Minimizing Derailments of Railcars Carrying Dangerous Commodities Through Effective Marshaling Strategies

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Effective marshaling and buffering strategies can reduce the likelihood of special dangerous commodity (SDC) cars being involved in a train derailment. The objective of these strategies should be to minimize the probability that an SDC car is located in a potential derailment block, subject to external rail corridor characteristics that affect derailments. A procedure is developed for predicting derailments for different railcar positions in a train, on the basis of the point of derailment and the number of cars involved. The number of cars involved in each derailment is assumed to be a function of the train operating speed, the cause of derailment, and the number of cars following the point of derailment. Canadian rail accident data for the period 1980–1985 are used to calibrate a probabilistic expression of number of cars involved in derailments. The Canadian accident data base is also used to estimate point-of-derailment probabilities for different railcar positions and derailment causes. Alternative marshaling and buffering strategies for SDC railcars are evaluated using a combinatorial approach. The results of this analysis indicate that SDC car derailments can be reduced appreciably by considering the derailment potential of different positions along a train for various rail corridor conditions.

Prior to 1987, all train accidents in Canada with consequent damages exceeding $750 were reported to the Canadian Transport Commission (*1*). For the period 1980–85, approximately 75 percent of these reported train accidents involved one or more car derailments. More than 7 percent of railcar derailments that occurred between 1980 and 1985 involved some type of special dangerous commodity (SDC). Commodities that are especially hazardous to population and environment (such as toxic substances, corrosives, flammables, radioactive materials, and explosives) have been designated as SDCs by Transport Canada (*2*).

Recognizing that railcars carrying SDCs are more apt to cause greater damage in a derailment situation, the focus of this paper is to apply efficient marshaling and buffering regulations so as to minimize the likelihood that these SDC cars will be involved in a potential derailment block.

A report prepared by A. D. Little (*3*) for the U.S. Department of Transportation suggested that the position of a railcar in the train is a major factor determining its involvement in a derailment situation. Swoveland (*4*) has suggested that the involvement of dangerous commodities in accidents can be reduced through appropriate marshaling and buffering strategies that take into account train derailment profiles on the basis of car position.

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OBJECTIVES OF THIS STUDY

Although it is known that the position of cars in a train can influence their involvement in a derailment, the specific nature of this relationship is not well understood. This paper presents a procedure for establishing and evaluating the effectiveness of alternative marshaling and buffering strategies for positioning SDC cars in a given train consist.

The specific objectives of this study are threefold:

1. Establish railcar derailment profiles for different positions in the train on the basis of the point of derailment (POD) and the number of cars involved.
2. Identify critical positions on a train assigned to designated classes of SDC cars for different train consists and marshaling and buffering regulations.
3. For different train derailment causes, evaluate the effectiveness of selected marshaling/buffering regulations in terms of reduced SDC car derailments.

APPROACH AND SOURCES OF DATA

In this section, the major components of a model for predicting derailments by position in the train are described, and the data base used in calibrating derailment expressions is introduced.

Model Framework

As illustrated in Figure 1, this study consists of two major phases:

1. Establishment of derailment profiles for railcars on the basis of position, and
2. Evaluation of alternative marshaling and buffering strategies.

Derailment profiles for railcars on the basis of position in the train are affected by two conditions: the position at which a derailment is initiated and the number of cars derailing thereafter. The probability that a railcar in the *i*th position will derail, given that the train is involved in a derailment, can be expressed as

$$P_d(i) = \sum_{k=1}^{i} P_{od}(k) * \sum_{x=i-k+1}^{n-k+1} P(x) \quad (1)$$

where

$P_{od}(k)$ = probability that the derailment starts at the *k*th position, and
$P(x)$ = probability that exactly x cars will derail.

Equation 1 assumes that a train derailment has already occurred. The term $P_{od}(k)$ for the POD is obtained from an analysis of Canadian rail accident statistics. In this study, the POD was found to be affected by the cause of the derailment and the operating speed of the train. The term $P(x)$, reflecting the number of cars involved in a derailment, is obtained by calibrating a probabilistic model, where the number of cars derailing was found to be a function of operating train speed, cause of derailment, and train length. The results of these model calibrations will be discussed later.

The involvement of SDC cars in a derailment block depends on the probability that certain positions in the train are subject to derailment and the probability that SDC cars have been marshaled into a potential derailment block.

Within the context of this paper, the term marshaling refers to the positioning of designated SDC car blocks along a given train length. Table 1 summarizes the current CTC regulations concerning the marshaling of SDC cars in a conventional train consist. In general, a five-car, non-SDC buffer is provided between any SDC block and inhabited sections of the train (i.e., locomotives at the front of the train and cabooses at the rear). Blocks of SDC cars with incompatible properties are

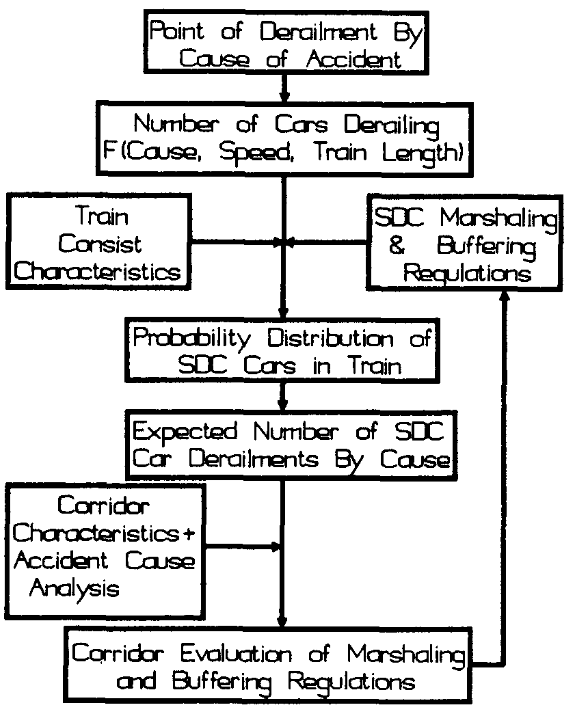


FIGURE 1 Model framework.

separated by additional five-car buffers. SDC materials having similar damage properties can be marshaled into the same block.

The number and mix of SDC cars assigned to a given train will affect the number and length of SDC blocks in a train. For example, all cars carrying liquefied chlorine gas would be marshaled into a single block. This block may contain non-SDC cars or cars carrying materials that are compatible with chlorine (i.e., similar toxic properties).

In this study, noncritical car buffers can be varied depending on the extent of material incompatibility among neighboring blocks. Incompatibility refers to the situation in which a given material can aggravate the damage potential of another material in an accident situation. An example of this is placing an explosive block adjacent to a highly toxic block. Marshaling regulations for critical SDC car blocks are established exogenously to the model.

Data Sources

The calibration of derailment models in this study is based on rail accident data reported to the Canadian Transport Commission. The CTC data base includes 6,739 train accidents for the two national railways (Canadian National and Canadian Pacific rail) for the period 1980–85. The CTC file provides information on mainline and rail yard accident location, subdivision and milepost location, primary cause of each accident, POD, position on the train where derailment occurred, number of cars involved, and total number of cars in the train.

Although the presence of SDC cars in the derailment block is noted in the CTC data base, the actual number of SDC cars involved in a derailment is not specified. All cars that are not carrying SDCs are available to serve as buffers. Where the requirement for buffer cars in a train exceeds the number of non-SDC cars available, empty cars must be added to each train consist.

The CTC accident data base classifies train accidents by primary and secondary causes for derailments and/or collision accidents, on the basis of FRA cause codes. Table 2 summarizes the FRA causes used in this study.

CALIBRATION OF DERAILMENT EXPRESSIONS

In this section, the calibration results for the POD and number of cars involved are presented.

Point of Derailment

The inclusion of a given car in a derailment block affects its position with respect to the POD. More distant positions from the POD are less likely to be involved in a derailment chain reaction.

In this study, the POD was found to be affected by the primary cause of derailment. Logically, causes that are track and roadbed related (for example, rail and joint bar faults, frogs, and switch defects) generally affect the front of the train, because the front cars initially impinge on these faults, producing the derailment. On the other hand, general car

TABLE 1 POSITION IN FREIGHT OR MIXED TRAIN OF CARS CONTAINING DANGEROUS COMMODITIES (CURRENT REGULATIONS)

1	2	3	4	5	6	7	8	9	10	11	12	13
The letter "X" at an intersection of horizontal and vertical columns means that the wording on the top applies for the considered group		When train length permit must not be nearer than 6th from engine, occupied caboose, or occupied car	When train length does not permit must be near middle of train but not nearer than 2nd from engine, occupied caboose, or occupied car	- - - - MUST NOT BE PLACED NEXT TO - - - -								
				Car in Placarded Group.				ENGINE	CABOOSE	Open-top car when lading protrudes beyond car or when lading above car end is liable to shift	Any car piggyback on container with automatic heating or refrigeration, lighted heaters, stoves, lanterns, or internal combustion engines	Loaded flat car
Type of Car	Placard group			1	2	3	4					
ANY CAR	Group 1	X	X		X	X	X	X	X	X	X	X
TANK CAR	Group 2	X	X	X		X	X	X(*)	X(*)	X	X (*)	X (+)
ALL OTHER	Group 2			X		X	X					
TANK CAR	Group 3	X	X	X	X		X	X	X	X	X	X (+)
ALL OTHER	Group 3			X	X		X	X	X	X	X	X
ANY CAR	Group 4			X	X	X		X	X			
TANK CAR	Group 5							X(*)	X(*)			

FOOTNOTES : (*) Except when train consists only of placarded tank cars.
(+) Except trailer-on-flat-car, container-on-flat-car, tri-level and bi-level cars and any other car specially equipped with tie down devices for handling vehicles. Permanent end bulk head flat cars considered the same as an open-top car, (Column 13).

PLACARD GROUP:
1. Group 1 consists of Explosives 1.1 and 1.2.
2. Grou 2 consists of Explosives 1.3, 1.4, 1.5; Flammable Gases 2.1;Non Flammable Gases 2.2; Poison Gases 2.3; Flammable Solids 4.1,4.2,4.3; Oxidizers 5.1,5.2; Poisons 6.1,6.2 and corrosives.
3. Group 3 consists of special commodities of the division 2.3.
4. Group 4 consists of Radioactive materials.
5. Group 5 consists of Flammable liquids 3.3 and "Empty Placarded cars!"

TABLE 2 FEDERAL RAILROAD ADMINISTRATION CODES OF DERAILMENT CAUSES

CODE	CAUSE OF DERAILMENT	FRA CAUSE CODES
1.1	ROADBED DEFECTS	101,102,110,709,710,715
1.2	TRACK GEOMETRY DEFECTS	110 --> 129
1.3	RAIL & JOINT BAR DEFECTS	130 --> 153
1.4	FROGS, SWITCHES, & TRACK APPLIANCES	160 --> 189 ; 560 --> 569
2.1	GENERAL CAR DEFECTS (MECHANICAL & ELECTRICAL)	400 --> 449 ; 470 --> 499
2.2	AXLES & JOURNAL BEARINGS & DEFECTIVE WHEELS	450 --> 459
3.0	MISCELLANEOUS, OPERATIONS & OTHER CAUSES	500 --> 559 ; 570 --> 708 711 --> 714 ; 716 --> 999

defects (such as wheel, axle, and journal faults) are more randomly distributed throughout the train, as is the resultant POD.

As illustrated in Figure 2, derailments in the CTC data base reflect trains of varying lengths and number of cars. Positions near the front of the train are more represented in the train length distribution than positions nearer to the rear of the train. For example, Positions 1–10 are represented in both a 10- and 20-car train, but positions 11–20 are only represented in the 20-car train. As a result, it becomes necessary to normalize the POD for each train accident with respect to the front of the train. In this study, the normalized point of derailment (NPOD) is expressed as the ratio of the actual position at which derailment takes place (the POD) to the total number of cars in the train.

The NPOD may fail to reflect differences in stability for trains of varying lengths. For example, the 50th percentile position on a 100-car train is subject to different dynamic forces than the 50th percentile position on a 10-car train. The latter position occurs near the front and is more prone to derail, while the former is nearer the middle section, which under certain conditions might be less likely to derail. Because the NPOD treats both cases equally, it is important to test for the effect of train length on the car position where the derailment is initiated.

In this study, the NPOD was estimated for trains of varying lengths (total number of cars) to account for the effect of the absolute car position on dynamic forces in a derailment situation. Figure 2 indicates the presence of two basic groupings of train length in the CTC accident data base: less than or equal to 50 cars, and 50 cars or more. Within each grouping, the POD was normalized and classified according to primary cause of derailment. The results are summarized in Table 3.

A two-way analysis of variance was applied to assess the effects of cause and train length class on the NPOD. From these results, it is apparent that the cause of derailment alone explains most of the variations in the observed NPOD from the data. The two categories of train length (less than or equal to 50 cars, and more than 50 cars) do not have a statistically significant effect on the NPOD. These results suggest that the total number of cars in the train consist can be ignored in estimating the NPOD point.

Figure 3 illustrates the POD probabilities for different normalized positions along the train consist for two derailment causes: (a) roadbed defects and (b) wheel, axle, and journal failures. In the figure, the number above every train section represents the probability of a derailment starting within that section of the train, given that a derailment had occurred on the train.

Number of Cars Derailing

Adopting a nonlinear regression approach, A. D. Little (*3*) suggested that the number of cars involved in a train derailment was a function of train operating speed. Using U.S. accident data for 1975–78, two expressions were calibrated for the mean (N) and standard deviation (SD) of number of cars derailing, such that

$$N = bV^a \quad (2)$$

$$SD = cV^d \quad (3)$$

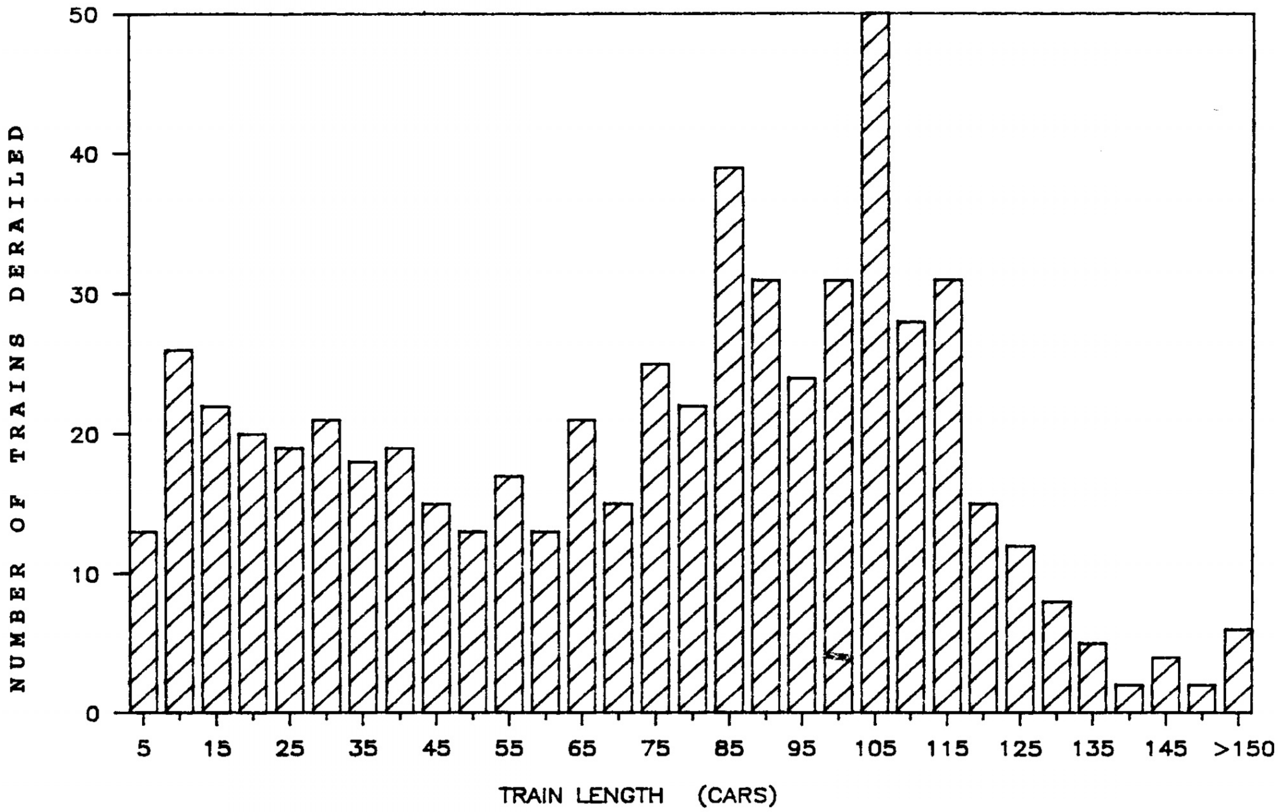


FIGURE 2 Train length distribution (CTC accident data 1980–1985).

where *a*, *b*, *c*, and *d* are regression coefficients and *V* is the train operating speed in miles per hour.

Although the number of cars derailing in an accident was assumed to be solely dependent on speed, the Little study found that the results of the model calibration were statistically significant only for trains with more than 25 cars. Even for these trains, the regression did not yield a good fit to the observed data.

The Little expressions (Equations 2 and 3) have been recalibrated using the CTC train derailment data for 1980–85. The expression for the mean cars derailing explained 19.0 percent of the variance in the observed data. An analysis of residuals indicated significant fluctuations in the observed car derailments about the fitted curve. A significant drop in the mean cars derailing was observed for the speed range 56–60 mph in both the Little report and the CTC recalibration exercise. While the Little report argued that this distortion is essentially statistical and can be ignored, it is apparent from these results that other factors beside speed may be affecting the number of cars derailing in a train accident.

In this study, the cause of derailment and the number of cars in the train are assumed to affect the number of cars derailing. Yang (*5*) demonstrated that the forces generated during certain types of derailments are conceivably localized (affecting only a limited section of the train especially at lower speeds), and under these conditions, fewer cars are likely to derail. Furthermore, the number of cars derailing is affected by the POD along the train. Train derailments usually reflect a chain reaction involving cars behind the POD. Accordingly, more cars are likely to be involved following a front section derailment because more cars are available in the trailing section of the derailment block.

Table 4 summarizes the number of cars derailing, on the basis of cause of derailment and speed. Three speed classes were used in this analysis, 0–20 mph, 20–30 mph, and more than 30 mph. A two-way analysis of variance suggests that these factors explain a significant amount of variation in the number of cars derailing. For each cause of derailment, the mean number of cars derailing increases exponentially with train operating speed.

Figure 4 illustrates the frequencies of cars derailing by position for the two derailment causes (roadbed defects and wheel, axle, and journal failures). From Figure 4, it can be seen that the probability distribution of the number of cars derailing is a negative exponential function with a sharp peaking effect for the one- and two-car intervals.

The effect of the total number of cars in the train on the number of cars derailing is demonstrated with reference to Figure 5. The mean number of cars derailing increases exponentially with the residual train length, where the residual train length is expressed as the number of cars from the POD to the end of the train. A function of the form

$$\text{Mean Cars Derailing} = A * (\text{Residual Length})^B \tag{4}$$

was fitted to these observations, with the coefficients A = 1.241 (T-value = 3.240) and B = 0.463 (T-value = 6.013). The results of this calibration were statistically significant,

TABLE 3 STATISTICAL SUMMARY FOR NORMALIZED POINT OF DERAILMENT

CAUSE OF DERAILMENT		TRAIN LENGTH < 50 CARS	TRAIN LENGTH > 50 CARS	ALL TRAINS
ROADBED DEFECTS	COUNT	28	22	50
	MEAN	0.371	0.420	0.392
	ST.DEV.	0.313	0.347	0.326
TRACK GEOMETRY DEFECTS		31	62	93
		0.585	0.607	0.600
		0.246	0.266	0.259
RAIL & JOINT BAR DEFECTS		21	59	80
		0.420	0.497	0.477
		0.262	0.319	0.305
FROGS, SWITCHES, & TRACK APPLIANCES		25	16	41
		0.457	0.323	0.405
		0.284	0.244	0.274
GENERAL CAR DEFECTS (MECHANICAL & ELECTRICAL)		3	44	47
		0.583	0.561	0.562
		0.300	0.263	0.262
AXLES & JOURNAL BEARINGS & DEFECTIVE WHEELS		22	134	156
		0.493	0.491	0.491
		0.280	0.263	0.265
MISCELLANEOUS, OPERATIONS & ALL OTHER CAUSES		21	46	67
		0.544	0.560	0.555
		0.272	0.309	0.296

SOURCE	SUM-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
TRAIN LENGTH	0.000	1	0.000	0.001	0.979
CAUSE OF DERAILMENT	2.104	6	0.351	4.424	0.000
LENGTH*CAUSE	0.299	6	0.050	0.629	0.707
ERROR	41.208	520	0.079		

MULTIPLE R: 0.244

where the residual train length alone explained 10 percent of the variation in the mean cars derailing.

It should be noted that, for train derailments with residual train length of more than 60 cars, the residuals from the above-fitted equation were higher than the other derailments. This is because only a few observed derailments had a residual train length of more than 60 cars.

In this study, the number of cars involved in a derailment is expressed in probabilistic terms on the basis of the geometric distribution. The geometric distribution was assumed to reflect the shape of observed cars derailing as in Figure 4. The probability of x cars derailing in an accident can be expressed as

$$P(x) = p\,(1 - p)^x \tag{5}$$

where $P(x)$ is the probability that x cars will derail, given an accident, and $(1 - p)/p$ is the mean number of cars derailing.

Equation 5 is defined for values of $P(x)$ in the range zero to infinity. In practice, the value of $P(x)$ for a given derailment should be confined to the range of 1 to RL, where RL is the residual number of cars available following the POD. To restrict $P(x)$ to the range of 1 to RL, Equation 5 was modified to yield

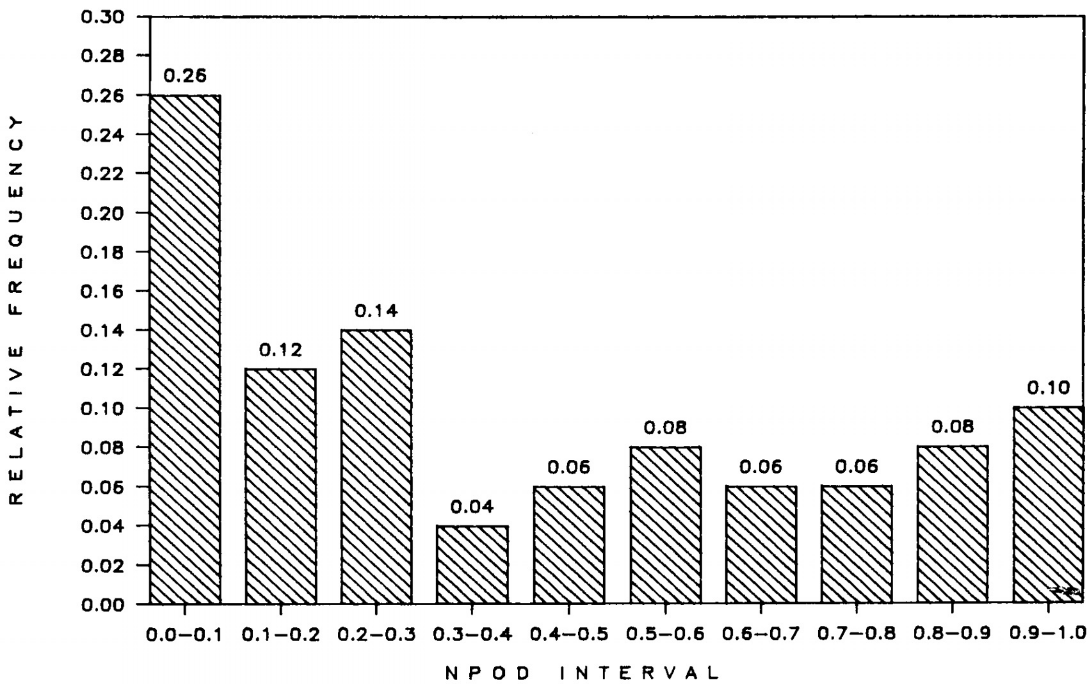
$$P(x) = \frac{p\,(1 - p)^{x-1}}{1 - (1 - p)^{RL}} \tag{6}$$

The mean number of cars derailing can be expressed as

$$U = \frac{1}{p\,[1 - (1 - p)^{RL}]} \tag{7}$$

A logistic function was chosen to evaluate p in terms of train speed (S), cause of derailment (CD), and residual train length (RL), such that

$$p = \frac{e^Z}{(1 + e^Z)} \tag{8}$$



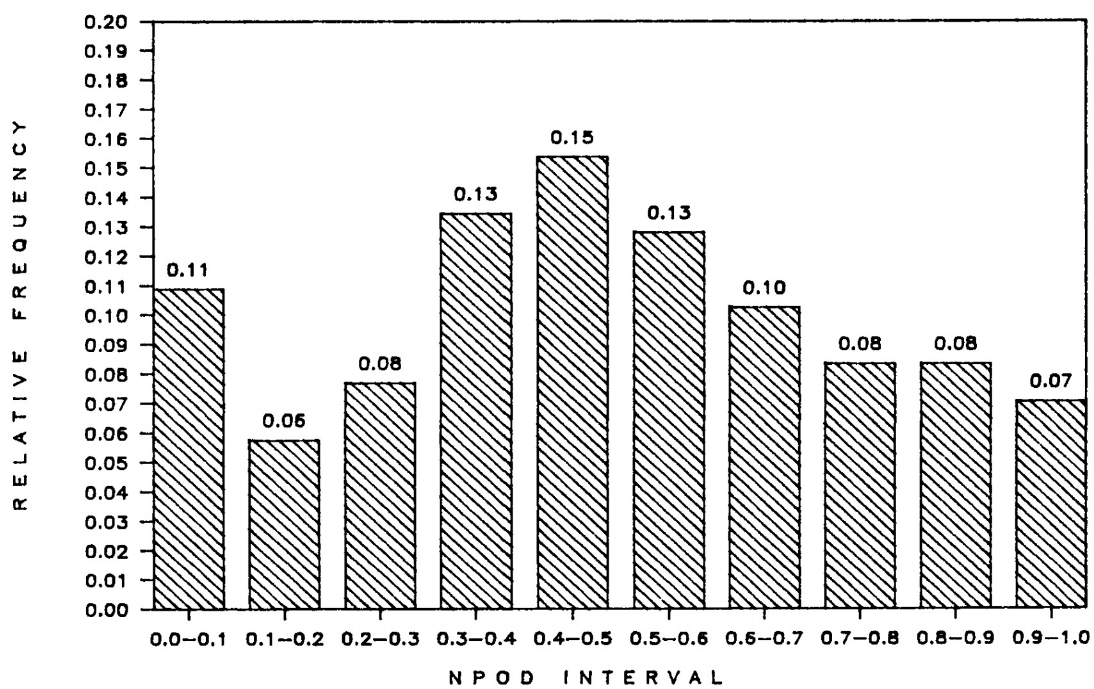


FIGURE 3 **Point of derailment probability distribution; cause of derailment: *top*, roadbed defects; *bottom*, wheel, axle, and journal defects.**

TABLE 4 STATISTICAL SUMMARY FOR NUMBER OF CARS DERAILING BY SPEED AND CAUSE OF DERAILMENT

CAUSE OF DERAILMENT	SPEED 0 TO 20 MPH	SPEED 20 TO 30 MPH	SPEED > 30 MPH	ALL SPEEDS
ROADBED DEFECTS 1.1	30 4.833 3.975	11 8.273 6.482	9 10.222 10.366	50 6.560 6.357
TRACK GEOMETRY 1.2	45 4.267 4.196	28 8.464 6.801	16 13.188 13.172	89 7.191 8.000
RAIL & BAR DEFECTS 1.3	43 7.070 6.442	17 14.000 8.754	23 18.565 12.350	83 11.675 10.133
FROGS & SWITCHES, 1.4	25 3.360 2.481	1 4.000 0.000	2 17.000 5.657	28 4.357 4.407
GENERAL CAR DEFECTS 2.1	13 3.385 3.618	19 3.526 5.243	11 3.545 8.116	43 3.486 5.586
AXLES, WHEELS & JOURNALS 2.2	20 2.450 2.460	26 5.115 9.450	86 4.709 7.614	132 4.447 7.502
ALL OTHER CAUSES 3	28 3.036 2.411	12 5.083 5.712	13 6.077 7.500	53 4.245 4.969
ALL CAUSES	204 4.426 4.458	114 7.289 8.014	160 8.044 10.495	478 6.320 7.946

COUNT
MEAN
ST.DEV.

SOURCE	SUM-SQUARES	DF	MEAN-SQUARE	F-RATIO	PROBABILITY
SPEED	1518.195	2	883.609	17.8832	0.000
CAUSE	4473.604	6	745.601	15.047	0.000
SPEED*CAUSE	1290.904	12	107.508	2.170	0.012
ERROR	28599.832	457	49.551		

and the term, Z, in Equation 8 is a response function of the form:

$$Z = A + B * (S) + C * (CD) + D * (RL). \quad (9)$$

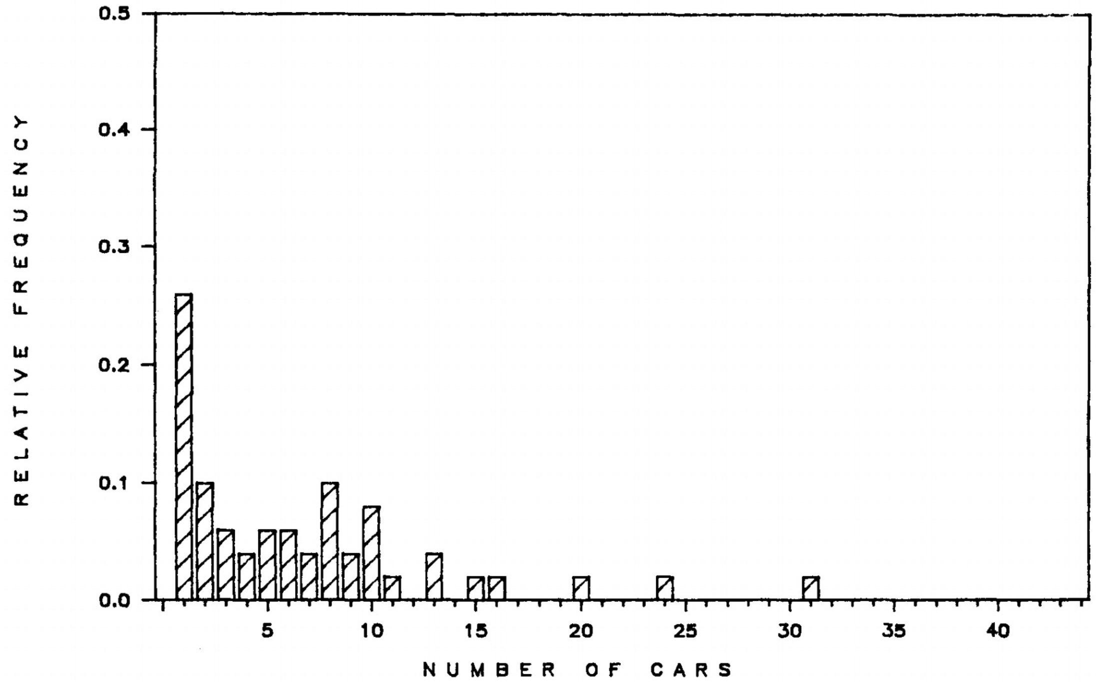
The parameters (A, B, C, and D) in this response function were calibrated using maximum likelihood techniques. The logistic function (Equation 8) forces the value of p to lie in the range of zero to one.

Table 5 summarizes the results of the calibration exercise. The intercept term "A" of the response function represents the global mean cars derailing in the data base—independent of train speed, cause, or residual train length. In this case, it explains the number of cars derailing in terms of rail and jointbar derailment cause. This was done so as to eliminate redundancy, and thus, no distinctive factor was included for these causes in the response function.

The term "B0" reflects the effect of speed on cars derailing. The negative sign of this parameter indicates that an increase in speed causes a reduction in the response expression Z and a subsequent increase in the number of cars derailing. The term "C0" is also negative, reflecting a positive relationship between the residual train length and the number of cars derailing.

The cause parameters of the response function explain the effect of derailment cause on the number of cars derailing, controlling for speed and residual train length. For example, the term "B5" for journal-related causes reflects the lowest number of cars derailing in an accident situation (highest coefficient).

In general, the values of the cause parameters in the response function agree with the mean number of cars derailing observed in the accident data base (Table 4). For example, rail and jointbar defects exhibit the highest number of cars derailing



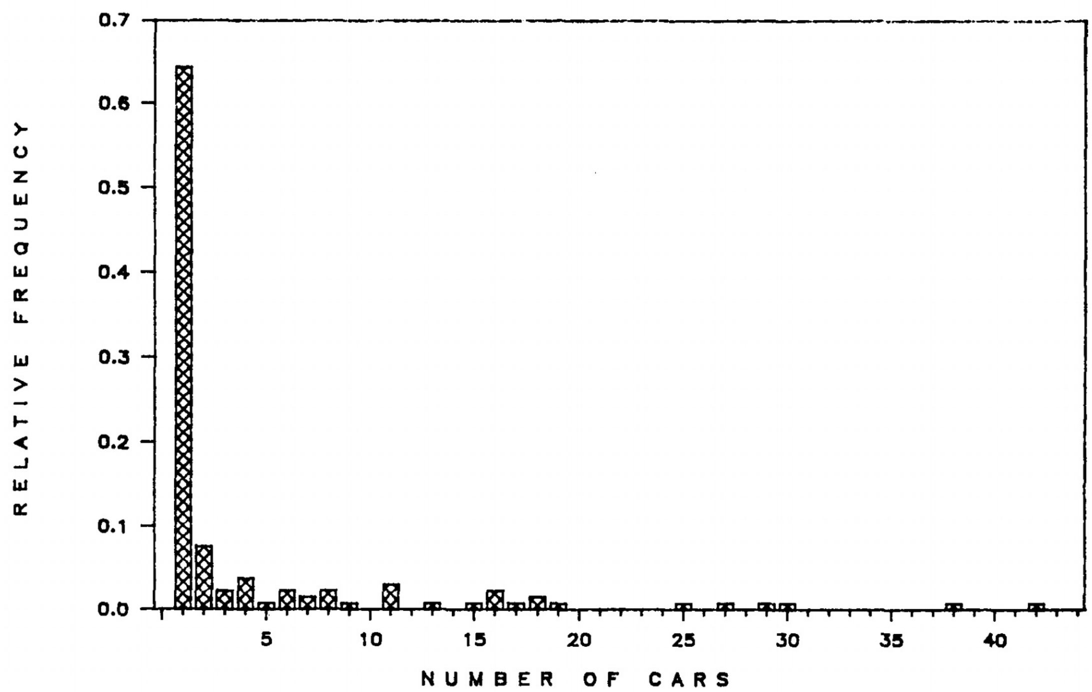


FIGURE 4 Relative frequency histograms for the number of cars derailing, for all speeds and two causes of derailment; *top*, roadbed defects; *bottom*, wheel, axle, and journal defects.

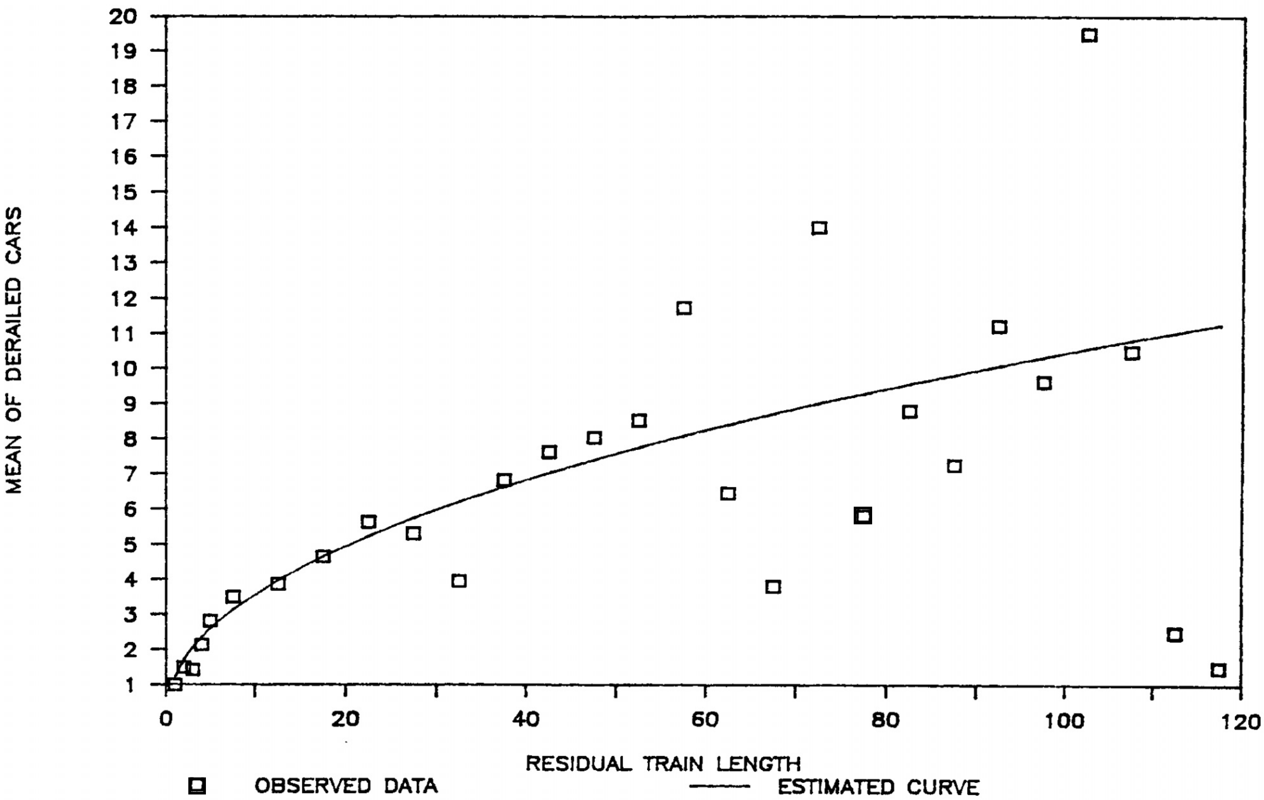


FIGURE 5 Number of cars derailing versus residual train length for all train speeds.

in the CTC data. The coefficients of the response function for all other causes are positive, suggesting fewer cars derailing as a result of rail and jointbar defects.

A comparison was undertaken between the geometric distribution in Equation 6 and the exponential expression calibrated by Little. Deviations from observed values are illustrated in Figure 6. Because the geometric expression in this study is desegregate in nature, it can account for speed, cause, and train length characteristics that are unique to each derailment profile. From Figure 6, it can be seen that the geometric model is better able to predict the number of cars derailing than the Little expression. The scatter of standardized residuals for the geometric expression is uniform and lies within two standard deviations of the zero-zero line, for the entire train speed range.

ANALYSIS OF MARSHALING AND BUFFERING STRATEGIES

The second major phase of the study involves evaluating the effectiveness of alternative railcar marshaling strategies for reducing derailments involving SDC cars.

Predicting the Placement of SDC Cars on a Train

In this study, the likelihood of encountering an SDC car along a given train length is developed using combinatorial procedures. A simple example illustrates the approach. Consider a train n cars long, with m cars carrying SDCs. In this example, it is assumed that individual SDC cars are treated in separate one-car blocks. A buffer of k cars is placed between any two SDC cars. The k-car buffer is also used to separate the inhabited locomotive and caboose segments from the rest of the train. The objective here is to estimate the probability that an SDC car will be in the ith position of the train.

Assuming that $m1$ SDC cars are assigned to the first half of the train, then the number of buffer cars required in the first half becomes $(m1 + 1) * k$ cars, including the front and rear buffer group. Assuming that position i consists of an SDC car, the residual number of non-SDC cars that remain in positions 1 through i is given as, $i - 1 - (m1 + 1) * k$ cars. The number of ways that $m1$ SDC cars can be arranged in the first half of the train becomes

$$\binom{i - 1 - (m1 + 1) * k}{m1} \tag{10}$$

Similarly, assuming that the remaining $m - m1 - 1$ SDC cars are assigned to the second half of the train (i.e., positions $i + 1$ to n), then the number of ways that this can be arranged becomes

$$\binom{n - i - (m - m1) * k}{m - m1 - 1} \tag{11}$$

This expression reflects the number of ways $m - m1 - 1$ cars can be arranged among a choice set of $n - i - (m -$

TABLE 5 MAXIMUM LIKELIHOOD SUMMARY STATISTICS FOR THE GEOMETRIC DISTRIBUTION

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F-TEST
REGRESSION	9	29477.4510	3275.2723	81.2851
RESIDUAL	431	17366.5490	40.2936	
UNCORRECTED TOTAL	440	46844.0000		
(CORRECTED TOTAL)	439	28564.6909		

PARAMETER	ESTIMATE	ASYMPTOTIC STD. ERROR	STUDENT T-TEST	ASYMPTOTIC 95 % INTERVAL LOWER	UPPER
INTERCEPT,"A"	1.6741	0.3342	5.0099	1.0173	2.3309
SPEED EFFECT,"B0	-0.5755	0.0818	7.0358	-0.7363	-0.4147
ROADBED,"B1"	0.6479	0.1438	4.5052	0.3652	0.9306
TRACK GEOM.,"B2"	0.3824	0.0942	4.0605	0.1973	0.5676
RAIL.&.JOINT.BAR.DEFECTS	----------------	NO PARAMETER	----------------		
SWITCHES,"B3"	0.4702	1.4246	0.3301	-2.3298	3.2703
GENERAL CAR,"B4"	1.6722	0.3228	5.1809	1.3078	2.3066
AXLES/WHEELS"B5"	1.5105	0.1283	11.7714	1.2583	1.7627
ALL OTHER,"B6"	1.3292	0.2611	5.0913	0.8161	1.8424
RES. LENGTH,"C0"	-0.6381	0.0538	11.8549	-0.7439	-0.5323

RESPONSE FUNCTION "Z"=
A + B0*LOG(SPEED) + C0*LOG(RESIDUAL TRAIN LENGTH) +(B1,FOR ROADBED DEFECT)
+(B2, IF CAUSE OF DERAILMENT IS TRACK GEOMETRY) +(B3,FOR RAILBAR DEFECT)
+(B4, IF CAUSE OF DERAILMENT IS SWITCH DEFECTS) +(B5,FOR GENERAL CAR)
+(B6, IF CAUSE OF DERAILMENT IS OTHER CAUSES)

$m1) * k$ available positions. The probability that the ith car in the train includes an SDC car becomes

$$P_i = \sum_{m1=0}^{m} \frac{\binom{i-1-(m1+1)*k}{m1} * \binom{n-i-(m-m1)*k}{m-m1-1}}{\binom{n-(m+1)*k}{m}} \tag{12}$$

Certain aspects of marshaling regulations can affect the nature of the probability expression as defined above; for example, allowing SDC cars carrying similar materials to be marshaled adjacent to one another in contiguous blocks without any buffer separation. In this study, current marshaling regulations are used to adjust the above expression:

1. SDC cars are separated from other incompatible types of SDC cars by a buffer of k cars (five-car buffers in the current regulations).
2. SDC cars are separated from locomotive and caboose units by the same k-car buffer.
3. SDC cars carrying the same or compatible materials are not separated from one another. These cars are marshaled together in SDC blocks of variable lengths along the train.

The basic features of these marshaling and buffering regulations are illustrated in Figure 7 and reflect current strategies for SDC placement according to CTC regulations.

The probability that ith car in train is lth car of the block carrying SDC type j can be expressed as

$$P_{jl}(i) = \frac{\binom{[(i-l)-(MF*K+KE)]-[\sum_{*} NC(*)-MF]}{MF}\binom{[NF-i+l-KE-ND+\sum_{*} NC(*)-(MB-MF-1)*(K-1)]}{[MB-MF-1]}}{** \binom{[NC+MB-(MB-1)*K-KF-KE]}{MB}} \tag{13}$$

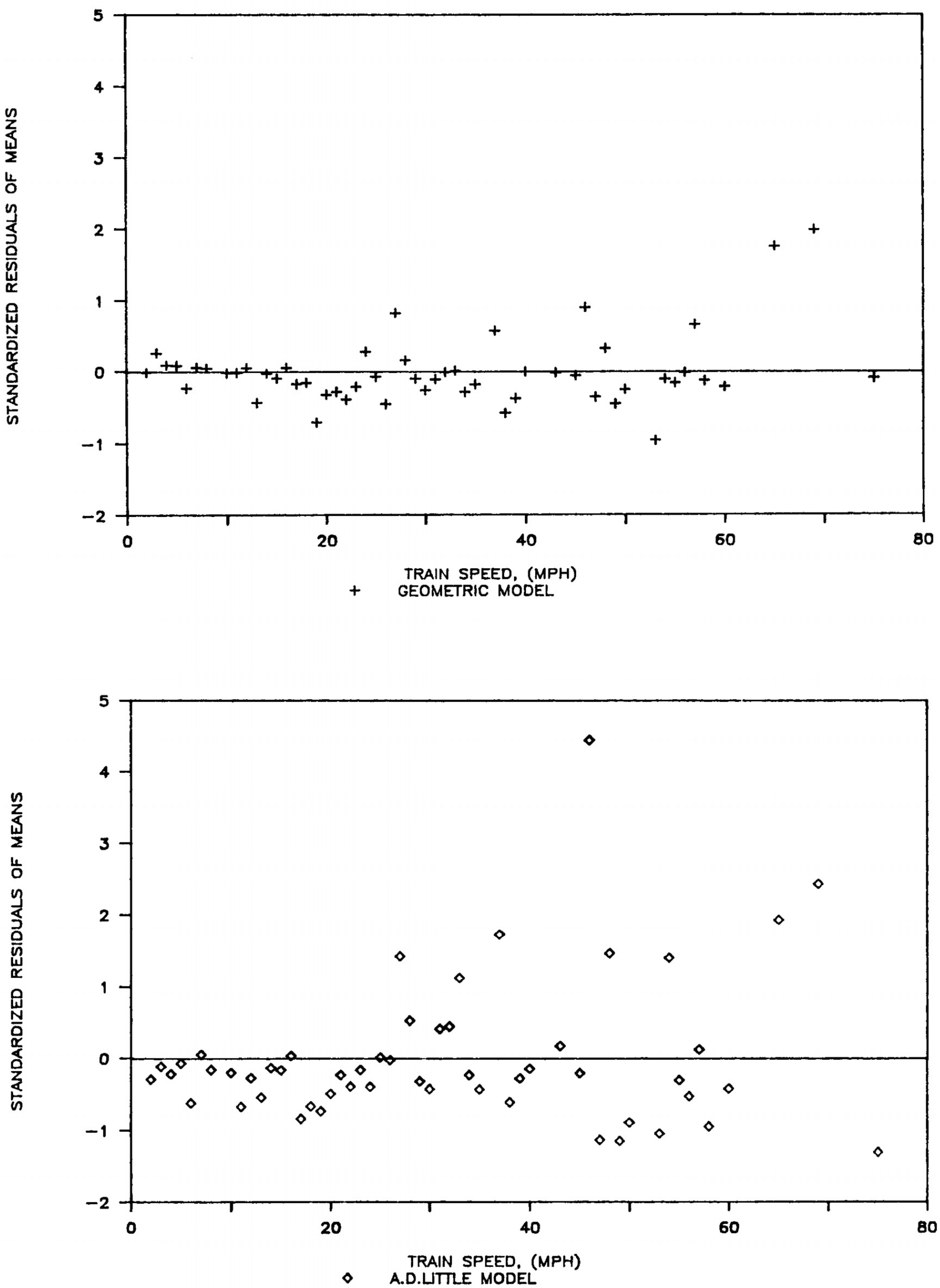


FIGURE 6 Standardized residuals of observed and fitted values for the geometric and Little models.

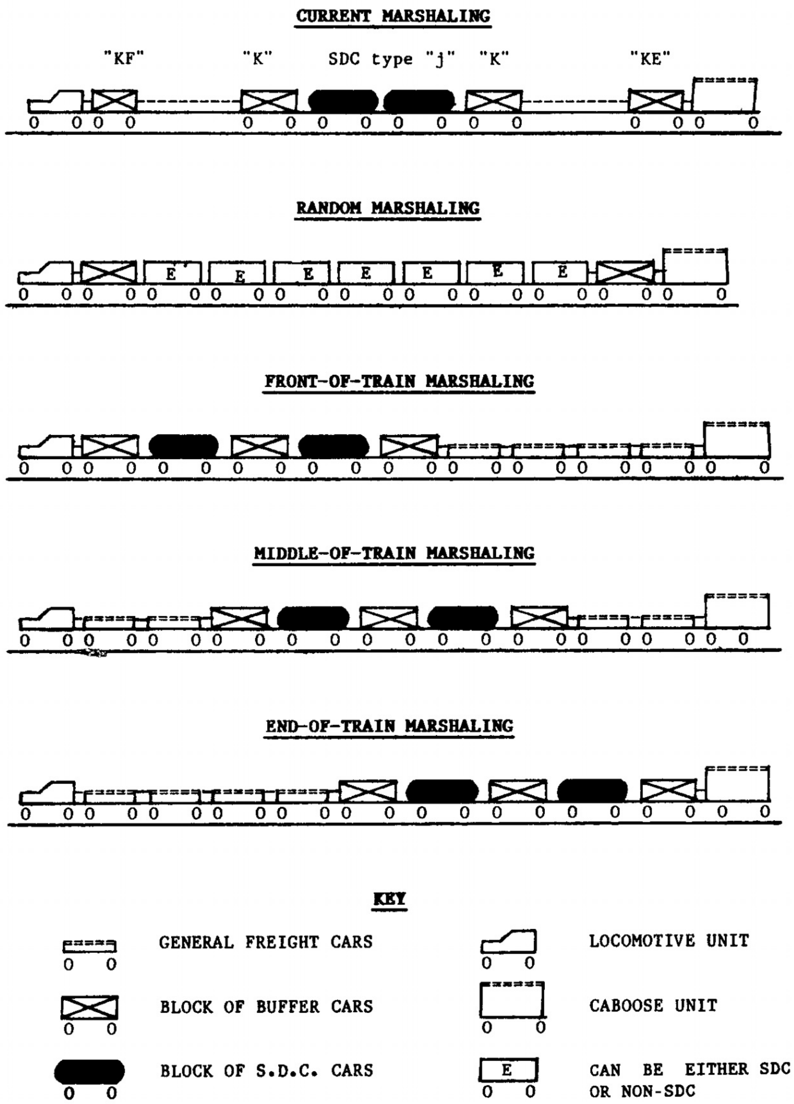


FIGURE 7 Alternative marshaling regulations considered.

where

NF = total number of freight cars;
NL = number of locomotives;
NE = number of caboose units;
NT = total number of cars, equal to $NL + NF + NE$;
MB = total number of SDC types or blocks in the train;
MF = number of SDC types in the section of the train preceding SDC block type j;
$NC(j)$ = number of SDC cars of type j, (j = 1 to MB);
ND = total number of dangerous commodity cars [SUM of $NC(j)$];
NC = number of nondangerous commodity cars ($NF - ND$);
KF = number of buffer cars at front of train;
KE = number of buffer cars at end of train; and
K = number of buffer cars between dangerous commodity blocks.

The summation terms Σ_* in Equation 13 give the number of SDC cars for a specific set of the MF SDC blocks that are assembled in the section of the train preceding SDC block type j. Similarly the term ** indicates that the above expression is summed over all possible types of the SDC blocks that can be fit in the section of the train preceding SDC block type j. Summing $P_{jl}(i)$ over all values of l in SDC block j, (l = 1 to $NC(j)$), gives the probability that the ith car in the train is carrying a type j dangerous commodity. Summing further over all types of SDC blocks (j = 1 to MB) gives the probability that the ith position in the train is in an SDC block. Further modifications to Equation 13 allow for the modeling of other marshaling strategies.

Evaluation of Alternative Marshaling and Buffering Strategies

From Equation 1, a derailment probability can be estimated for every position in the train as a function of operating train speed, cause of derailment, and train length. The probability that any position in the train is occupied by an SDC car can be obtained from a combinatorial expression, as in Equation 13, for each marshaling strategy and train consist. The expected number of SDC cars involved in any derailment can be estimated by summing positional joint probabilities of derailment and SDC car involvement in each accident situation. These estimates are a function of the cause of derailment and the train operating speed.

In this paper, five alternative marshaling and buffering strategies are evaluated (Figure 7):

- *Current marshaling*. Marshaling and buffering regulations currently in effect in Canada.
- *Random marshaling*. No restriction on the separation of SDC car blocks, excluding the front and rear buffers.
- *Front-of-train marshaling*. All SDC cars are marshaled to the front of the train with variable buffering.
- *Middle-of-train marshaling*. All SDC cars are marshaled in the middle section of the train with variable buffering.
- *Rear-of-train marshaling*. All SDC cars are marshaled at the end of the train with variable buffering.

For illustrative purposes, several assumed train consist characteristics were considered in this evaluation exercise:

Number of locomotives	5
Number of caboose units	2
Classes of SDCs in each consist	5
Number of SDC cars in the entire train	15
Type 1 SDC cars	5
Type 2 SDC cars	4
Type 3 SDC cars	3
Type 4 SDC cars	2
Type 5 SDC cars	1
Total number of freight cars in the train	70

The evaluation of marshaling strategies was carried out for each of the seven train derailment causes listed in Table 1 and three train speed classes (5, 30, and 60 mph).

Assuming current marshaling regulations (Figure 7), the effect of changing buffer lengths on SDC car positioning can be illustrated with reference to Figures 8a and 8b for a five- and ten-car buffer, respectively. The distribution for the five-car restriction in Figure 8a is relatively uniform throughout the train length. This is expected, given the low proportion of SDC cars in the total train length and the reduced number of cars allocated to buffer positions. When the buffer length is increased to ten cars as in Figure 8b, the distribution of SDC car involvements becomes more peaked, because fewer positions are available for SDC assignment. In the extreme case, where placement of SDC in a train is unique, the distribution becomes discrete and a selected number of positions is assigned SDC cars with probability equal to one.

Derailment probability distributions were obtained for all derailment causes and various classes of train speeds. Figures 9a and 9b illustrate two such distributions for roadbed defects and wheel, axle, and journal failures, respectively. For each derailment cause, three speeds were also considered (5, 30, and 60 mph). Regardless of train operating speed, the cause of derailment has a significant effect on derailment position. Furthermore, it can be shown from Figure 9, that roadbed defects are more likely to affect derailments near the front section of the train than wheel, axle, and journal failures, where the rear positions are more critical. Regardless of cause of derailment, the higher the operating speed of the train the higher the probability of derailments for all positions in the train consist.

Figures 10a and 10b represent the distribution of derailments for two causes (roadbed defects and wheel, axle, and journal failures) for each of the four marshaling strategies (random, front, middle, and rear SDC assignment). Figure 10 clearly demonstrates that the effectiveness of marshaling strategies in reducing SDC derailments is strongly influenced by the potential cause of derailment. The middle marshaling option varies slightly from current regulations. The front marshaling option is more effective for axle and journal failures than for roadbed defects. For roadbed defects, the best policy would be to marshal SDC cars to the rear of the train. In general, train operating speed increases SDC derailments for all positions and marshaling strategies.

CONCLUSIONS

In this paper, the derailment of cars carrying dangerous commodities is described by the POD, the number of cars derailing, and the position of SDC cars in the train. Accordingly, the following conclusions can be observed:

1. The POD was found to be strongly affected by the cause of derailment and train length. Relative frequency tables were generated for predicting the POD position for several causes of derailment and train sections.
2. The number of cars derailing is a function of the cause of derailment, train speed, and the residual train length and depends on the POD and train length. A probabilistic model based on the geometric distribution is used to estimate the number of cars derailing in an accident. The geometric distribution exhibits favorable goodness-of-fit characteristics for the 1980–1985 data.
3. The derailment probability of every car in a train was obtained from probability distribution of the POD and the number of cars derailing. Accordingly, the distribution of railcar derailments by position was found to be prescribed by the cause of derailment and train speed.
4. Derailments involving SDC cars could be reduced significantly by marshaling these cars into positions that are less likely to be involved in a derailment, under certain conditions. This was clearly shown in Figure 10, where different marshaling regulations had different number of SDC cars derailing.

It is apparent from this study that the marshaling regulations considered result in different numbers of SDC cars derailing under each of the different causes of derailment. However, it is important to study these results for the combined causes of derailment. To find the marshaling regulation with the fewest SDC cars derailing, the results of Figure 10 should be combined using the observed distribution of causes of derailment.

However, the distribution of causes of derailments is affected by the rail corridor considered. For example, a new or properly maintained track is expected to have more car- and equipment-related derailments than track-related derailments. Effective marshaling policies for SDC cars in a train consist must reflect rail corridor conditions that influence both the cause of derailment and position of derailed cars along a

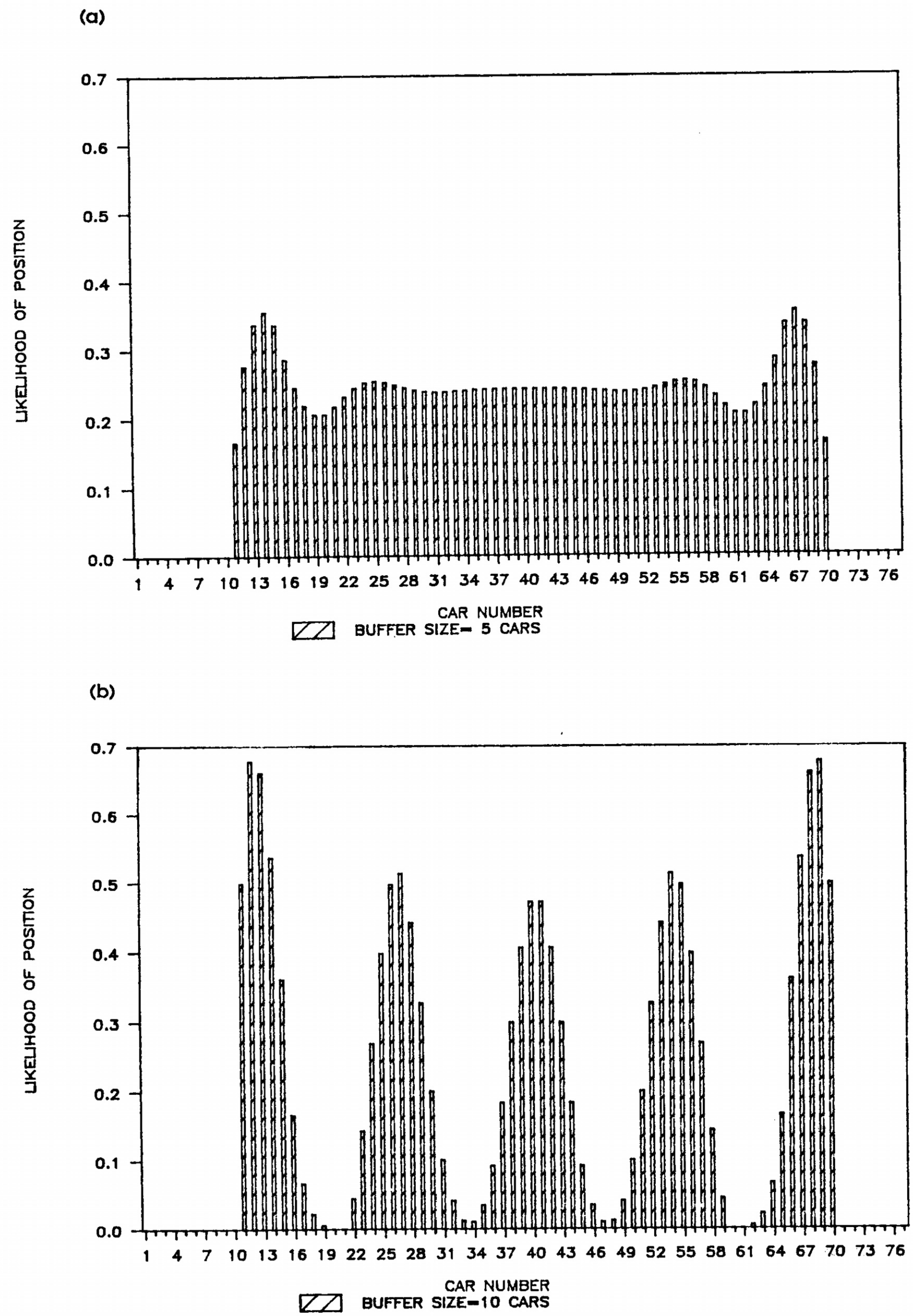


FIGURE 8 SDC car positions for current marshaling regulations: (a) five buffer cars, (b) ten buffer cars.

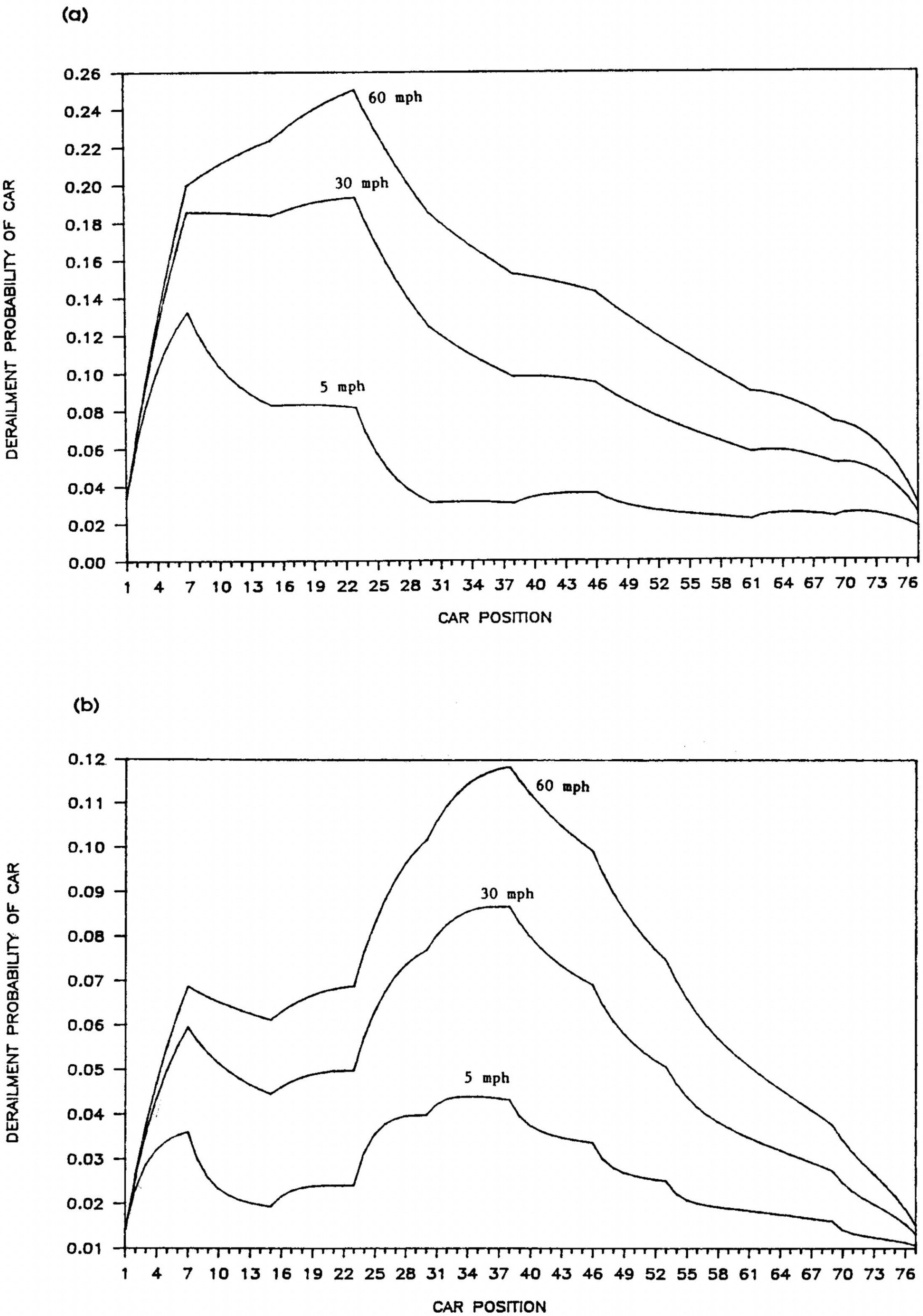
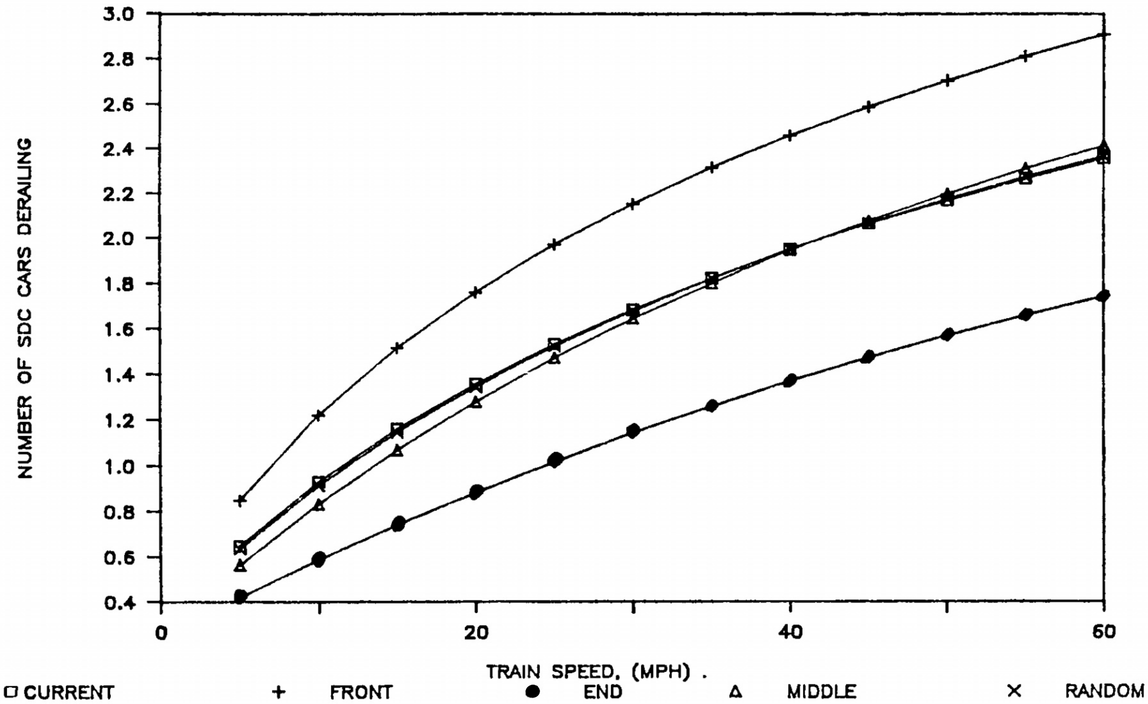


FIGURE 9 Derailment profiles for different car positions by causes of derailment: (a) roadbed defects, (b) wheel, journal, and axle defects.

(a)



(b)

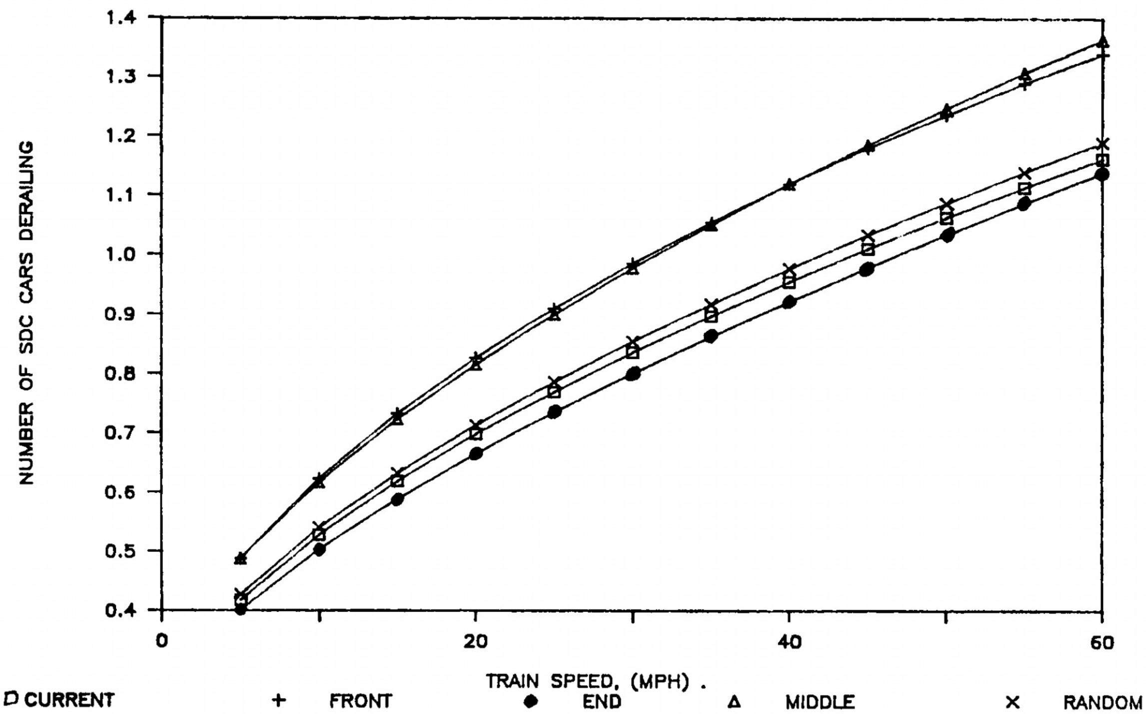


FIGURE 10 Number of SDC cars derailing versus speed for the alternative marshaling strategies: (a) roadbed defects, (b) wheel and axle defects.

train. Therefore, it is recommended that any analysis of marshaling regulations be performed for a specific rail corridor. The approach discussed in this paper can provide useful information for evaluating alternative marshaling strategies for SDC cars.

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