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ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER ABERDEEN
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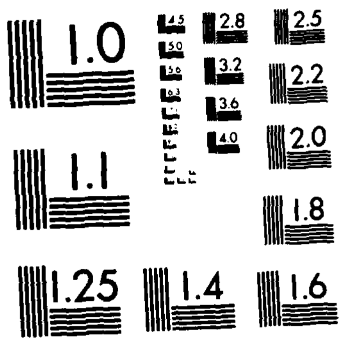
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MEMORANDUM REPORT ARBRL-MR-03311

# STATISTICAL MODELING OF RAILROAD SAFETY PERFORMANCE

Barry A. Bodt
Jerry Thomas

September 1983

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Railroad Safety
Safety Quantification
Multivariate Analysis
Cluster Analysis
Discriminant Analysis
Statistical Analysis

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In recent years the Department of Transportation and the Association of American Railroads have become concerned over the safety performance of this nation's railroads. Recent statistics showed that the frequency of accidents was alarmingly high. Acting on this concern, the D.O.T. asked the Ballistic Research Laboratory to determine how railroads could be made safer. One approach to this problem would be to develop a mathematical model which would allow a railroad's safety to be expressed as a function of safety program characteristics. In (Cont'd)

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this manner, guidelines for spending which could improve a railroad's safety record would be established.

Several statistical techniques, including Cluster Analysis, Discriminant Analysis, and Multiple Linear Regression, were employed in the development of this mathematical model. The model is a good predictor for the years 1976-1979, and should assist railroads in developing guidelines for spending which should improve their safety performance.

TABLE OF CONTENTS

# I. INTRODUCTION

In recent years, the Department of Transportation (D.O.T.) and the Association of American Railroads have become concerned over the safety performance of this nation's railroads. Recent statistics showed that the frequency of accidents was alarmingly high. Acting on this concern, the D.O.T. asked the Ballistic Research Laboratory to determine how railroads could be made safer. One approach to this problem would be to develop a mathematical model which would allow a railroad's safety to be expressed as a function of safety program characteristics. In this manner, guidelines for spending which could improve a railroad's safety record would be established.

# II. AVAILABLE DATA

Data available for the analysis pertained to safety performance records, safety program's size and safety program content. Of these data, the first two are quantitative, comprised of 26 statistics compiled for 1979 by the Association of American Railroads. For example, some possible safety descriptors are Accident Frequency and Accident Severity. Some possible safety program indicators are Estimated Safety Program Costs and the Number of Safety Representatives. The third data source category, safety program content, consisted of subjective variables whose values were formed as follows. A survey, conducted under D.O.T. sponsorship, addressing safety related topics was given to each safety director of 15 railroads. Their responses were assigned scores based on how well they matched the "ideal" response. These scores became the values for this category of data. In addition to the 1979 data, some safety performance and program information from years 1976-1978 was made available for this study. The data sources and variable definitions can be found in Appendix C.

# III. DATA ANALYSIS

The data were first checked for accuracy and completeness, correcting obvious errors and eliminating variables where insufficient "good" data were present. In performing this task, one of the 15 railroads was eliminated due to insufficient data.

The next step in the data analysis was to classify the railroads into safety groups according to their safety performance variables. In order to do this objectively, a statistical technique called cluster analysis was used. This is a multivariate statistical technique wherein railroads were separated into groups based on the minimization of variance within a group and the maximization of the distance (variance) between groups.* To be objective, the number of groups in which to separate the railroads was not specified. Using cluster analysis on the 1979 data, the railroads were separated into two groups based on three safety performance variables, namely, Injury Costs, Accident Frequency, and Accident Severity. From an intuitive standpoint this grouping was satisfactory. That is, one group could be called "safe" railroads and the other "unsafe."

*See Appendix B.

The next step was to take these three clustering variables and combine them into a single index that could be called Safety. To do this, another statistical technique, discriminant analysis, was employed based on the results of the cluster analysis. The discriminant index or score is a function of the individual safety variables whose value increases monotonically with respect to each of the component variables, thereby indicating poorer safety performance.*

Similar procedures were used on the variables associated with the safety program. Thus, two groups were identified using two variables that objectively described a safety program namely, Safety Cost and Safety Staff. The table below shows the cross classification of the safety groups and the safety program groups. This table is very encouraging in that railroads with good programs tend to be "safe," and those with poor programs tend to be "unsafe." *

**TABLE 1. CROSS CLASSIFICATION**

| | GOOD SAFETY PROGRAM | POOR SAFETY PROGRAM |
|---|---|---|
| GOOD SAFETY RECORD | 4 | 1 |
| POOR SAFETY RECORD | 4 | 5 |

## IV. A SAFETY MODEL

Using multiple linear regression, a safety model was developed based on the safety program variables. This model was deemed useful based on the 1979 data. Therefore, it was time to validate the model using previous years' data. Due to insufficient 1976-1978 data for Safety, an available safety variable (Accident Index) closely related to the discriminant score, Safety, was substituted into the model and corresponding model adjustments were made. For brevity, Accident Index will be referred to as Safety. The validation process showed that the model was not useful for predicting the 1976-1978 data. Investigation into the cause of poor prediction led to the elimination of four of the railroads. These four railroads are different for some unknown reason(s). The reason(s) could be bad data, poor reporting procedures or some lurking variable, that is an unaccounted—for—variable having an influence on response data. After the elimination of the four railroads, one of the three safety program variables dropped out of the model. Further analysis revealed that separate regression models using the remaining two safety program variables explained at least 72% of the variation of Safety for the 10 remaining railroads in each of the years 1976-1979. So that one model to explain Safety for each of the four years could be developed, the data for those years were pooled for the multiple regression analysis. The resulting model was able to explain 71% of the variation in Safety over the four years. Figures 1-4 illustrate the predictive powers of the model for the 10 railroads over each of the four years.*

*See Appendix A for a more detailed discussion.

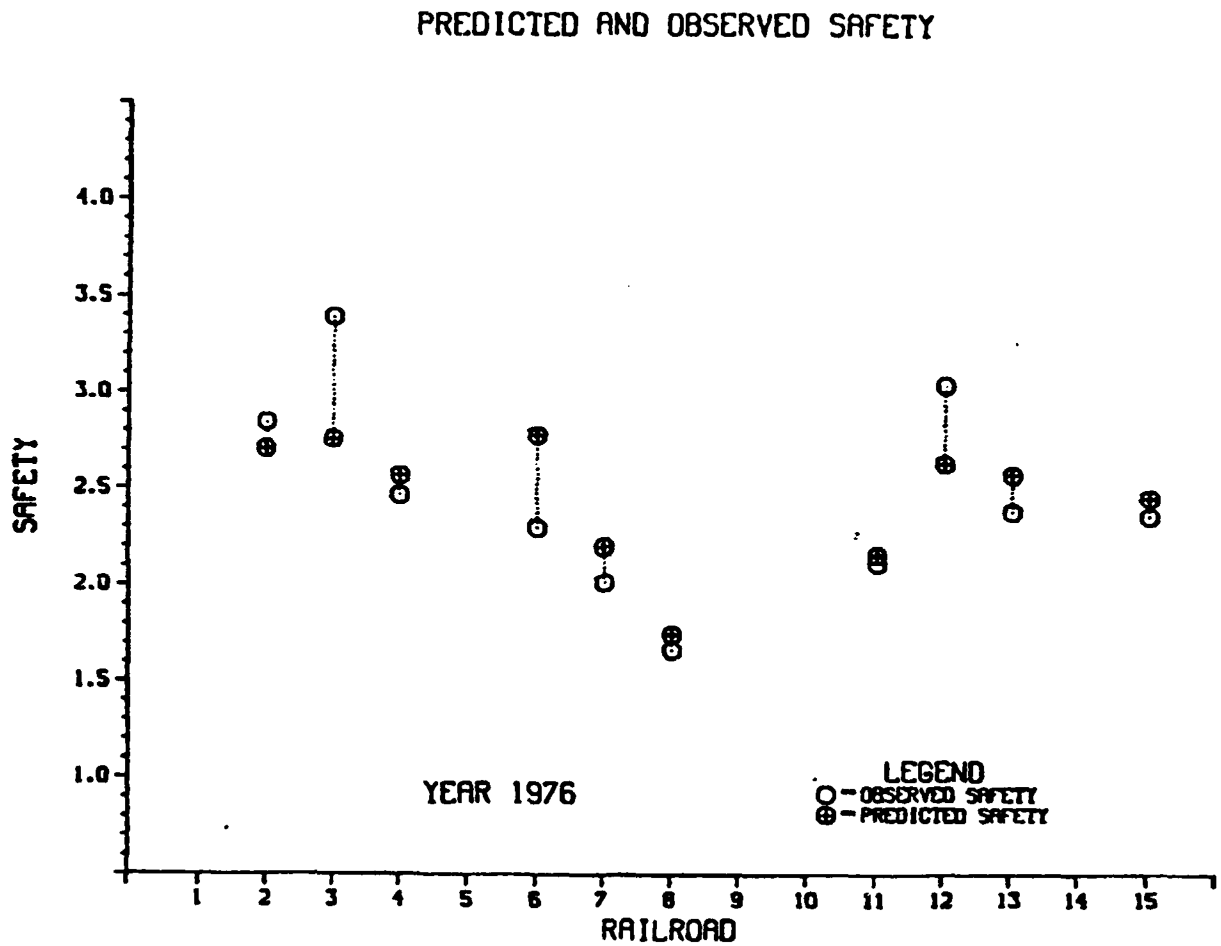

PREDICTED AND OBSERVED SAFETY
SAFETY
4.0
3.5
3.0
2.5
2.0
1.5
1.0
YEAR 1976
LEGEND
OBSERVED SAFETY
PREDICTED SAFETY
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
RAILROAD

Figure 1

PREDICTED AND OBSERVED SAFETY

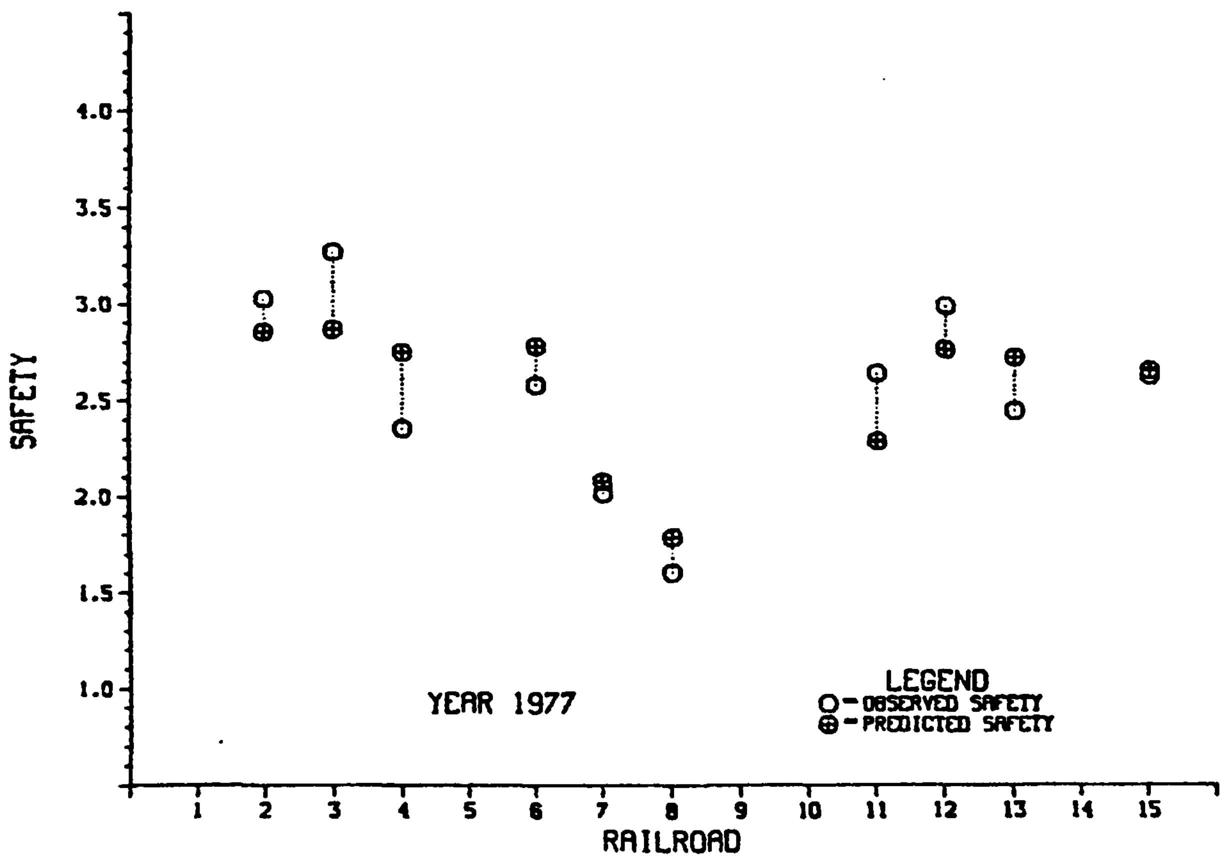
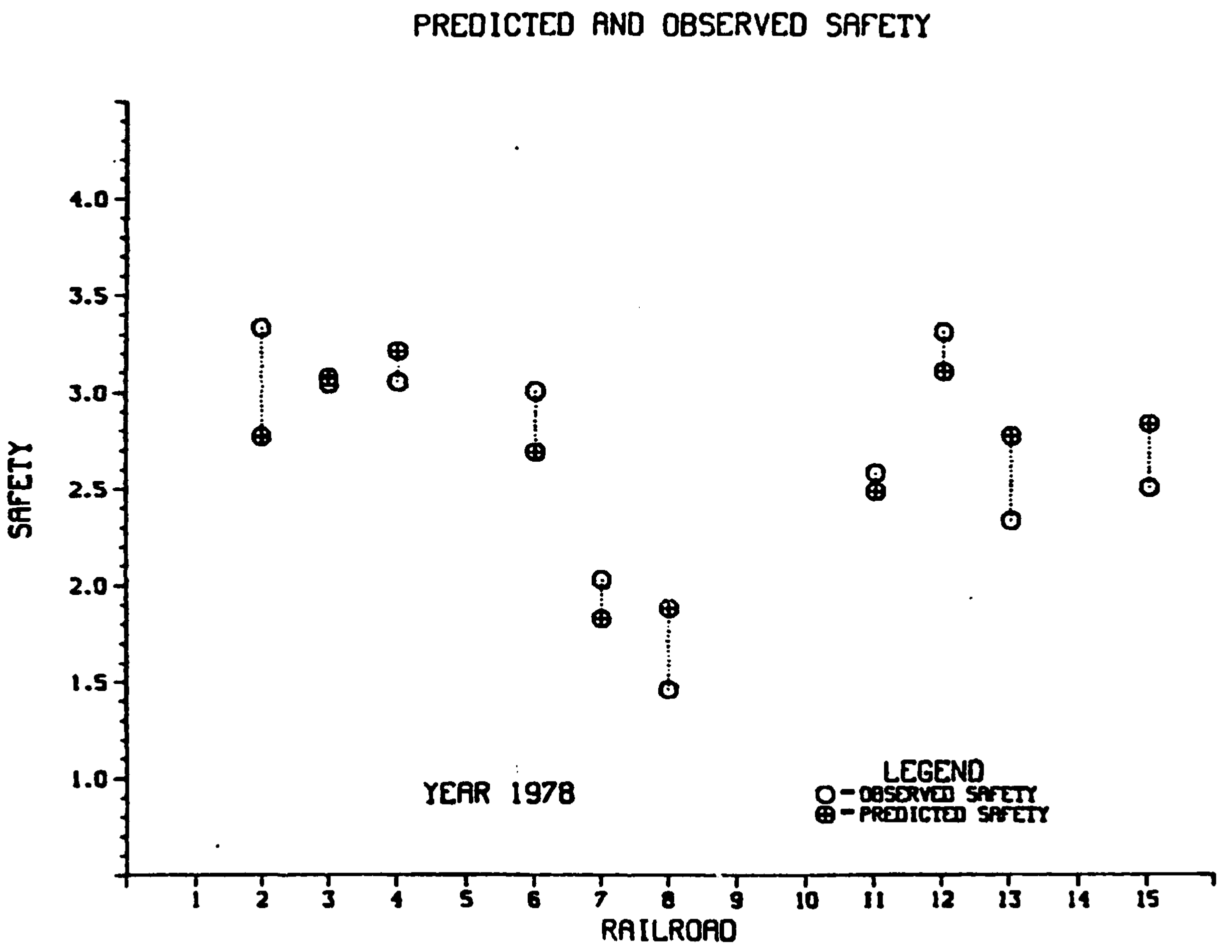



Figure 2


PREDICTED AND OBSERVED SAFETY
SAFETY
4.0
3.5
3.0
2.5
2.0
1.5
1.0
YEAR 1978
LEGEND
O - OBSERVED SAFETY
⊕ - PREDICTED SAFETY
1
2
3
4
5
6
7
8
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10
11
12
13
14
15
RAILROAD

Figure 3

PREDICTED AND OBSERVED SAFETY

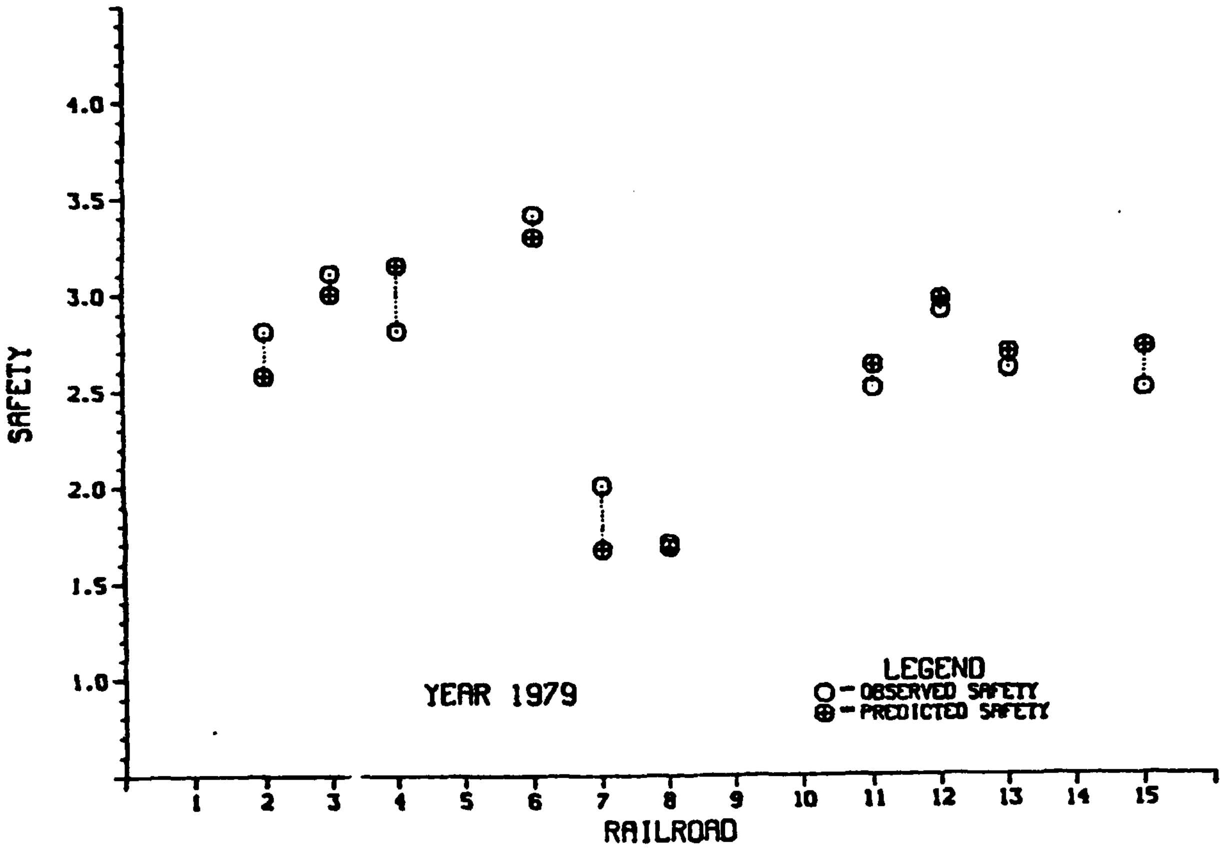


Figure 4

## V. RESULTS

The mathematical model developed to predict railroad safety as a function of safety program characteristics is given below. Keep in mind that small values for Safety are preferred.

$$Safety = 3.342 - 2.075(Efficiency) + .033(Equipment\ Load) + 1.(Yearly\ Bias)$$

where Yearly Bias is equal to -.353, -.211, .058, .000 for 1976 through 1979 respectively.

Safety is defined as the square root of ( the number of reported injuries times the number of days lost due to injury divided by 200) divided by (the number of man-hours employed times .000005). Efficiency is defined as 1/1000 times the ratio of revenue ton miles to man-hours employed. Equipment Load is defined as 1/1000 times the ratio of ton miles to train hours. Using the specified model to improve Safety, the Equipment Load should be reduced and the Efficiency increased. Efficiency was one of several profitability and efficiency indices considered for use at the recommendation of Mr. Edward O. Baicy, BRL's liaison with D.O.T. It was felt that a favorable overall efficiency rating would tend to indicate efficient safety program management as well. How to increase Efficiency may or may not be obvious to a railroad.

The following table indicates how much the 10 railroads could improve their safety performance by increasing Efficiency and decreasing Equipment Load. The improvement is given in terms of money saved due to fewer work-days lost due to injury. The estimate is based on the improvement to be made by the average 1979 railroad and uses the functional relationship between Severity Rate and Work-Days-Lost. The average Efficiency, average Equipment Load and average Man-Hours-Employed were used to characterize the average railroad. A work day was taken to be worth $80; this was based on a yearly salary of $20,000 and 250 work-days. The average railroad lost approximately $2,592,182 in 1979 due to Work-Days-Lost caused by injury.

NOTE: cost of improvements should be subtracted in order to obtain "true" savings.

**TABLE 2. SAFETY IMPROVEMENT**

| Efficiency (%avr.) | Load (%avr.) | Safety | Improvement | Savings ($K) | % Savings |
|---|---|---|---|---|---|
| 100% | 100% | 2.63 | | | |
| 120% | 100% | 2.21 | .42 | $618 | 24% |
| 100% | 80% | 2.35 | .28 | $413 | 16% |
| 120% | 80% | 2.07 | .56 | $1000 | 39% |

## VI. CONCLUSION

A mathematical model has been developed to predict Safety as a function of two quantitative safety program indicators using the data obtained on 10 railroads for the years 1976-1979. The model indicates that a savings of a million dollars is possible for an average railroad by improving Efficiency by 20% and decreasing Equipment Load by 20%. Although a "good" fit for the 1976-1979 data was obtained, a word of caution is in order about the use of this model for predicting Safety for future years. This is due to the uncertainty of what values the explanatory variables, Efficiency, Equipment Load, and Yearly Bias, will assume for a future year. There are other quantitative variables that could possibly improve the model. However, we were not successful in obtaining the data for the individual railroads. If further analysis is performed on data obtained in the 1980's, it is suggested that additional quantitative variables be added to the data base.


## ACKNOWLEDGEMENTS

The authors would like to acknowledge Edward O. Baicy, Linda L. Crawford, Jock O. Grynovicki, Paul V. King and John F. Polk Jr. for their suggestions and assistance in completing this analysis.

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# APPENDIX A. DETAILED DATA ANALYSIS

## APPENDIX A. DETAILED DATA ANALYSIS

To establish guidelines for spending which could improve a railroad's safety record, a mathematical model expressing Safety as a function of safety program variables had to be established. In order to arrive at this model, extensive data analyses were performed. The following is a sequential accounting of the analyses performed.

### 1. Procedure

1. Objectively define Safety as a function of one or more possible safety indicators.
2. Model Safety = f(X) where X is a vector of safety program indicators and f is a function defined over X. This model is to be based on 1979 data.
3. Validate the established model for data from 1976-1978.

Each was to be completed in a separate phase of the analysis, contingent upon the successful completion of the previous phases.

#### a. Phase 1 - Define Safety

To begin phase one of the analysis, quality of the data was assessed.* Due to insufficient data, one railroad was eliminated from the analysis. To eliminate possible bias in the definition of Safety, it was first assumed that each of the safety indicators was equally likely to be considered the most informative about a railroad's safety performance. Assuming that among railroads there existed differences in safety performance, the object here was to determine which subset of the several safety indicators best illustrated those differences. Using a statistical technique, cluster analysis, the railroads were objectively separated into two groups exhibiting differences in safety performance. This separation is said to be objective because cluster analysis makes no judgement about the two groups except that they are different. Not until values for safety indicators within those groups were examined, was one group classified as having poor safety records and the other classified as having good safety records. Those safety indicators which showed significantly different means between the good and poor safety record groups were taken to be the most informative safety indicators. The three indicators chosen were Injury Costs, Accident Frequency, and Accident Severity.

Though three important safety indicators had been determined, Safety had not as yet been defined. Using a statistical technique, discriminant analysis, information from all three indicators could be condensed to one discriminant score. This score is an indication of how firmly a railroad is implanted in its assigned group, in this case how good or how poor the railroad is. Hence, this discriminant score was chosen to represent Safety.

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*See appendix C.

The next step was to insure that the variable Safety made sense intuitively in its relation to the safety program indicators. At this point, a variable, Safety, had been established, with which one could classify the 14 railroads in terms of their safety records.

In a similar fashion, using safety program indicators a variable Safety Program was established, with which one could classify the 14 railroads as being varying degrees of good and poor in terms of their safety programs. Intuitively, one would like those railroads with good safety programs to have good safety records and those with poor programs to have poor records. Table 1., in the body of this report, indicates that for 5 of the 14 railroads this was not the case. In the establishment of the variables Safety and Safety Program, an artificial dichotomy was created between good and poor safety records and safety programs. In reality, a gray area exists between the two groups, though not sufficiently so that the creation of a third middle group is warranted. Three of the five railroads yielding counterintuitive results were within this gray area. Hence, only two of fourteen railroads yielded strictly counterintuitive results. This gave us increased confidence in our objective formation of the variable Safety so that we could then proceed to the modeling phase of the analysis.

**b. Phase 2 - Model Safety = f(X)**

It was desired to establish a functional relationship between the safety record of a railroad and its safety program. The dependent variable Safety was formed from the three most informative safety record indicators, Injury Costs, Accident Frequency and Accident Severity. The variables Safety Cost and Safety Staff were the safety program indicators deemed most informative in separating railroads on the basis of safety program quality. These two were determined as such during the process in which Safety Program was established. It was reasonable to assume that a function of Safety Cost and Safety Staff would aid in explaining the variation in Safety among railroads. This assumption was put to practice in a multiple linear regression model. It became apparent, when performing the regression analysis, that Safety Cost and Safety Staff were strongly correlated. To avoid multicolinearity, a condition which inflates regression coefficient variances, Safety Cost was eliminated from the model. The stronger variable, Safety Staff was able to explain 52% of the variation in Safety among railroads using the model:

$$Safety = -9.706 + 10.173\, Ln\,(Safety\ Staff).$$

In examining the model it is useful to note that low values of Safety and Safety Staff indicate good safety records and good safety programs, respectively.

For the purpose of improving the model and gaining use of the available information, the remaining quantitative safety program indicators were included in the analysis. The resulting regression model could be given as

$$Safety = 72.94 + 7.87\,Ln(Safety\ Staff) - 15.84\,Ln(Efficiency) + 7.80\,Ln(Equipment\ Load).$$

This model exceeded the previous simple linear regression model by explaining 68.5% of the variation among railroads. The interpretation of Safety and Safety Staff are the same as before. According to the model, to provide for a better Safety value a railroad must be made more efficient and its equipment must be under less load.

Late in this phase, the qualitative results from the safety director survey were made available for inclusion in the model. The analysis suggested that two of the three quantitative variables in the previous model be replaced by one of the qualitative variables. The new model could be given as

$$Safety = -4.53 + 8.98\,Ln(Safety\ Staff) - .14\,(Hazard\ Control)$$

Safety and Safety Staff can be interpretated as before. Hazard Control is defined as hazard control technology employed by the railroad. Limited Hazard Control would cause a railroad's safety performance to decline. This new model explains 62% of the variation of Safety among railroads. Unfortunately, there is no similar data for other years with which this last model can be validated.

**c. Phase 3 - Model Validation**

To validate the 1979 quantitative model over the years 1976-1978, a variable substitution had to be made. Although attempts were made to gather needed data, information necessary for the formation of Safety using discriminant analysis was not available for 1976-1978. For this reason, a reasonable substitute dependent variable had to be considered for the validation phase. One of the most informative safety performance variables was not included in the discriminant analysis because it was a function of Accident Frequency and Accident Severity which were already incorporated in the analysis. This variable, Accident Index, was then related to Safety and was used as the dependent variable for the 1976-1978 data. Hence, the quantitative 1979 model was reformulated in terms of Accident Index, leaving the three independent variables as before. The amount of explained variation for this model was 64%, approximately the same as when using Safety. It was also true that when using Accident Index for the cluster analysis, the railroads were partitioned in the same manner. Furthermore, when regressing Accident Index on the 1979 data, the same three independent variables prove to be the most important to the model. For these reasons, it was thought that the substitution was reasonable. The validation phase then consisted of trying to predict Safety(Accident Index) for 1976-1979 using the new 1979 model with Accident Index as the dependent variable.

Upon completion of the modeling phase of the analysis, data was supplied for the years 1976-1978 with which to validate the model established with the 1979 data. If the model performed well over these four years, confidence in it would increase.

Unfortunately, the model did an extremely poor job predicting Safety over those four years. The model predicted best for 1978 where it was able to explain only 24% of the variation of Safety among the 14 railroads.

Analysis then turned toward trying to establish whether or not the model had any useful significance. Although the attempt to predict Safety was fruitless, it was thought that the model may preserve the relative rankings of the railroads from good to poor on the basis of Safety. The predicted values of Safety and the actual values of Safety were used to establish predicted rankings and actual rankings of the railroads. These rankings were studied for similarities, but none were found.

The next step taken was to see if any of the independent variables in the 1979 model seemed to have any bearing on Safety for each of those three years. To this end, three separate multiple linear regressions were performed, one for each year, where Safety for each year was taken as the dependent variable and Safety Staff, Efficiency, and Equipment Load were taken as the independent variables. Obviously, if they had a bearing, the explained variation of Safety among railroads for each of those three years would be high. Once again, however, poor light was shed on the 1979 model because its independent variables did not seem to have any relationship with Safety in the other three years. The regression coefficients for these three models were examined for informative trends, but none were found.

Residual analysis was performed on these three models. It was observed that four railroads consistently had high residuals (predicted Safety subtracted from observed Safety). Furthermore, it was observed that for each of the four railroads, the predicted value of Safety was consistently less or consistently more than the observed value of Safety for those three models. Assuming that the models did in fact have merit, these four railroads were classified as being different due to possible reporting inconsistencies and were temporarily eliminated from the analysis.

Based on the remaining ten railroads a new model was formed for Safety as a function of the three safety program indicators. This model was then used to predict Safety for the other three years. The predictive powers of this model were much better than its predecessor in 1977 and 1978 but remained poor for 1976. It was interesting to note that the safety program indicator deemed most informative, Safety Staff, did not significantly add any information to the model.

Four separate regression models were then formed for each of the years 1976-1979. The four regression models each explained 72% or more of the variation of Safety among the ten railroads. This indicated that there was a relationship between Efficiency, Equipment Load, and Safety while Safety Staff again added no information to the models. So that one model to explain Safety for each of the four years could be developed, the data for those years were pooled for a multiple linear regression.

## 2. Results

The resulting model was able to explain 71% of the variation in Safety over the four years. The predictive powers of the model are illustrated in Figures 1-4 in the main body of the report. Keep in mind that small values for Safety are preferred. The model is given below.

$$Safety = 3.342 - 2.075(Efficiency) + .033(Equipment\ Load) + 1.(Yearly\ Bias)$$

where Yearly Bias equals -.353, -.211, .058, .000 for 1976 through 1979, respectively.

# APPENDIX B. STATISTICAL TECHNIQUES

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## 1. Cluster Analysis

Cluster analysis was incorporated in the analysis in the following fashion. It was assumed that there existed a difference among railroads in terms of their safety performance. It was also assumed that each of the available safety performance variables, were equally likely to explain the safety performance difference among railroads. Cluster analysis is a multivariate technique which allows one to separate multivariate data into k populations based on Euclidean distance. The many observations taken on each of the railroad's safety performance comprised the multivariate data with which to perform cluster analysis. Railroads within each population were similar in that they were positioned close together in Euclidean n-space. A difference in values among populations for a safety performance variable was said to exist if the hypothesis of equality of means among groups was rejected with an F-test of significance .05. Obviously, those safety performance variables showing a difference in value among populations contributed more to the separation than did those safety performance variables which showed no difference among populations. For this reason those variables were considered the most informative in discriminating among railroads in a safety performance sense. By examining primarily the values of those informative variables among populations, one population of railroads was considered to have better safety performance than another. In this manner railroads were classified as good or poor and important safety performance indicators were identified.*

## 2. Discriminant Analysis

Discriminant analysis had application in the following sense. In the case of safety performance, two populations, good and poor, were determined using cluster analysis. Furthermore, three safety program variables were determined important in that population determination. It was reasonable then that some combination of these three variables could be used to represent Safety, a univariate value describing the safety performance of railroads. Discriminant analysis is a procedure with which one can discriminate between populations of multivariate data. It does so in terms of a univariate value formed by first establishing a mathematical dividing-line achieving maximum separation between the two groups which were established using cluster analysis. The univariate value is then, in a sense, the distance away from the dividing-line for each railroad. With this distance, the discriminant score, the railroads could be classified. Those railroads whose discriminant value placed them below the aforementioned mathematical dividing-line were classified as good, and those whose discriminant value placed them above the dividing-line were classified as poor. A railroad's relative safety performance is thus indicated by its distance from the dividing-line. More important than its classification properties, the discriminant score served as a reasonable dependent variable for a regression model established using information from several safety performance indicators.

*A similar procedure was used for safety program indicators.

APPENDIX C. DATA

# APPENDIX C. DATA

## 1. Data Sets

Data used in these analyses came from the following sources. Paul King, a consultant to BRL, compiled the first three data sets listed. Sets four and five were compiled by the Association of American Railroads (A.A.R.). The sixth set was comprised of the results of the Safety Director Survey which were determined by a committee consisting of Edward O. Baicy (BRL), Paul King, and several railroad safety directors.

1. Railway Operating Expense Rates - Class I Roads 1979
2. Comparison - Efficiency / Profitability Indices - Class I Roads 1979
3. Accident & Injury Statistical Data - Class I Roads 1979
4. A.A.R., Class I. Railroads Operating and Traffic Statistics 1976-1979
5. A.A.R., Rankings of Class I. Railroads 1976-1979
6. Safety Director Survey 1979

**2. Safety Performance Indicators**

1. equipment damage expense / gross operating revenue
2. equipment damage expense / man-hours employed
3. reported accident damage / gross operating revenue
4. reported accident damage / man-hours employed
5. wreck clearing expenses / gross operating revenue
6. wreck clearing expenses / man-hours employed
7. **injury costs (injury payoffs / gross operating revenue)**
8. injury payoffs / man-hours employed
9. accident and injury costs / gross operating revenue
10. accident and injury costs / man-hours employed
11. **accident frequency (# of reported injuries / (man-hours employed x .000005))**
12. number of lost-work-day injuries / number of reported injuries
13. **accident severity (lost-work-days / (man-hours employed x .000005))**
14. accident index (SQRT(accident frequency x accident severity / 200))

**3. Safety Program Indicators**

1. **safety staff ((man-hours employed x.000001) / # of safety representatives)**
2. **efficiency (.001x(revenue ton miles / man-hours employed))**
3. **safety cost (estimated safety program costs / man-hours employed)**
4. freight revenue / freight expenses
5. **equipment load (.001x(ton-miles / train-hour))**
6. train-miles / train-hour
7. percentage of freight-car-miles loaded
8. total investment / miles of track
9. track miles operated / man-hours employed
10. number of locomotives / man-hours employed
11. number of safety representatives / number of employees
12. track miles operated / track miles operated for 14 railroads

**4. Subject Categories in the Safety Director Survey**

1. section organization program value
2. staffing position value
3. documentation
4. signature authority
5. program content
6. decision authority
7. operating relations
8. skill resource
9. equipment and facility resource
10. available safety equipment
11. monetary resource
12. reviews, audits and inspections
13. procedures
14. correct action
15. accident reporting and analysis
16. safety training
17. safety motivation programs
18. **hazard control technology**
19. general action and procedures
20. recommendations
21. past actions
22. current actions
23. safety survey score

## 5. Additional Variables of Interest

The following safety program indicators have been identified as possible contributors to a better model. At the time of the writing of this report, this information was unavailable for the 15 individual railroads.

1. hours of maintenance on freight cars / freight-car hours

2. hours of maintenance on passenger cars / passenger-car hours

3. hours of maintenance on locomotives / locomotive hours

4. safety director's salary / top executive's salary

5. implemented suggestions resulting from accident investigations / number of accidents

6. recommended suggestions / implemented suggestions

7. number of thorough maintenance inspections / number of cars

8. number of thorough maintenance inspections (track) / 100 track miles

9. safety director's time spent on safety / safety director's time

10. safety personnel's time spent on safety / safety personnel's time

11. investment in track and equipment / miles of track

12. miles of track in city / miles of track

13. track requiring reduced speed due to condition / miles of track

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