITY and CONFLICT models, so that an evaluation and choice could be made. Various members of the technical team were observed at work in the simulation project, and it became obvious that much had been learned in the past months, because this complex process was handled well. Because of their experience in working on the Coyotepec Yard, the technical team was well qualified for another project, and a set of alternatives for a yard in Monterrey has been drawn up.

Approval was obtained from the Ministry of Communication and Transport for the final layout of Coyotepec Yard with the following specifications:

1. Receiving yard;
2. Hump with a capacity of 6 cars/min;
3. Classification yard with 64 tracks in 8 groups of 8 tracks (the first 8-track group will receive cars for TVM yard only), a master retarder, 8 group retarders, and another group retarder for 6 tracks to the one spot (each of the 64 tracks on the bowl will have tangent-point retarders and inert retarders at each end); coupling speed will be controlled at 4 mph by a double radar measuring device;
4. Two trim-end designs, one with a single key and one with three keys;
5. One on-line departure yard;
6. One parallel departure yard;
7. One transit train yard (relay yard);
8. One minihump with 5 tracks of 35 cars each;
9. One transfer yard; and
10. Two support yards.

Besides all the yards, there are support facilities: a one-spot repair facility and a servicing and repair facility for electric and diesel-electric locomotives.

Dual servicing facilities are necessary because there will be an electric double-track main line beside the yard. Allowance for future electrification has been made in the receiving and departure yards as well. Furthermore, 43 different types of buildings have been designed--for example, the main control tower and administration building, the trim-end tower, the receiving-yard crew building, the departure-yard crew building, the shops for work on electric and diesel-electric equipment, car facility, caboose office, hospital center, and fire center.

Yard Data System

The computerized yard data system is a relatively new phenomenon in the railroad industry. It was not invented; it evolved. Before the use of the computer, yard data were collected manually. Required information was passed from location to location in the form of switch lists, hump lists, consists, and so forth. The user then read, manipulated, and interpreted these data for his own use. This process was slow, inefficient, and incompatible with the needs of a modern, high-technology railroad yard. Consequently, data systems used by two modern U.S. railroads were examined--the Missouri Pacific System (MoPac) at St. Louis, Missouri, and the Southern Pacific System (SP) at San Francisco, California. MoPac built the switch system and SP built its transportation commodity classification system. Both railroads spent a number of years and millions of dollars in developing the individual systems.

Coyotepec Yard will need systems like these in order to operate. The question is to decide what kind of data system to use. Both MoPac and SP submitted proposals to supply their respective systems to the Coyotepec Yard project. These proposals have been evaluated and submitted to the Ministry of Communication and Transport for action.

When a specific system has been selected, it will be necessary for representatives from the operating computer systems, signals, and communications to go over the system in detail with the vendor to ensure that the capabilities for the job are available. Knowledge of yard operations should be reviewed from the flow of yard data and the information requirements of Coyotepec. This process will be a tremendous learning experience for those involved and the required knowledge cannot be gained in any other way. The technical group will then become the core of expertise that will be necessary to further expand, develop, and use efficiently the data system selected. During this third step of detailed activity it will also be necessary to work with the PCS suppliers to design an operating interface between the two systems.

PCS

One of the most important elements in a modern railroad hump yard is the PCS and the humping function it serves. If the Coyotepec Yard is examined, it is easy to see that the hump is a center of great activity and also that many functions support the hump work. Furthermore, the sorting process done by the hump has a strong and direct bearing on the capacity and efficiency of the whole yard and, in this case, the whole railroad. Because of this, the efficiency of hump support functions must be proportional to humping capacity or the inherent capacity of the hump is restricted. This is the reason for careful study of the specific data interface between the management inventory system (MIS) and the PCS, the weigh-in-motion scale (ahead of the hump), and the specialized design of the pull-out end of the classification yard, which will be discussed later.

The stated goal for the first yard at Coyotepec was 6,000 cars per day at the peak. Observation of the SP West Colton Yard near San Bernardino, California, in which cars are humped by using the PCS, gave evidence that this humping rate was economical and safe on a regular, ongoing basis. Therefore, a recommendation to the Ministry of Communication and Transport was made without hesitation that the West Colton system be used at Coyotepec if anticipated humping levels were to be achieved. However, it was necessary to review in detail how the system works and its many features and components such as retarders and electrical supply systems. The ability of various suppliers to produce this kind of PCS was also discussed. Project team members and Mexican railroad personnel must now review and evaluate each proposal. If possible, the vendors should make an exhaustive presentation of their products. Important items include data flow from inbound trains and return of individual car data from the PCS to the MIS for inventory updating. Data needed by the PCS to hump cars include such problems encountered during humping as the wrong list, catch-ups, stalls in the switching section, and breakaway of uncontrolled cuts.

Trim-End Design

If the PCS is one of the most important elements in a modern railroad hump yard, what about the trim-end design for this project? Once a hump had been developed to handle 6,000 cars per day, a trim-end design with at least the same capacity became necessary. The first step was to translate into Spanish the section on hump yard trim-end design of SRI's Railroad Classification Yard Technology Manual (1), in which a manual procedure to evaluate engine conflicts and interferences at the trim end is described. This was used to simulate the pullout end. A matrix with the number of classification and departure tracks (on-line and parallel departure yards) was constructed. In one layout (1:2000 scale) all the switches were shown that the trim end needed to permit any car in any classification-yard track to pass through the throat to the departure tracks (both on-line and parallel yards). The switches were all numbered and values were given to the parameters describing various engine movements.

The manual simulation was used to screen many different alternatives, one of which was the alternative presented to SRI. With the help of Peter J. Wong and Masami Sakasita, some changes were made and further simulations were conducted. The three-key design by Bill Williamson was simulated as well. Both plans proved to be good designs. Williamson's is more expensive in its construction and maintenance, but it has more capacity (7,200 cars in a peak day). However, it also needs personnel with advanced knowledge of yard operation, which is a type of expertise not available on this project.

Although this is a satisfactory design with a new layout and a new trim-end design, there are many unknown factors. Theoretically, this project will be able to handle 6,000 cars in a peak day, but it may not. The quality of work by contractors and construction supervisors will have an impact on the eventual performance as well. Only when such a yard is actually in operation, such as the new Queensgate Yard in Cincinnati, Ohio, will it be known whether the projections for Coyotepec Yard are correct.

One-Spot System and Engine Facilities

An efficient car repair facility is essential to the operation of a large yard because of the anticipated 2 percent bad-order rate during normal operations. If the bad-order (defective) cars are not handled consistently, their backup and consequent storage and switching requirements can soon have a detrimental effect on the entire yard operation. Moving bad-order cars by means of "mechanical rabbits" into the repair shed has been considered. The repair building is equipped with stationary hydraulic jacks, small retarders, all necessary tools, car parts, wheel sets, blue flag systems, and so on.

The specifications of the facility are standard; the location of the one spot is important. It must be placed so as to minimize handling of cars to and from the shop. That is why it will be located in the middle of the yard between the North-South Phase (first phase) and the South-North Phase (second phase). The car repair facility will have the capacity for 61 light repairs and 120 on the one spot (four tracks). It will also be able to wash and supply 100 cabooses, to repair 5 cabooses, to wash 20 tanks, and to transfer freight loads between two tracks.

The facilities for electric engines will have the capacity to handle washing, travel inspection, and sanding of 121 engines. For diesel-electric engines the facility will have the capacity to handle washing, fueling, and light repair of 181 engines (capacity, 12 per day).

Blue-flag systems are the means by which mechanical and locomotive department employees are protected from injury while they are working on or under engines, cars, or other rolling equipment. Performance specifications for the various blue-flag systems to be used in the yard have been supplied. This includes those to be used in the one-spot facility along with other protective devices required and operating restrictions to be observed in moving cars through the one spot.

Operating Philosophy

Because of the many new concepts that were being explored, it was felt that a document was needed that would help explain how the new yard should operate. Consequently, early in 1982 an extensive document was prepared that discusses in considerable detail the main functions, processes, and systems involved with moving cars into, through, and out of Coyotepec Yard. This document also contains discussions and recommendations concerning the importance of the main lines at each end and how Coyotepec Yard should accommodate the flow of trains to and from these lines. This document provides a good overview of the kind of yard Coyotepec will ultimately become and of the kind of operating problems that will be faced.

Operating Management Control Points

Because of the high throughput expected of this yard, it was not feasible to design it without exploring as many of the common weaknesses found in existing yard operations as possible. A great deal of time was spend discussing with operating personnel the need for coordination and control in a yard expected to handle 6,000 cars per day. This problem was addressed not only in the document on operating philosophy but also either directly or indirectly during the entire project. Every track layout and system recommended inherently contained the elements needed to control and coordinate the operation at Coyotepec. Detailed recommendations were made for two operating control points--the crest tower and the trim tower. These are the two points from which all activities in the yard are directed, from the arrival of trains to their departure, as well as all related processes. The actual design of these towers reflects the many discussions on this important subject.

Key Operating Buildings

Considerable time (about 6 to 7 weeks) was spent working on the key operating buildings to be included in Coyotepec. The largest of these is the main administration building, to be located near the crest of the hump. This building will include administrative offices, the main yard office for clerical functions, the main operator tower, and the process-control computer room. If the management computer system is to be located at Coyotepec, its computer center could be in this building as well.

The second most important building is the trim tower, to be located at the pull end of the classification yard. All train makeup activities will be directed and monitored from this point. The remaining buildings to be designed were the mechanical and locomotive force buildings. In this process drawings made by the coordinator of each building were reviewed in terms of the functions it was to support. After two or three iterations of this process, concept drawings of these key operating buildings were made. The drawings were then sent to the architects for preparation of the final plans.

Communication and Signals

Signals and communication are involved in almost every element of yard operation. A few of the more important topics discussed are mentioned here.

Intrayard Communication

The major portion of oral communication within the yard would be via telephone and intercom systems; there would be minimum use of two-way speakers. This follows recent trends in other yards.

Interlocking Design

There was considerable discussion about whether the yard should have direct contact with the dispatcher when trains move into and out of the yard or whether it should be surrounded by an independent interlocking system. In other words, should trains move from central traffic control (CTC) directly into yard territory or from CTC territory interlocking into yard territory? This was studied carefully. After two or three meetings with the operations personnel it was decided to install a manned interlocking system because it is less restrictive. Moving the trains, cuts, and engines into and out of a yard through a local interlocking system is much more flexible and efficient than operating directly into a CTC system.

Control of Yard Movements

In a large yard such as Coyotepec there is always substantial movement. Trains are arriving and departing, road locomotives are moving from trains to the servicing facilities and from the servicing facilities to trains, and light yard engines and yard engines with cars are moving about in and between various sections of the yard. In many yards this profusion of movement generally results in significant confusion and delay, particularly when there is a large work load and decreased efficiency. To avoid this problem, it is necessary to establish a central control over routes and signals in order to coordinate them. This will be done by the wide use of power switches and various signals controlled from two points, the hump operations tower and the trim tower. This system was thoroughly discussed with operating, signal, and communications personnel and advisors, and visits to existing yards made it possible to see the system and its components in operation. Signals and communications personnel worked with the advisors to lay out a centralized control system for yard movements at Coyotepec.

TV Monitoring System

One item discussed in detail was the possible use of a TV system for monitoring inbound and outbound trains. Because of the success of this type of system in yards in which it has been installed, it was recommended that such a system be used at Coyotepec.

It is not possible to mention all the activities and details covered in such a complex project as this. Nevertheless, some of the more interesting aspects of design concern the physical layout of the tracks. A more detailed discussion of this part of the design process follows.

COMPUTER SIMULATION OF YARD DESIGN

Background

Because of the shape of the available land, the basic design of Coyotepec Yard will have an in-line receiving yard, a classification yard with 64 tracks, an in-line departure yard for trains departing to the south, and a parallel (pullback) departure yard for trains departing to the north. This basic design is called the one-key design (Figure 1). A proposed modification of the basic one-key design was to subdivide the in-line departure yard into three in-line departure yards; this design is called the three-key design. One of the important issues in this project was to decide which of the two designs could better meet the projected needs of Coyotepec Yard.

The other design and operational questions to be resolved for Coyotepec Yard were the following:

1. How many cars can Coyotepec Yard classify?
2. How many trains can Coyotepec Yard process?
3. What should the humping rate be?
4. How many tracks should there be in the receiving, classification, and departure yards?
5. How many inspection, hump-engine, and trim-engine crews are required to operate the yard?

Evaluation Methodology

SRI International developed the computer simulation models CAPACITY and CONFLICT to aid in the design and operational evaluation of railroad classification yards. These two models were used to simulate various aspects of Coyotepec Yard.

The CAPACITY model represents the entire yard, whereas the CONFLICT model focuses on the trim end of the classification yard. The CAPACITY model estimates the requirements for and use of the receiving, classification, and departure tracks; the hump; and inspection, hump-engine, and trim-engine crews. However, in many situations, especially in large hump yards, the trim end of the classification yard can be a bottleneck. Consequently, examining the trim end in more detail than is provided in the CAPACITY model is often useful; this is accomplished in the CONFLICT model. The CAPACITY model uses the average rates of work in the performance of tasks, but in the CONFLICT model the work of each trim engine is monitored and evaluated in detail.

These yard models enable the user to operate the yard in the computer in much the same manner as in the real world. Performing operational experiments in the computer, however, is much more practical and efficient than performing the experiments in the real world. To run the models, the user must develop a detailed train schedule and operational scenario for each case to be studied. Specifically, the data include inbound and outbound train schedules and consists, instructions for the order of humping inbound trains, classification-track assignments, instructions for the order of making up out-

Figure 1. Approximate schematic of one-key design.

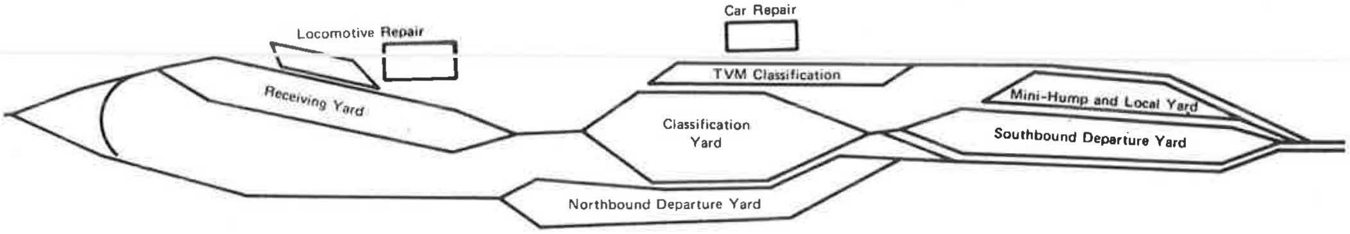
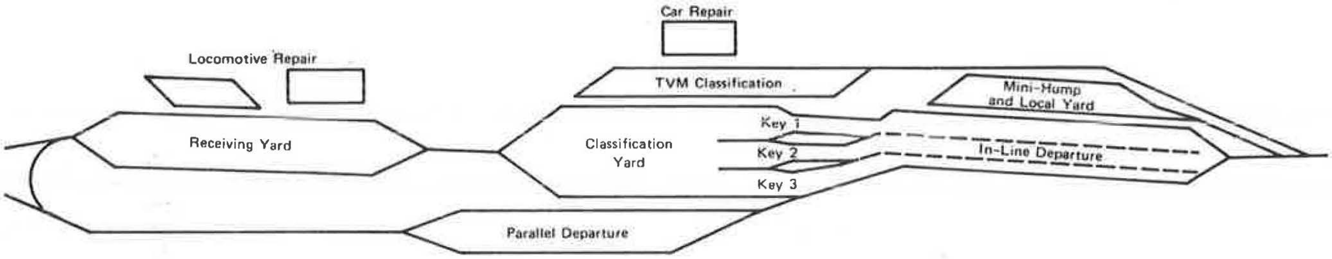


Figure 2. Approximate schematic of three-key design.



bound trains, assignment of inbound and outbound inspection crews, and the allocation of work to hump- and trim-engine crews.

Thus the preparation of input data for the models requires considerable thought to properly plan the yard operations. This is especially true for examining projected scenarios for which no data or experience exists. Consequently, on the basis of projected traffic data provided by INPLAN, the joint INPLAN-SRI team created realistic train schedules and operational scenarios for the years 1985, 1990, 1995, and 2000.

One of the fundamental tasks of this study was to evaluate the one-key and three-key designs and select the better alternative. Because the designs are essentially the same except for the trim end, the CONFLICT model was used to quantitatively evaluate the trim-end capacity of the two designs.

Then the CAPACITY model was used to estimate the overall capacity of the design alternative selected and the track and crew requirements for the years 1985, 1990, 1995, and 2000. A base-case scenario was developed for each year, and then a sensitivity analysis was performed to test the ability of the yard to respond to changes in the base-case scenario. For example, the hump rate was varied, arriving trains were concentrated into a 2-hr period, and outbound trains were delayed on the departure tracks. In this manner, the sensitivity of the yard to normal operational disruptions could be analyzed.

Selection of One-Key Design

SRI analyzed the basic one-key Coyotepec Yard design, shown in Figure 1. It consists of an in-line receiving yard, a main classification yard adjacent to the TVM classification yard, an in-line departure yard, a parallel (pullback) departure yard, and a minihump yard.

SRI also examined a modification in the trim end of the basic design, which is called the three-key design. As indicated in Figure 2, the three-key design is essentially the same as the one-key design. The difference is that the main classification yard is subdivided into three classification yards that are connected to three in-line departure yards via three segregated sets of trim-engine routes called keys. The three-key design concept is a variation of SP's West Colton Yard trim-end design. The purpose of the three-key design is to provide as many segregated routes as possible from classification yard to departure yard so that as many trim engines as possible can be used without conflict and interference.

However, the segregation of routes between the classification yard and the in-line departure yard makes it difficult to pull a cut of cars from the classification yard to tracks in a departure yard not in the same key. This geometric restriction constrains operations in the yard because cars assigned to classification tracks associated with a given key must be made up on trains in the departure tracks associated with the same key; that is, crossovers from one key to another are virtually impossible. This operating restriction profoundly limits the yard's flexibility in responding to daily changes in outbound train schedules and makeup instructions and in the inbound traffic level and mix of cars. For example, changing the classification-track assignment for a group of cars to either a longer or a shorter track to fit the expected volume is more difficult because the yardmaster must ensure that the train carrying that group of cars departs from the departure track corresponding to the changed classification-track assignment. Similarly, if a classification track overflows, the overflow cars must be put on an empty track on the same key. Also, if on a particular day it is necessary for a departing train to have a different consist mix, the only cars that can be assigned to the departing train are those from classification tracks in the same key.

The detailed CONFLICT model analysis indicated that for a given classification-track assignment and a specified departing-train schedule and consist, the capacity of the one-key design is slightly greater than that of the three-key design. The layout and operations of the three-key design dictate that all southbound trains and a significant portion of the northbound trains depart to the south from the in-line departure yard. (Note that the north trains departing to the south reverse direction before entering the main line via a balloon track.) The analysis also revealed considerable congestion

Table 1. Recommended minimum requirements: one-key design.

Design Feature	1985	1990	1995	2000
No. of tracks				
Receiving yard	14	15	18	22
Departure yard				
North	7	9	10	12
South	7	9	10	12
Minimum hump speed (cars/min)	4.0	4.0	5.0	6.0
Crew[a]				
Inbound inspection	4, 4, 4	4, 4, 4	5, 5, 5	7, 7, 7
Hump-engine	2, 3, 2	2, 3, 3	3, 3, 3	3, 3, 3
Trim-engine				
North departure yard	2, 2, 1	2, 2, 2	2, 2, 2	3, 3, 3
South departure yard	2, 2, 2	3, 3, 3	3, 3, 3	3, 3, 3
TVM yard	1, 1, 1	1, 1, 1	1, 2, 1	2, 2, 2
Outbound inspection				
North departure yard	1, 1, 1	1, 1, 1	2, 2, 1	2, 2, 2
South departure yard	2, 2, 2	2, 2, 2	2, 2, 2	3, 3, 3

[a] The group of three numbers indicates the size of crew for the first, second, and third shifts.

and a crossing conflict between northbound and southbound trains leaving the in-line departure yard for the main line.

An analysis of the layouts in the three-key and one-key designs indicated that the three-key design has 30 percent more tracks and switches. Therefore, the three-key design will be substantially more expensive to build and maintain.

Compared with the three-key design, the one-key design has slightly lower capacity, is less expensive to build and maintain, and is more flexible in responding to changes in traffic and operating conditions. Consequently, SRI recommended the adoption of the one-key design.

Capacity of Coyotepec Yard

Coyotepec is expected to have a peak capacity of approximately 6,000 cars and 70 trains per day. To achieve this peak capacity in the CAPACITY model analysis, it was assumed that the hump engines worked at rates slightly faster than normal. The normal rates of work were conservative estimates; the INPLAN coordinators believe that the higher rates of work can be sustained for short periods. Therefore, it was estimated that the peak capacity can be sustained over a period of several days but that the long-term steady-state capacity will be approximately 5,500 to 5,600 cars per day.

Major Design Recommendations

SRI recommended that Coyotepec Yard ultimately have 22 receiving tracks, 12 northbound departure tracks, and 12 southbound departure tracks. In Table 1 the increased track requirements for the years 1985 to 2000 are given.

It is also indicated in Table 1 that Coyotepec Yard must be designed to hump 6 cars per minute by the year 2000. Although the minimum hump speeds for the years 1985 to 1995 are lower, the rate of 6 cars per minute must be designed into the yard at the beginning because the humping rates are fixed by the hump grades and retarder placements.

To facilitate the humping activity, SRI recommended that a hump-engine escape route be designed so that once an engine has finished humping, it can quickly clear the hump by going onto an escape track. The escape track should be so constructed that the hump engine can return to either side of the receiving yard via a tunnel under the hump.

Overpasses may be desirable at both ends of the yard so that trains entering and leaving the yard from one main-line track can cross above the traffic on the other main-line track. This will prevent congestion from trains entering and leaving the yard from the main line.

To allow flexibility for the TVM classification tracks to handle transfer traffic when needed, SRI recommended that a reasonably short and conflict-free route exist from the TVM classification tracks to the minihump yard.

If a peak humping rate of greater than 6,000 cars per day is desired, INPLAN should consider the possibility of constructing a dual-lead hump with scissors crossovers down the hump grade to support simultaneous humping operations. However, for dual-humping operation trains arriving in the yard must be blocked by the outlying yards so that they carry cars for only one side of the classification yard; this ensures that no cars cross over during simultaneous humping operations.

Yard-Crew Requirements

The minimum yard-inspection and engine-crew requirements for the years 1985 to 2000 are given in Table 1. The sets of three numbers (for example, 2, 3, 2) indicate that there are two crews on the first shift, three crews on the second shift, and two crews on the third shift. The translation of crews into actual personnel is as follows:

1. One inbound inspection crew, six persons;
2. One hump-engine crew, five persons;
3. One trim-engine crew, five persons; and
4. One outbound inspection crew, three persons.

The minimum crew levels recommended can produce a considerable operational cost saving at Coyotepec Yard. Also, staffing the yard initially at the minimum crew levels is wise because extra crews can be added when the need arises. If too many crews are planned initially, eliminating crews later may be difficult because of established labor agreements. If Coyotepec Yard is operated at minimum crew levels, the crews will become used to working at high efficiency, even with low traffic levels; otherwise, when the traffic levels rise to those anticipated for the year 2000, the workforce will not be efficient enough to handle 6,000 cars on the peak days.

Coyotepec Yard has been designed to allow a specified maximum number of hump and trim engines to work productively without conflict. Consequently, in the year 2000 the Coyotepec crews must be capable of working efficiently because inefficiency cannot be compensated for by the addition of extra yard engines, which will begin to interfere with each other and decrease operational efficiency.

CONCLUSIONS

Coyotepec Yard is approximately twice the size of large yards in the United States. It has been designed with the best technology and methods available. The ability of the yard to meet its peak capacity potential, however, will be determined not only by its physical design but also by the efficient coordination of train schedules with other outlying yards and the efficient management of engines and crews within the yard. To achieve long-term goals, the planning of operations for the successful opening of Coyotepec Yard in 1985 is critical because a number of labor practices will be established that will be difficult to change later.

The most visible results of this project are as follows:

1. The array of yard designs was narrowed to a choice between two specific, new yard designs.
2. The yard was designed to handle 6,000 cars on a peak day.
3. The classification yard was designed to work together with the TVM yard and was dedicated to serve only a group of eight TVM tracks.
4. A trim end was designed with a capacity equal to that of the hump and with great flexibility, few conflicts, and low cost.
5. The minihump was designed with the trim end east of the on-line departure yard and later changed to be beside the classification yard west of the TVM group. With this change there will be fewer conflicts at the trim end.

Employee acceptance of the new yard and its new systems may pose problems when the yard is opened. It is not too early to start a program of familiarization for the employees. First, sessions could be held with union leaders and their local representatives to tell them what is being planned and why and invite their cooperation and suggestions. Second, when possible, some of the new devices and systems could be set up in a demonstration mode so they could be tried. Third, comprehensive training programs could be offered before the yard is opened. The training sessions should feature hands-on training by using actual devices and procedures. A program along these lines will help to overcome possible problems of nonacceptance.

ACKNOWLEDGMENT

In order to design the Coyotepec Yard, an interdepartmental group was set up as follows: Vicente Ortego, planning; Jaime Hueso, signals; Antulio Morgado, communications; Miguel Ruiz, locomotives and cars; Roberto Castellanos, systems; Ignacio Salaza, track and structures; and Manuel Gonzalez, operations.

Advice was also given by William V. Williamson and Barney Gallagher of Southern Pacific Transportation Company during 1981 and Hubert Hall of the Atchison, Topeka, and Santa Fe Railway Company in 1982. Assistance was received from SRI International, represented by Peter Wong. The final design is the result of the high degree of cooperation, understanding, patience, and hard work of all concerned.

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A Modular Approach to Classification Yard Control

ROBERT KUBALA AND DON RANEY

A design is described that focuses on existing yards. It provides basic control functions and is cost-effective, expandable, and maintainable. The distributed system provides natural partitioning, expansion, system flexibility, and modularity through the use of microprocessors. Hierarchical relationships of each function within the yard are explained and illustrated. Suggested hardware for the system includes racks, chassis, and power supplies. Estimates of facility requirements such as power, floor space, and heating or cooling are also provided.

In late 1979 the need became apparent for a yard-control system with characteristics somewhat different from those of existing computer-based control systems. Most new control system development had been targeted for new yards designed for increased levels of automation and functional capability. These systems provided a level of control that could not be obtained by using previous technologies. However, these systems did not lend themselves to applications in existing yards where a high degree of automation was impractical either because of existing field conditions or the configuration of the yard. Therefore a project was launched to analyze existing control systems and determine whether a system could be developed that would provide basic control features in a configuration more applicable to an existing yard facility.

DEFINITION OF FUNCTIONS OF A YARD-CONTROL SYSTEM

The first step in the project was to identify and define those functional features that might be required in the target system. The track and equipment layout of a yard is shown in Figure 1. A list and brief description of each function required of the control system follow:

1. Cut detection: The control system must detect a cut after it has been separated from the train. The presence of the cut must be detected soon enough to allow characterization of the cut (see item 2).
2. Cut characterization: Each cut must be characterized with respect to length, axle count, number of cars, weight, and rolling resistance. Characterization must be complete before the cut enters the master retarder.
3. Cut tracking: The system must track the movement of cuts through the control area. If a cut proceeds on a path other than the intended path, an alarm should be generated. The track on which the cut leaves the control area should be recorded for reporting purposes.
4. Switch control: The system must provide for automatic switch movement to ensure that each cut is routed to the requested classification track.
5. Distance to couple (DTC): The system must maintain a record of distance from tangent point to standing cuts on each classification track. This information is derived from a car-count algorithm or from electronic hardware measuring distances.
6. Exit-speed calculation: Given the cut characteristics, cut destination, curves, grades, elevation drop, distance to go on the classification track, and target coupling speed, the system must

System Flexibility

Dispersion of a system into a distributed set of substantial subsystems is an answer to general problems universally found in large industrial and military systems. An example of this type of distribution is the public telephone system as it was recognized a number of years ago.

At one time, the Bell System sought to grow and maintain its large network by maintaining control over all aspects of design, manufacture of components, installation, and operation. As technology advanced, Bell engineers recognized that the approach was unworkable; it amounted to a replication of a highly evolving technology-based economy within one organization.

There was another way, namely, not to try to predict and control everything but to construct the whole system out of important subsystems whose functions and interfaces to the system could remain constant over the lifetime of the system. This approach has been successfully applied by the telephone companies. As technology advanced, the newer, more advanced systems, which were cheaper and more reliable, could be incorporated into new subsystems with the expected economy and performance. Because the interface (electrical levels, signals, connector dimensions, and so on) remains constant, the system continues to work without disruption. The system still has ultimate limits. It will not handle TV signals into homes or businesses nor lend itself to optical fibers on every subscriber loop, but the limits are the consciously specified system limits, not the everyday, unpredictable happenings of equipment obsolescence or parts availability.

Modularity

The perceptions listed thus far led to a system architecture of distributed subparts--each subpart stands substantially independent of the other subparts. Two important aspects in the specification of these subparts or subsystems are

1. The idea of modular independence and
2. The notion of logical interface.

By independence it is not meant that there is absolutely no relation to or connection with the other parts of the system. That would deny that there is a meaningful system. Rather it is meant that small, arbitrary, local changes in a subsystem have no consequence and no impact on other subsystems. For example, if the number of possible positions of a retarder mechanism or the wiring list for a specific terminal block is changed, those differences should cause changes only within the retarder controller itself, not in any other part of the control system. Knowledge of implementation-dependent details should be confined to the controller or zone or subsystem involved. Therefore the system and the subsystems are independent in that superficial, implementation-dependent details and changes do not propagate throughout the system.

This relates to the idea of a logical interface. Because communication to and from a subsystem, such as a retarder, is in terms of the work it does (e.g., desired exit speed, actual exit speed, weight of cut, and length of cut) rather than how it does the work (i.e., set 24 volts to terminal block pin B2-7), modular independence is supported.

These ideas are essential. If modular independence in the sense described previously is not accomplished, any hope of segregating a complex system into tractable portions is lost. The resulting system will not be easily expandable and modifiable because any change will tend to subtly propagate into hidden parts of the system, making change impracticable.

Microprocessors

One may ask why such a distributed approach to yard design was not considered previously. The answer is that the ideas of modular independence and logical information transfer are impractical unless it is possible to place substantial information-processing power into the individual subsystems and controllers. The local control of retarders, switching, and so on, requires sophisticated logic such as that associated with computers and substantial computer programs. Furthermore, the translation of information such as desired speeds and other parameters in logical form into specific electrical commands and sequences also requires processing of a complexity and degree that implies computers in some form.

Until recently providing this type of processing power in a form other than a mainframe computer was next to impossible. Today, however, distributed architecture is made feasible by microprocessor technology--the placing of computers into a dozen or so integrated circuits on a single printed circuit board.

SYSTEM OVERVIEW

With the assistance of this microprocessor technology, General Railway Signal (GRS) has developed a distributed classification yard control system. This control system parallels the level of automation desired in a yard and allows computerization of functions of the yard in phases. Self-diagnostics and user-initiated diagnostics of the system allow rapid detection and isolation of system and field failures.

This yard-control system begins with a series of modules loosely coupled together. Most modules contain an interface to field equipment as well as sufficient computing power to perform individual functions. Communication is handled through a simple interface in which information is passed from one module to another.

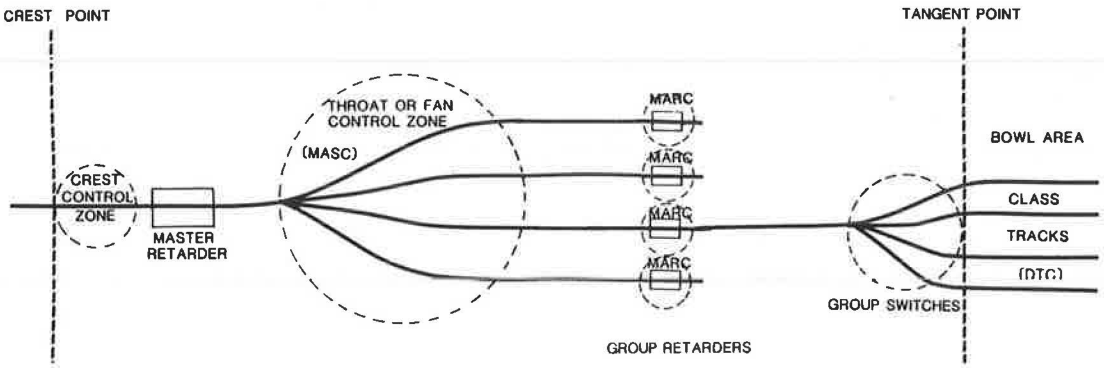
In its simplest conceptual form, a yard process-control system consists of inputs and outputs both to field devices and to the operations personnel. In the distributed classification yard-control system developed by GRS, the various control system functions are handled by separate processors. Interfaces between personnel and machines are performed by the operator communications (OPCOM) module. Field input and output (I/O) as well as the logic necessary to effect logical control are distributed into individual controllers, each capable of fully controlling one specific function in one specific place. For example, one controller is responsible for the master retarder logic, whereas another may control the group-3 switching. This configuration combines the best of both a functional organization (retarder, switching, reports, and so on) with a geographic arrangement (throat region, group region, and so on). Both complexity and cost are reduced by including only those modules needed to effect the desired control. The final logical subsystem in this concept is hump control (HCON). This module along with communications multiplexers make up the nerve center that links the various modules together.

Figure 2 shows a functional block diagram of the proposed classification yard control system. A description of the functional parts follows.

Operator Communications

OPCOM handles all commands from the operators of the

Figure 1. Track and equipment layout of a yard.



compute a target exit speed for release of the cut from the master and group retarders.

7. Retarder control: The system must provide control of retarders to release cuts at a preselected or computed exit speed. The control should be safe with minimum retarder movements.

8. Operator interface: Appropriate input and output must be provided for dialogue with the system's users.

9. Maintenance interface: Means must be provided for diagnosing system failures, changing various internal parameters, and monitoring system performance.

10. Report generation: The system must provide for hard copies of various reports of system activity.

SYSTEM REQUIREMENTS

The second step in the project was to describe characteristics needed in the new system. Basic items included expandability, maintainability, physical plant, and long system life.

Expandability

An acceptable system must be expandable in two respects. It must be easy to add more of what has already been installed, e.g., more group retarders and switching groups. That is, revision to previously installed portions of the system should be minimal, preferably only to identify the new equipment to the system.

The system must be expandable, or modifiable, with respect to alternative or new types of equipment and to functions nonexistent in the initially installed system. It should be possible to include new types of retarders, distance to couple, and enhanced operator interfaces without extensive impact on the previously installed control system.

Maintainability

Systems are often impossible to maintain to the point where a fault can typically leave competent maintenance personnel staring at the equipment in hopeless frustration. The only recourse may be to call the original designers.

For a system to be maintainable, it must be possible for a maintainer (knowledgeable about the overall functioning of the system and its basic structure) to pinpoint (in a methodical way) what is working properly and what is not. This pinpointing allows the maintainer to isolate a fault to the level of a broken wire or faulty circuit board, power supply, or relay.

Physical Plant

A minimum amount of floor space for the equipment, an uninterruptable power source (UPS), and adequate cooling and heating are required to keep the office-based portion of the control system reliably operable.

As a target, two relay racks 85 ft high by 19 ft wide should be sufficient to contain the signal-processing and information-processing portion of the control system. (This would not contain the UPS, incoming termination panel, any test panel, or power-handling relays.)

Long System Life

Obsolescence is a major risk in most systems. To protect the investment, it should be possible to

1. Replace subsystems at those times in the future when spare parts become unavailable without altering or replacing the remainder of the system and
2. Incorporate desirable or necessary enhancements into the system without major modification to the system [e.g., new types of retarders or DTC or management information systems (MIS) interface].

Furthermore, upgrades should be possible without the replacement of expensive and properly functioning parts, e.g., retarders and their controllers.

THE DISTRIBUTED SYSTEM

A number of perceptions led to the specification of a distributed control system. These perceptions included natural partitioning, expansion, system flexibility, modularity, and use of microprocessors.

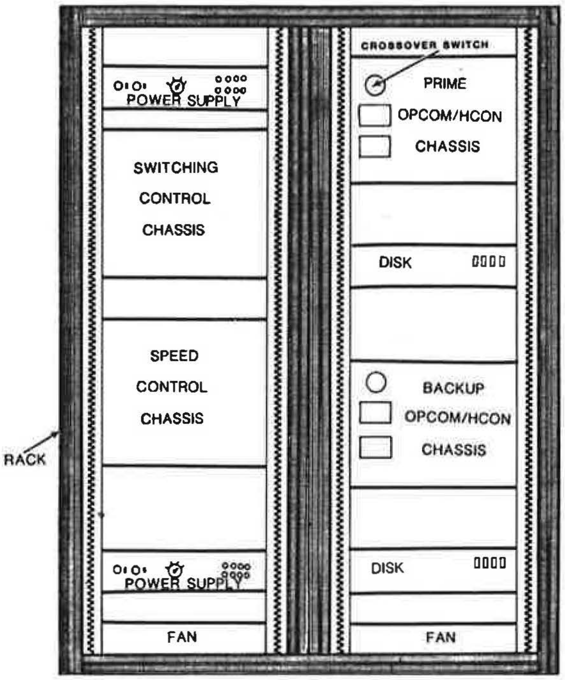
Natural Partitioning

Classification yards are naturally partitioned into clusters of equipment and geographical regions that correspond quite well to subfunctions of the yard. The characterization function (and equipment cluster) in the crest region, the retarder region, the throat switching zone, and so on, each constitutes a parcel of localized sensing or control or both sufficiently complex to warrant a dedicated controller.

Expansion

The naturally partitioned zones and subfunctions are the usual units of expansion. Adding groups or extending a limited control system to include group switching (for example) are typically required for updating or for seeking a higher degree of automation.

Figure 3. Packaging diagram.



5. As the cut leaves the control region of the yard, HCON delivers the contents of the overall cut history to OPCOM. OPCOM prepares a report for the printer.

HARDWARE DESCRIPTION

Figure 3 shows the typical rack layout of the control system parts shown in the functional diagram. Not shown are the UPS, test panel, the incoming termination panel, surge protectors, or the relays and logic that provide manual retarder override.

This portion of the control system requires less than 10 ft^2 and less than 3 kW of 115-V AC power (and consequent equipment cooling).

SYSTEM MAINTENANCE

Run-Time Diagnostics

During normal operation of the system consistency checks are performed and messages reported for abnormalities. For example, should a message arrive between subsystems that in some respect is inconsistent or unintelligible, this is reported. Should an input-output signal value be improper (e.g., a pressure grossly different from that commanded), this is reported. Should the microprocessor of a controller reset via its watchdog, a message is reported to an operator and to a report printer.

It is believed that a maintainer will be armed with information provided by these normally running diagnostics before ever approaching the system in response to a complaint.

Backup

In the area of the controllers, backup can take the form of duplication of controllers with inputs provided simultaneously to prime and backup printed circuit boards. Outputs must be switched, which might be done manually by a maintainer or automatically by the control system. Impact on system complexity and complexity of the controller programs is minimal; the transition is primarily a matter of switching messages to the alternate unit.

In the region of OPCOM and HCON, the higher-order region of the control system, it appears desirable to manually control any transition from a prime OPCOM/HCON pair to a backup. A fully automatic transition would be complex and not foolproof. If an operator cannot communicate with OPCOM or feels the sequencing of action on cuts from HCON is incorrect, he or she can simply ask the maintainer in the equipment office to switch to the backup equipment.

Logical Progression

The purpose of maintenance activity is to isolate a faulty printed circuit board, broken interconnect wires, or faulty power supply. Maintenance activity can also circumscribe a control program error (which should be rare) in which yard operation may be resumed through a manual reset of a processor. But for the class of problems requiring immediate repair, a fault is sought in the hardware.

If a problem is known at the onset to be specific to a controller (for example, a retarder controller, MARC module), then the problem is already isolated to the two printed circuit boards, cabling, or field equipment associated with that retarder. Either through local attachment of a terminal with CRT and keyboard or through the maintainer's terminal, the maintainer may communicate with the controller microprocessor to obtain information on the controller and the value of field input signals and establish output values that may be checked by direct observation or electrical measurement.

If the problem has not yet been isolated, the maintainer progresses in the following fashion. First, the communication with OPCOM is checked from the maintainer's terminal. If there is no response to various requests, then the OPCOM microprocessor is faulty, the terminal is faulty, or there is a bad cable connection.

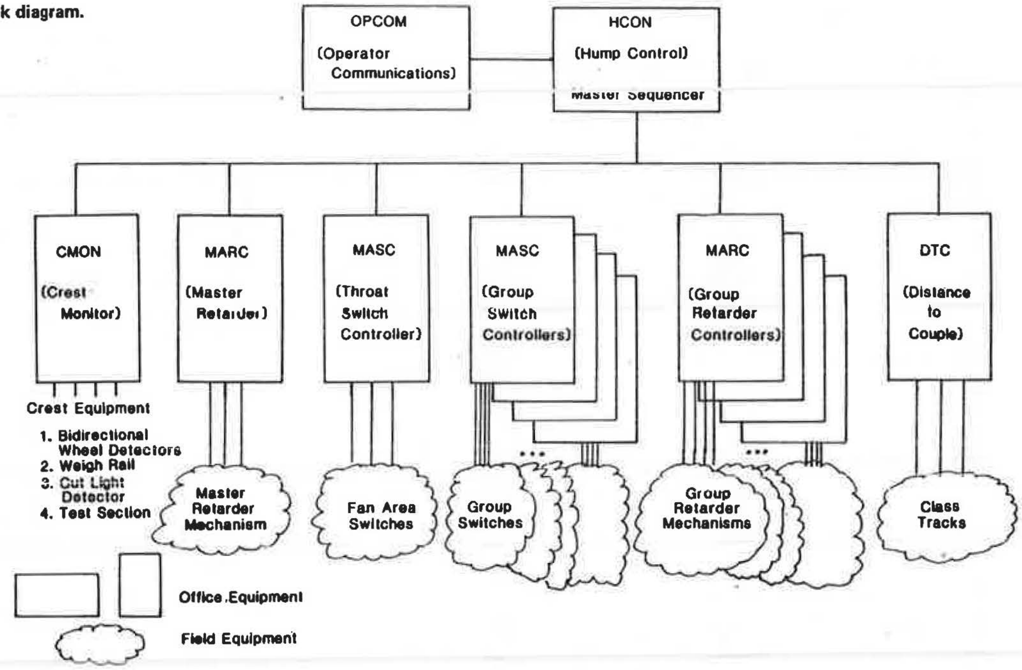
If communication with OPCOM is possible, the maintainer can interrogate HCON, again from the maintainer's terminal. Interrogation of HCON should reveal whether HCON is operable or whether a downstream subsystem is the problem. If HCON is faulty, examination of power supply voltage values and cables and swapping of circuit boards is in order. If a downstream unit cannot be accessed, the problem has been isolated to that unit.

In this system, communication with the various distributed entities is possible, both through the normal system communications means and locally through a specific plug-in point. Local processing power permits substantial, structured access.

Association of I/O Wires to Corresponding Controller

When trouble has been isolated to a specific functional region (for example, a switching zone, a MASC module), examination of signals at the module that lead to and from the field is especially easy. The maintainer does not have to work from a bulky set of diagrams to find the pertinent terminal blocks. The module is located in a clearly defined slot position in the switching controller chassis. The I/O board is immediately below the MASC processor board. The I/O connector on that I/O board is cabled directly to the corresponding plug coupler on the hinged rear panel. All signals are available at the edge connector and at the plug coupler. The same signals are brought to the same pins on all of the MASC modules and are furthermore segregated in a consistent pattern. This expedites maintenance considerably.

Figure 2. Microyard functional block diagram.



system--yardmaster, hump conductor, retarder operator, and maintainer. Depending on the degree of automation, OPCOM can be a simple control machine with speed-select dials or destination-track pushbuttons or both or, at the other extreme, a set of terminals with CRT or keyboard with full status displays and MIS connections.

Hump Control

Hump control (HCON) is a high-level master sequencer of real-time yard-control activity. As cuts enter the control region, HCON determines what subsystem handles what cut at what time. It arms the various equipment controllers with functional information concerning the approaching cut, conditions affecting control, and behavior desired. As traffic leaves a subsystem, HCON is notified, keeps track of traffic changes, and delegates control to subsequent subsystems.

HCON ensures that the cut characterization is reasonable, calculates the requested exit velocity from each retarder, and maintains a set of cut statistics regarding each cut in the system.

Crest Monitor

Crest monitor (CMON) detects new cuts coming into the control region and measures the relevant characteristics of the cut such as number of cars and axles, weight, height, and rollability.

Microprocessor-Assisted Retarder Controller

Each microprocessor-assisted retarder controller (MARC) controls a retarder mechanism to establish the desired exit speed, given the cut weight, length, and number of axles.

Microprocessor-Assisted Switch Controller

Each microprocessor-assisted switch controller (MASC) tracks the movement of cuts in its zone of the yard and positions switches to effect correct movement of cuts.

Distance to Couple

Distance to couple (DTC) is measured on each of the classification tracks through either direct electrical measurement based on shunting or car-count processing.

SYSTEM DESCRIPTION

A typical car transit in the distributed system follows a general progression, described as follows:

1. A car is identified by desired destination track before it encounters detection equipment in the crest region. In more complex yards a hump list, generated from a remote MIS data-processing facility, is transmitted to OPCOM before the train arrives at the hump. In other yards a button on a control panel is pushed by the hump conductor to distinguish destination tracks.
2. As the cut crosses the CMON bidirectional wheel detectors, HCON is notified of traffic. A sequence number is assigned to the cut and a memory block is assigned in HCON to specify its desired routing and to record its history through the control region. As the rear knuckle of the cut passes the cut light detector, CMON determines the number of cars in the cut and passes the information to HCON.
3. As the car's weight, wheelbase, and rolling resistance are measured by CMON, HCON is informed. HCON issues information to the master MARC and throat MASC to permit initial speed control and routing control.
4. Each subsystem or controller queues (saves up) information it receives from HCON pertaining to arriving traffic before its arrival. Hardware events sensed by each controller are interpreted as the movement of traffic unless faults are discerned. Cuts are handled and final reports on the cut behavior, handling by the controller, and state of controller equipment are sent to HCON as the cut leaves the control zone. Each controller purges its information about the cut after the cut has completely passed through.

SUMMARY

The design described does not purport to be the answer to all classification yard control problems. It will not fulfill the functional requirements of all classification yard installations; nevertheless, it is believed that a system could be developed from this design to economically meet the needs and requirements of many existing yard facilities. The designers of this system maintained a practical approach in hopes that modern computer technology could produce a system (while not providing the ultimate in functional capability) that could be applied in yards where existing systems have been cost prohibitive.

ACKNOWLEDGMENT

The assistance and cooperation of the Signal Department of the Missouri-Pacific Railroad in the preparation of this paper is acknowledged. MoPac has been an active participant in this project, and thanks to their trust and patience, the development of the system is now proceeding.