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Simulation Model for Risk/Benefit Evaluation of Rail Inspection Programs

Office of Research
and Development
Washington, DC 20590

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A Monte Carlo simulation of certain aspects of rail inspection is presented. The simulation is used to compare alternative practices in railroad rail inspection programs. The results show that equipment performance and/or inspection frequency control service defect rate and suggest that allowance of delayed remedial action on non-critical defects can potentially improve detector car utilization.

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PREFACE

This report documents a Monte Carlo model that has been developed to simulate certain aspects of rail inspection programs carried out by railroads. The purpose of inspection is to enable the railroads to find and repair or remove defects before they can cause rail failure and derailment. Rail defects generally develop from metal fatigue and continue to grow in size under train traffic. Thus, it is necessary for the railroads to re-inspect their rail on a regular schedule.

The simulation model provides a means of evaluating and comparing the expected performance of alternative inspection practices. Examples of such practices are the frequency of inspection, the capability of the equipment used to detect defects, and whether or not remedial action is delayed under certain conditions. The model provides quantitative estimates of both risk and benefit: the risk of missed detection or proportion of detected defects for which delayed action is allowed, and the benefit of inspection vehicle productivity.

The work was carried out by the Volpe National Transportation Systems Center under Project Plan Agreement RR-19 sponsored by the Track Research Division, Office of Research and Development, Federal Railroad Administration.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (k) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (he) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)

1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

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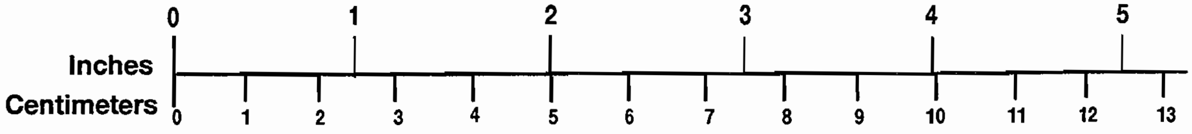
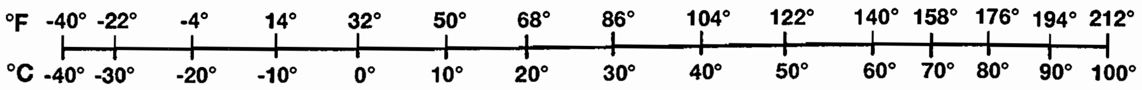


QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures.
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EXECUTIVE SUMMARY

In 1993 the Union Pacific Railroad (UPRR) requested that the Federal Railroad Administration (FRA) approve a waiver from certain provisions of the Track Safety Standards (49 CFR Part 213) in order to improve the efficiency of scheduled rail inspection. The railroad has been inspecting more often than is required by the Track Safety Standards, but records from the three preceding years suggested that the average for daily miles of track inspected was declining, while the percentage of rail defects not being detected by scheduled inspection was increasing. After a safety review, FRA granted a test waiver for two heavy haul lines in southern Wyoming and western Nebraska. The UPRR began its modified inspection program in June 1994.

Under the present regulations, a railroad is generally required to immediately impose a speed restriction and/or make a temporary repair when a rail defect is discovered. Since speed restriction reduces traffic capacity, railroads operating on heavy haul lines often choose to make permanent repairs immediately, when rail defects are discovered on those lines. In territories with high concentrations of rail defects, this usually limits the daily number of miles inspected, based on the number of permanent repairs that a chase gang can make in a work day. The UPRR proposed to free the inspection vehicle from the chase gang constraint by allowing, for certain kinds of rail defects, delayed action on those not exceeding a specified size.

Earlier work done by the Volpe Center under the FRA Track Safety Research Program had shown that most rail defects tend to grow at slow and predictable rates. Therefore, there was a sound basis for the UPRR proposal, provided that the size specification was prudently established. FRA took a cautious position by specifying a small size and limiting delayed action to days on which the forecast temperature would be above 0 °F, based on Track Safety Research Program findings, to assure that there would be no undue risk of rail failures from defects left in track.

This report documents a study of the potential for delayed action to improve inspection vehicle utilization. The study also included evaluation of the percentage of defects not detected by scheduled inspection. (Undetected defects, as well as defects that are detected but left in track, pose a risk of rail failure.) A Monte Carlo model was developed, incorporating averages for rail defect rates of occurrence, defect growth rates, and inspection equipment performance, based on results from the Track Safety Research Program. The model was used to simulate a hypothetical heavy haul line having uniform defect occurrence and growth characteristics. The simulation included scheduled inspections with a hypothetical rail flaw detection vehicle, and limitation of the vehicle's daily run if the chase gang capacity was exceeded.

Vehicle utilization and percentage of undetected defects were compared for three remedial action scenarios: immediate action in accordance with the present Track Safety Standards, delayed action on defects not exceeding the size specified in the UPRR test waiver, and delayed action on defects not exceeding a larger specified size. The model input was also varied in order to assess the effects of equipment performance, inspection frequency, chase gang capacity, and defect occurrence/growth rates.

The major findings of the study are that adoption of the delayed action concept has the potential to improve inspection efficiency without affecting the percentage of undetected defects, and that the benefit is greater for the larger specified defect size. The results suggested that the potential can be realized either on lines on which track possession time does not limit the day's run of the inspection vehicle, or on lines on which track possession is limited but the rate of detections averages at least one defect per track mile per year. Other significant findings are that the percentage of undetected defects can be reduced by increasing inspection frequency or by improving equipment performance. Also, detection equipment with current performance (as opposed to the lower performance of early 1980s equipment) is essential in order to realize the potential for better inspection efficiency.

1. INTRODUCTION

This report summarizes a study of the potential for improving rail inspection programs by modification of the remedial action requirements for detected rail defects. A Monte Carlo model was developed and applied to carry out the study. The model is a simulation of rail defect formation and growth caused by traffic, together with the effect of periodic inspections on the defect population, on a hypothetical single-track line along which the rail age is assumed to be uniform. The parameters used to establish the simulation (average rate of defect formation, average rate of growth for detail fractures, and average probability for detection as a function of detail fracture size) are based on earlier research conducted by the Volpe Center in support of the Federal Railroad Administration (FRA) Track Safety Research Program [1, 2]. The model is extensively based on the detail fracture (DF) because this is the most common type of rail defect in continuous welded rail carrying heavy freight traffic.

The model has been used to compare current procedures with a modification that relaxes some of the remedial action requirements for certain types of defects not exceeding specified "critical" sizes when detected. The present safety standards set forth in 49 CFR §213.113 generally require some form of action to be taken as soon as a defect is detected, with various options allowed depending on the defect type and size. When inspecting a main line with high traffic density, a Class 1 railroad generally elects to make immediate permanent repairs or to immediately replace the defective rail because the alternative of placing a temporary slow order on the track causes unacceptable traffic delay. In practice, this leads to restriction of detector car utilization (miles inspected per day) to keep the car from finding more defects than the repair gang can deal with in a normal work day.

Under the modified procedure, after detection, up to three days are allowed before an action must be taken, for those defects not exceeding the critical size when detected. Such "non-critical" defects are marked and left for a second gang to repair, allowing the inspection car and its chase gang to continue down the track. The logical basis for the modification is that it frees the inspection car to continue searching for larger defects, which pose greater risk of rail failure than the non-critical defects. Thus, inspection car utilization should be improved and overall risk should be decreased.

The Union Pacific Railroad (UPRR) has been conducting a trial of the modified procedure on two main lines, under FRA test waiver H-94-1, granted in response to the railroad's petition. The petition requested that the DF critical size be set at 25 percent of the rail head area (%HA). After considering other sources of opinion, which ranged from 10 to 20 %HA, FRA set the DF critical size at 15 %HA. In the application discussed in this report, the Volpe Center's simulation model has been used to assess the effects on an inspection program of different choices for DF critical size, in comparison with baseline cases of inspection under the full 49 CFR §213.113 requirements, which allow no grace period. The sensitivity of model predictions to changes in other parameters were also studied.

There are two conflicting elements of performance associated with selection of a critical size: the risk that a non-critical defect might cause a rail failure during the grace period, and the opportunity to find other larger defects before they can cause rail failures. Risk and opportunity both increase or decrease as a larger or smaller critical size is chosen.

For the DF type defect, the entire range of proposed critical sizes (10 to 25 %HA) entails little or no risk in average weather but can pose high risk in cold weather. FRA track inspectors have investigated cases in which a DF as small as 10 %HA has caused a rail failure and derailment. Such cases tend to occur during night operations when the ambient temperature is below 0 °F. The Volpe Center's DF fracture mechanics model explains such occurrences as results of the combined rail stresses from train loads, residual stress accumulated during prior service, and thermal tension from soaking continuous welded rail (CWR) to cold temperatures below 0 °F [1]. Consequently, test waiver H-94-1 includes a special condition that suspends the grace period for DFs when the forecast weather includes temperatures below 0 °F.

At higher temperatures a DF must grow to a size well above 25 %HA in order to pose an equivalent risk, and traffic is required to make the defect grow. Depending on the choice of critical size, the Volpe Center's DF model [1] gives estimates of the required traffic ranging from 5 to more than 20 million gross tons (MGT). In contrast, the highest density main line traffic in the United States does not exceed 1.5 MGT per track during a three-day grace period.

It thus appears that the risk of rail failure from a non-critical DF can be adequately controlled by suitable choice of critical size and the minimum forecast temperature for which the grace period will be allowed. This aspect of risk is not treated by the simulation model. The primary objective for the model and application presented here is to assess the risk of increased rail failure rate due to missed detections in relation to the benefit of more efficient detector car utilization. A secondary objective is to evaluate the sensitivities of the model to both those variables that can be controlled in a rail inspection program and those that characterize rail manufacturing quality or usage conditions.

2. SIMULATION MODEL

The simulation is performed for a single-track subdivision of a specified length. There are three major parts in the simulation: (1) crack formation; (2) crack growth; and (3) crack detection and removal. The defect population is assigned by whole number milepost. All defects are assumed to be detail fractures, with occurrence and growth rate characteristics modeled on the basis of prior research [1, 2]. Uniform rail section and age are assumed for the entire subdivision. The analysis is generally carried out for a number of consecutive years and is repeated to average out small-sample fluctuations.

2.1 DEFECT FORMATION

DF defects are assumed to form at an increasing rate as the rail accumulates tonnage. The occurrence rate model for the defects is based on Weibull parameters derived from observations of defect occurrence on the Transportation Test Center's Facility for Accelerated Service Testing (FAST) and on several segments of revenue track studied by the Association of American Railroads (AAR). These data can be characterized by the Weibull distribution:

$$F(T) \quad = \quad 1-e^{-(T/\beta)^3} \tag{1}$$

where T is the rail age in cumulative MGT, β is a parameter called the characteristic life, and $F(T)$ is the cumulative fraction of rails that have developed a defect by age T. The characteristic life depends on axle loading, for example: $\beta = 1000$ MGT on FAST, $\beta = 2000$ MGT on mixed freight revenue track. These parameter values are based on data obtained from track with 39-foot rails.

If ΔT is a specified interval of tonnage ($\Delta T \ll T$), then the fraction of rails expected to develop defects in that interval is given by $(dF/dT)\Delta T$, where dF/dT is obtained by differentiating equation (1). The corresponding number of defects, n, is obtained from the product of $(dF/dT)\Delta T$ and the total number of rails in the population. Since the results were obtained from observations of 39-foot rails, the appropriate multiplier is 270 rails per track mile. Thus:

$$n \quad = \quad \frac{810NT^2\Delta T}{\beta^3}\cdot e^{-(T/\beta)^3} \tag{2}$$

where N is the total number of track miles, and the tonnage interval expected to produce the next defect ($n=1$) is:

$$\Delta T \quad = \quad \frac{\beta^3 e^{(T/\beta)^3}}{810NT^2} \tag{3}$$

Rail generally reaches its economic life limit before the cumulative tonnage, T, exceeds the characteristic life. In this regime, T^2 increases faster than $\exp(T/\beta)^3$, and thus the tonnage interval to formation of the next DF decreases as the rail ages. Tonnage intervals of this order are also suitable for keeping track of the sizes of defects which have already formed, and for relating the rail inspection schedule to the defect population.

2.2 DEFECT GROWTH

After a defect is formed, it will grow under continued service. Each defect is assumed to have an initial crack size of 0.506 %HA. This was the smallest size at which DF growth curves were established by measurements of the exposed crack surface after an experiment on curve track at the Transportation Test Center [3]. The growth rate of the defect depends on factors such as axle load, weather, rail properties, and other service conditions.

A simplified model of defect size progression was derived from the Volpe Center's DF growth rate model [1]. This model was calibrated from the original detail fracture growth test on FAST tangent track [4, 5] and has been further verified by comparison with the more recent 4th Rail Metallurgy Experiment (RME-IV) results obtained from 5- and 6-degree curves on the FAST High Tonnage Loop [3]. The growth rate model estimates size progressions for specified conditions, which include track foundation, curvature, train makeup and axle loads, dynamic effects on axle loads, and rail temperature differential. The model is in the form of an expected progression curve, giving DF size in %HA as a function of the tonnage interval since defect occurrence. This characteristic is applied individually to update the size of each simulated defect as the rail is aged through several years of simulated track usage and rail inspection.

Figure 1 illustrates the baseline DF growth curves used in the simulation model. These curves are simplified representations of the DF growth model results, one to represent spring/summer and the other to represent fall/winter conditions. The difference between the two curves is intended to approximate the seasonal influence of thermal stress in CWR. Based on comparison with DF growth model calculations, the spring/summer curve represents rail at service temperatures within ±5 °F of the CWR neutral temperature, whereas the fall/winter curve represents rail at service temperatures from 10 to 35 °F below the CWR neutral temperature.

2.3 DEFECT DETECTION AND REMOVAL

Defect detection performance depends on the type of equipment used. Although larger defects are more likely to be detected, they still can be missed during the inspection process. Defect detection performance is modeled in terms of a detection probability curve, $p(s)$, as a function of the defect size, s. Figure 2 is a schematic illustration of the curve, which is interpreted as follows. For a particular defect size, the curve gives a fractional number between 0 and 1, which defines the chance of detecting defects of the given size. If $p(s) = 0.1$, for example, then the expectation is that one out of ten defects of that size will be detected.

It is impractical to obtain $p(s)$ by means of experiment because any test result would apply only to the specific combination of equipment, calibration procedures, operator experience, track, and weather conditions tested. Also, $p(s)$ could not be obtained without an immediate supplemental inspection by a system of near-perfect detection capability to identify the defects missed by the tested system, and breakage of rail samples containing the defects in order to establish their true sizes. Under these circumstances, the only practical approach is to infer $p(s)$, via a trial-and-error process, from the available statistics for overall system performance. During prior research, national statistics were fitted with a detection curve corresponding to older rail inspection equipment. The derived curve is given by [2]:

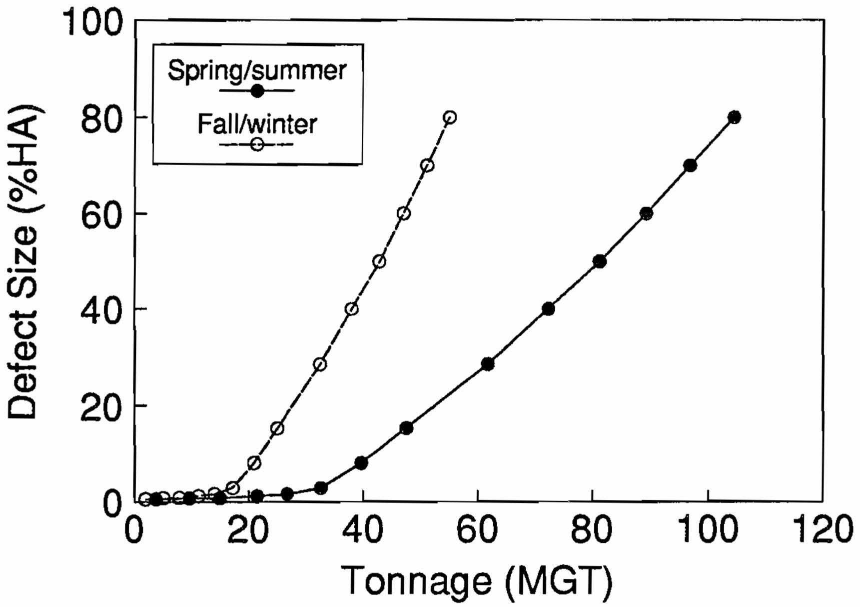

Figure 1. Detail Fracture Growth Curves

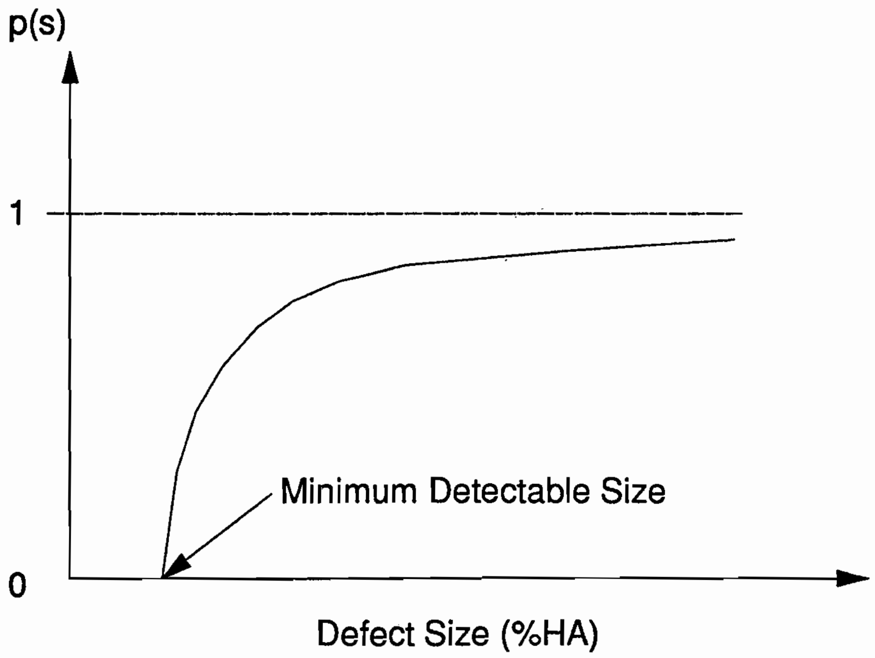

Figure 2. Detection Probability Curve

$$p(s) = 1-\exp\left[-\left(\frac{s-5}{14}\right)\right] \qquad (4)$$

where s is greater than or equal to 5 %HA (the minimum detectable size). This characteristic represents the DF detection performance of ultrasonic systems equipped with a single 70° sensor per probe wheel. As an initial estimate for modeling of the technology currently used by the UPRR, the following curve has been adopted:

$$p(s) = 1-\exp\left[-\left(\frac{s-3}{0.636}\right)^{0.35}\right] \qquad (5)$$

where s is greater than or equal to a minimum detectable size of 3 %HA. The difference is that the newer equipment has two extra 70° sensors per probe wheel to extend coverage toward the gage and field corners of the rail head. The specific parameters chosen to represent the current sensor technology were selected, after extensive numerical experimentation, to match the UPRR field experience during the first phase of the test waiver (see section 4.3). Table 1 compares the detection probabilities given by these two curves.

Table 1. Comparison of Detection Models

s (%HA)	5	10	20	40	60	80
$p(s)$ - old, eq. (4)	---	0.30	0.66	0.92	0.98	0.995
$p(s)$ - new, eq. (5)	0.78	0.90	0.96	0.98	0.99	0.995

The simulation does not account for defect detection by any means other than the inspection vehicle. Thus, the possibility of detection during the track patrols required by 49 CFR §213.233 is excluded because visual inspection is generally ineffective for discovery of internal defects.

Each defect in each mile of the hypothetical track is checked for detection during each inspection. Detected defects are assumed to be removed from the track, either immediately or within the three-day grace period. Defects not detected are allowed to continue growing until the next inspection or until reaching 80 %HA, whichever comes first. Defects that reach 80 %HA are counted as rail failures (service defects) and removed from the population.

No attempt is made to predict derailments, since analysis of railroad records has shown that only a small percentage of rail failures actually cause derailments. Most such rail failures are discovered by means of signal system indications, train crew reports, or track patrols, and are repaired. The total number of service defects is used as a relative, albeit indirect, measure of derailment risk.

3. MODEL IMPLEMENTATION

The model has been implemented as a PC-executable FORTRAN computer program. Subroutines represent defect occurrence, growth, detection, and removal (see appendix A for source code). The hypothetical track is assigned an arbitrary length of 1000 miles, based on numerical experiments, to assure stable averaging of Monte Carlo fluctuations.

In order to implement the Monte Carlo method, a standard library subroutine is used to sample the unit uniform probability distribution. This subroutine returns, at random, fractional numbers between 0 and 1 with approximately equal likelihood for any value. The actual distribution was verified by numerical experiment, and autocorrelation analysis was performed to verify the random character of the sampling.

The simulation is started from Year 1 with a rail age of 100 MGT. Each year is divided into 365 days, each of which is assigned 1/365 of the assumed annual tonnage. The defects are generated according to the occurrence rate model as shown in equation (3), which gives the interval of tonnage to the next defect occurrence. The baseline characteristic life is assigned as 2000 MGT to represent the effects of mixed revenue freight traffic. On the corresponding calendar day, the next defect is assigned to a randomly chosen milepost number from 1 to 1000 with the aid of the unit uniform distribution.

Random assignment means that the defect population has no tendency to cluster in certain mileposts. The tendency for the defects to occur in clusters has been intentionally omitted in order to keep the simulation as simple as possible. Prior research has shown that rail defects do tend to cluster in many cases [6]. However, among the railroad lines studied in the prior research, a UPRR division of 500 miles was included and showed little tendency for defect clusters. Therefore, the at-random assignment of milepost best represents the conditions on UPRR track.

Each defect is assigned the initial size of 0.506 %HA as of its occurrence date. The defect growth rate depends on both the size of the crack and the season. The program allows the input of one or two curves of crack size versus tonnage. The two crack growth curves used in the present cases (figure 1) represent spring/summer and fall/winter, respectively. For convenience, the spring/summer curve is applied for the first half of each simulated year, and the fall/winter curve for the second half. The size of each defect is increased by linear interpolation of the appropriate curve each day, based on 1/365 of the annual tonnage.

The detection process is simulated by randomly sampling the unit uniform probability distribution for each rail test of each defect that has grown to at least the minimum detectable size. A random value between 0 and 1 is selected from the uniform distribution. A detection is counted if the random value is less than or equal to $p(s)$, or a miss is counted if the random value is greater than $p(s)$, where $p(s)$ is the detection probability curve defined by either equation (4) or equation (5). New equipment performance, equation (5), is used as the baseline.

The track is inspected in order of milepost number, with a certain number of miles inspected per day, as outlined below. Each inspection is started on the calendar day on which the traffic tonnage carried since the preceding inspection reaches a prescribed value (the inspection interval). The inspection is assumed to continue for however many consecutive days are required to move the detector car across the whole subdivision. In other words, weekends and holidays are not accounted for in the simulation.

Two limits are placed on the number of miles inspected per day. First, an absolute limit of 100 miles/day is enforced to represent the best possible track occupancy, i.e., a full shift on track for the detector car with no significant delays. Second, the detector car is stopped short of the absolute limit on any day during which the count of detected defects exceeding critical size reaches a prescribed limit. This limit represents the existing practice of stopping the car as soon as it has identified a full day's work for the chase gang. The value of 10 critical defects per day is used as the baseline.

The program is automatically run ten times for each case. Each run is a complete simulation that starts at the beginning of Year 1 with rail of 100 MGT age. The simulation is repeated in this way to obtain enough data for good averaging of the random fluctuations associated with detection/non-detection decisions. Averages are calculated from the annual data produced for the ten independent runs. The number of detections and number of service defects are averaged for each year. The number of track miles inspected per day is averaged over all days of each inspection conducted in each year.

4. RESULTS AND DISCUSSION

Several sets of simulation cases have been run to meet the objectives stated in the introduction. Section 4.1 contains the results for a hypothetical medium traffic density subdivision with only the critical crack size varied. This example is used to introduce and explain some of the graphical presentations, as well as to illustrate the main effect of critical crack size under modified rules in comparison with the present 49 CFR §213.113 rules. Section 4.2 contains additional cases at higher traffic densities and summarizes the results of the model sensitivity study. In section 4.3, results from the foregoing cases are revisited in order to compare the model predictions with field experience gathered by the UPRR under test waiver H-94-1.

4.1 ILLUSTRATIVE EXAMPLE

Figures 3 through 6 are graphs plotted for an illustrative case of a line carrying 40 MGT per year, with inspections at 20 MGT intervals, using new equipment with detection performance specified by equation (5). In each graph, results for the baseline case (no critical defect size, no grace period) are compared with results for two different assumed critical crack sizes.

Figure 3 summarizes the annual total of defects detected. All cases are virtually identical in this plot, since most defects are detected and the rise in detections thus reflects the rising rate of defect formation. This plot is of most use for identifying the range of years for which the density of defects represents actual circumstances. For example, one would focus on Year 5 for results corresponding to an annual detection rate of 0.25 defect per track mile (250 defects for the 1000 miles).

Figure 4 summarizes the annual rate of service failures as a percentage of detected defects. No service failures occur in the first three years. Afterward, there are minor but insignificant differences between the cases, which are the results of random fluctuations that have not been completely averaged out. The beginning of a consistent common trend of rising service failure rate with increasing rail age is visible from Year 7 onward. This trend is a consequence of keeping the inspection interval constant, whereas both FRA research [2] and industry analysis [7] have shown that more frequent inspection is required to maintain a constant service failure rate as rail ages.

Figure 5 summarizes the annual averages of detector car utilization (miles inspected per day). Here a significant trend is evident starting in Year 3. At that point, enough defects are being found to begin affecting utilization via daily shutdowns dictated by chase gang capacity. The choice of critical size also has a significant effect. After Year 3, a consistent improvement in car utilization is evident in proportion to critical crack size.

Some of the foregoing results have been cross-plotted in figure 6, as follows. Years 5 through 8 were selected on the basis of detected defect rate (figure 3). Detected defect rate has been used as the abscissa in figure 6, together with car utilization as the ordinate. This type of cross plot is most useful for interpreting the simulation results in practical terms because the detected defect rate can be related to field situations. Generally speaking, rail defect occurrence is not considered to be a statistically significant phenomenon until the detected defect rate exceeds 0.25 defect/mile/year, and most railroads begin to implement rail renewal programs by the time the rate has exceeded 1 defect/mile/year. Thus, the plot in figure 6 is a vignette of car utilization at defect rates that would be expected on revenue track.

4.2 MODEL SENSITIVITY STUDY

Other cases with high annual tonnage were simulated to complete the study of model sensitivities. Baselines of track carrying 60 and 160 MGT per year were run to represent typical medium to high traffic density and the most heavily utilized track in the United States, respectively. A comprehensive

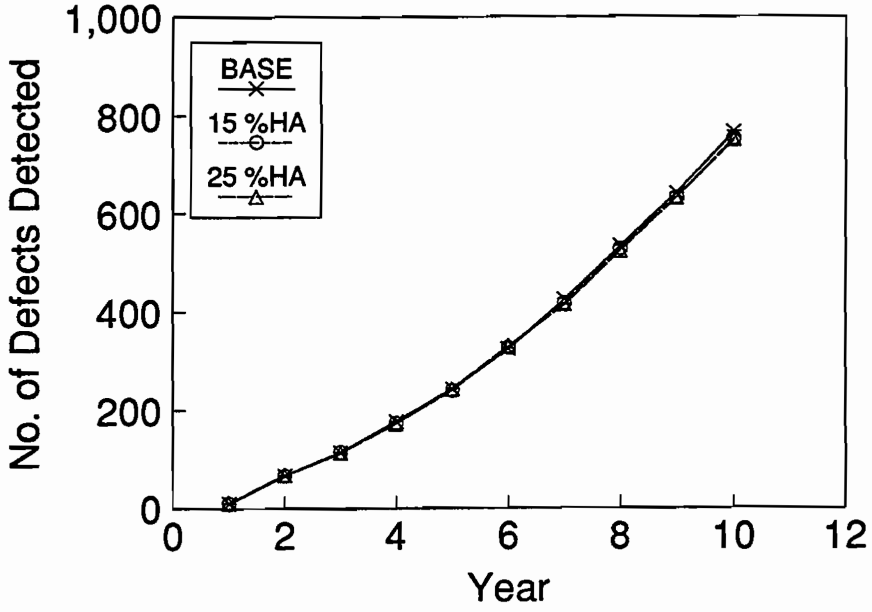

Figure 3. Ten-Year History of Detected Defects

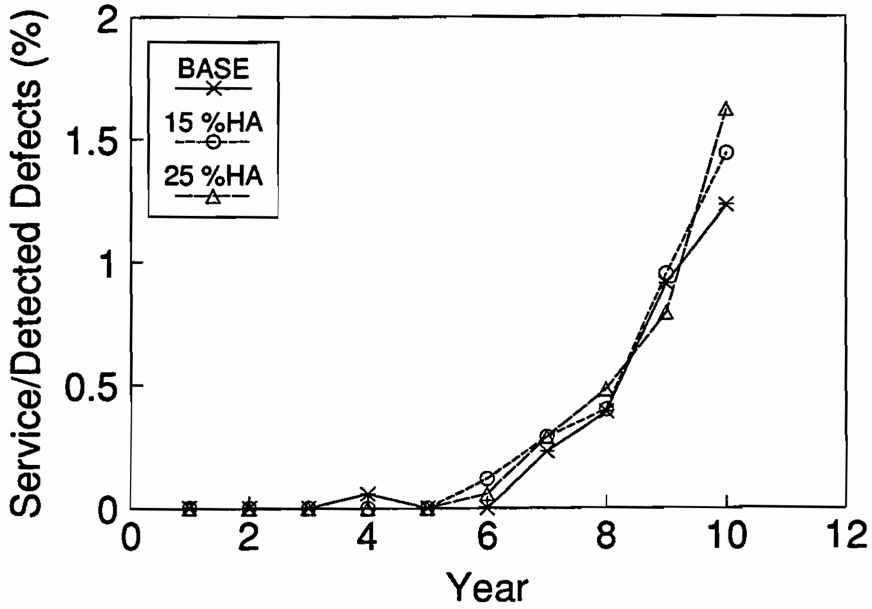

Figure 4. Ten-Year History of Service Defect Rates

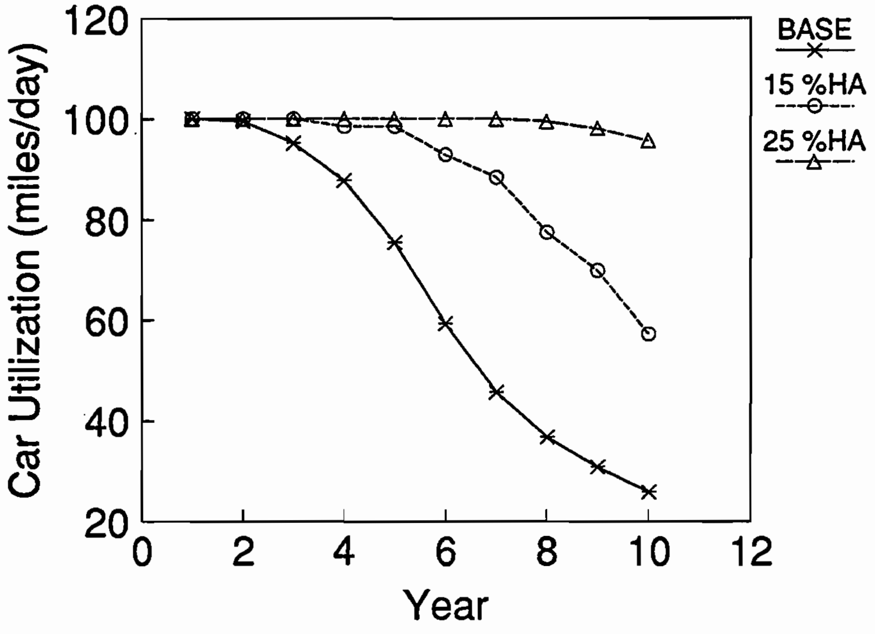

Figure 5. Ten-Year History of Detector Car Utilization

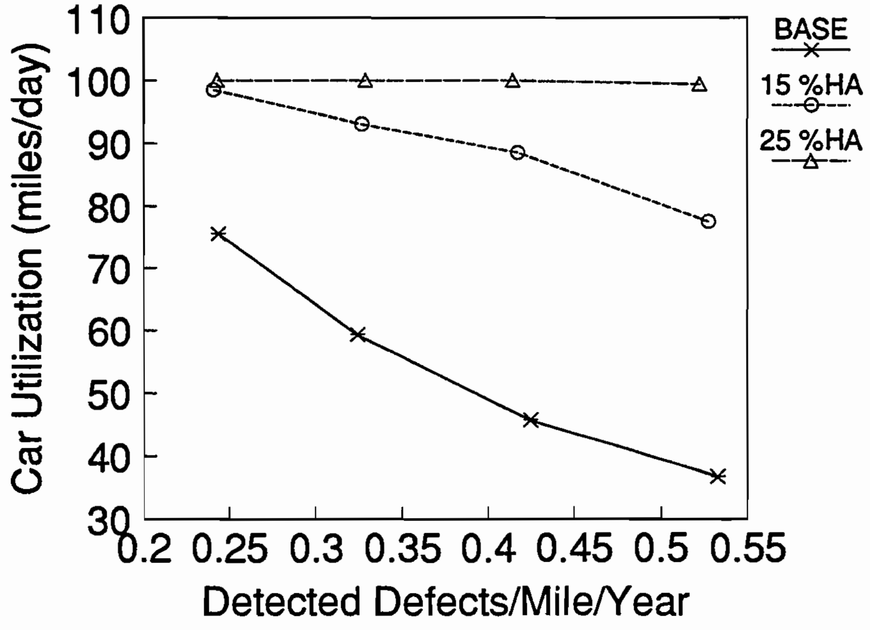

Figure 6. Service Defect Rates for Detected Defect Rates between 0.25 and 0.55 Defect/Mile/Year

sensitivity study was carried out for the hypothetical 60 MGT/year track by varying the other model parameters one at a time (see table 2). For the hypothetical 160 MGT/year track, only the effect of inspection interval was investigated.

Simulations of all cases were conducted for present 49 CFR §213.113 rules (no critical defect size, no grace period) and for the modified rules with 15 and 25 %HA critical sizes. Most of the results are presented as vignette graphs of service/detected defect ratio and car utilization versus detected defect rate.

Table 2. Simulations with 60 MGT Annual Tonnage

Parameter	Baseline Value	Variation
Inspection interval (MGT)	20	30
Detection performance	New equipment, equation (5)	Old equipment, equation (4)
Chase gang limit on critical defects per day	10	6
Defect growth rates	Per Figure 1	10% faster
Characteristic fatigue life β (MGT)	2000	3000

Figures 7 and 8 illustrate the baseline cases of 60 MGT annual tonnage with inspection at 20 MGT intervals. The general trends are the same as predicted for the 40 MGT/year illustrative example in the preceding section, i.e., increasing the critical defect size does not affect the service defect rate but does improve car utilization.

The strong effect of inspection interval on service defect rate is shown in figure 9. Increasing the inspection interval from 20 to 30 MGT (i.e., decreasing the frequency of inspection from three times to twice per year) increases the service/detected defect ratio roughly by a factor of 4. Car utilization is also degraded, but since inspection frequency is involved, it is better to evaluate detector car economics from the viewpoint of demand (car days per year):

$$\text{Car demand} = \frac{\text{(Track miles)}}{\text{(Car miles per day)}} \cdot \text{(Inspections per year)} \qquad (6)$$

Figure 10 shows the results for car demand. At very low detected defect rates, under 0.5 defect/mile/year, less frequent inspection produces some economic gain independent of critical defect size. However, the benefit disappears at rates exceeding 0.5 defect/mile/year.

Figures 11 and 12 illustrate the effects of detection equipment performance, as characterized by the detection probability curves assumed for new and old equipment. As expected, the improvement in detection probabilities associated with the new equipment dramatically reduces the service defect rate, relative to that obtained with the old equipment (figure 11). As shown in figure 12, the assumed new equipment performance yields no benefit to car utilization under present rules, but a substantial improvement under the modified rules when the detected defect rate exceeds 0.3 defect/mile/year.

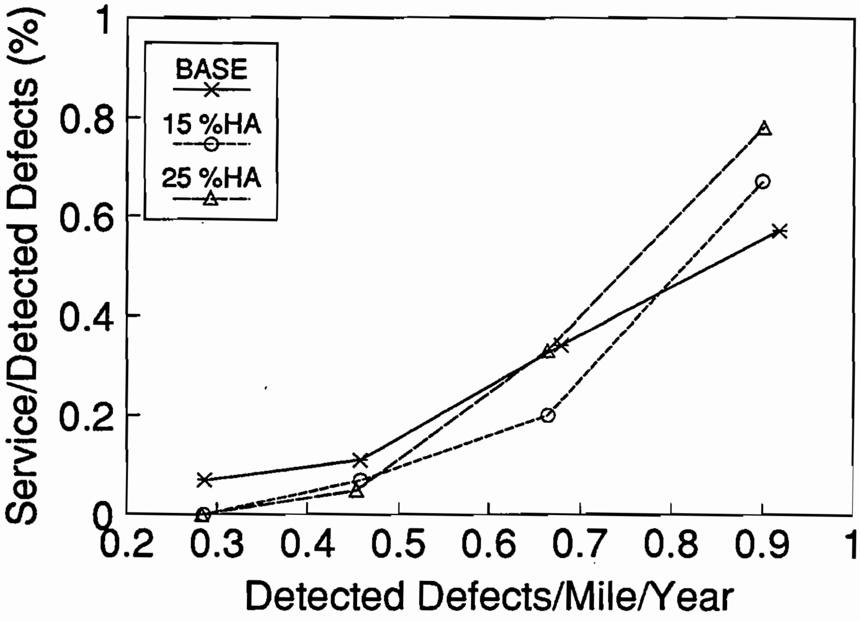

Figure 7. Service Defect Rates for 60 MGT/Year Baseline

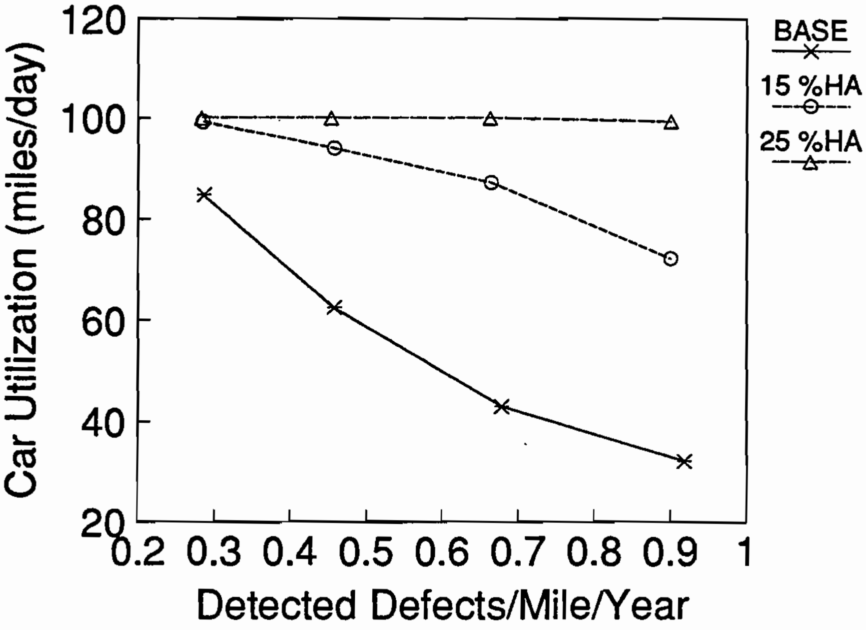

Figure 8. Detector Car Utilization for 60 MGT/Year Baseline

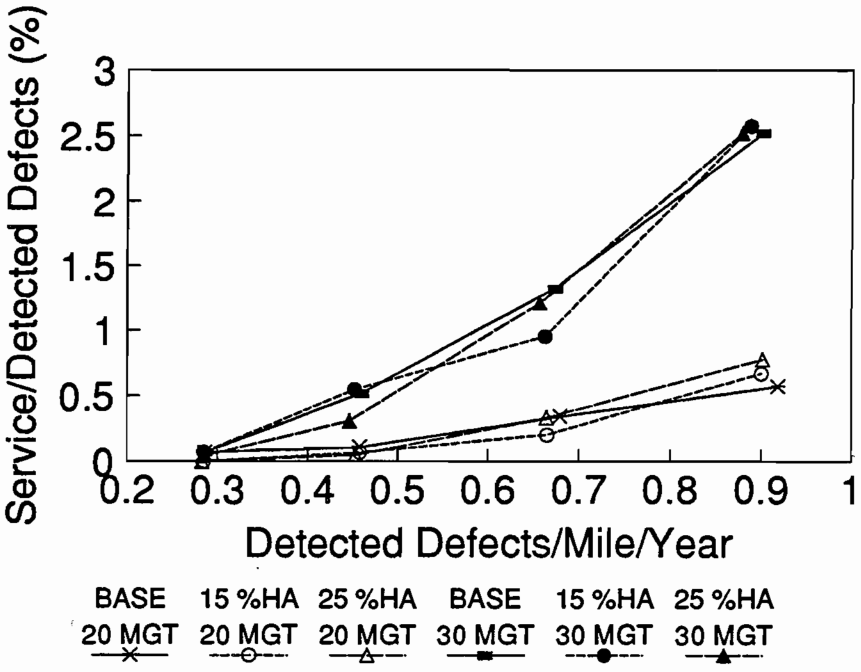

Figure 9. Effect of Inspection Interval on Service Defect Rate

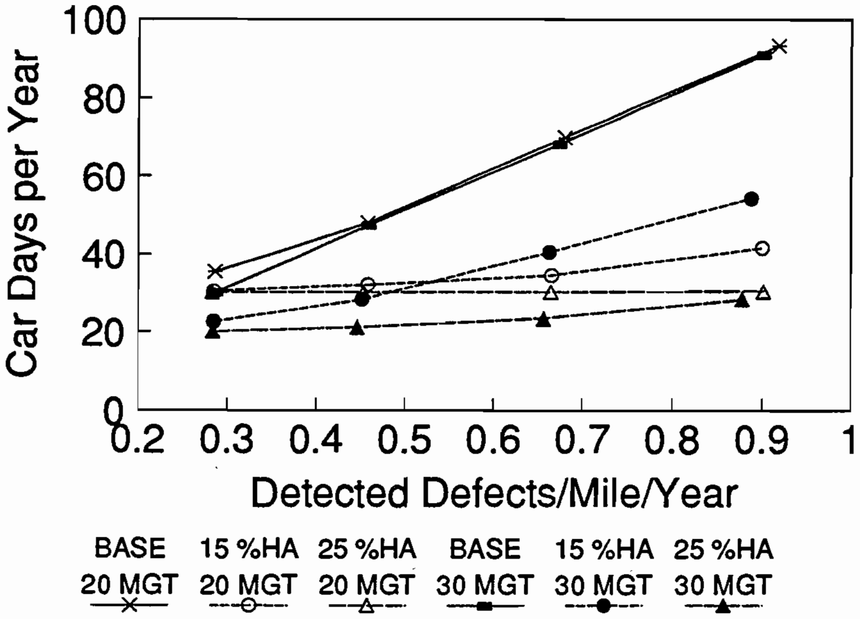

Figure 10. Effect of Inspection Interval on Car Demand

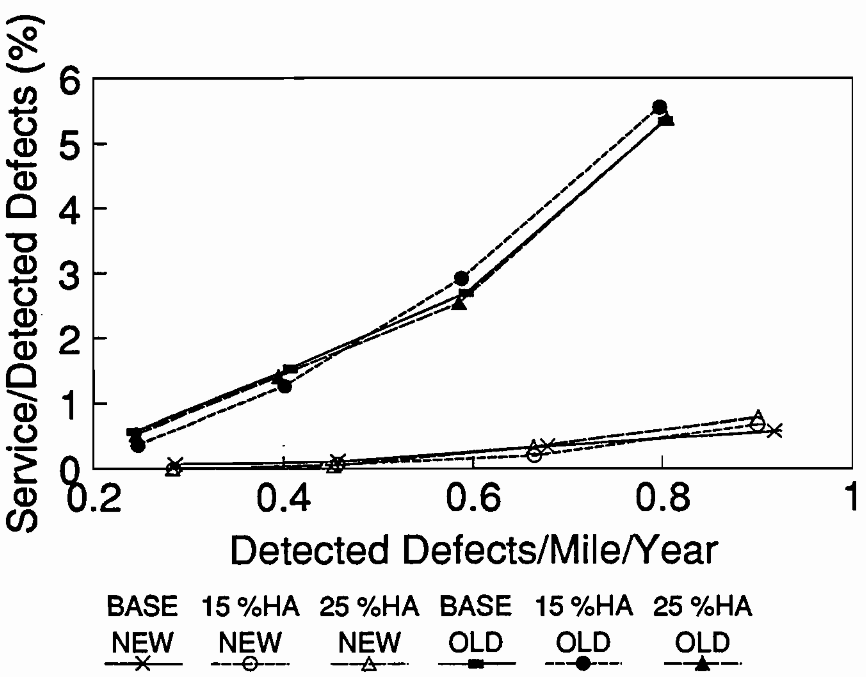

Figure 11. Effect of Equipment Performance on Service Defect Rate

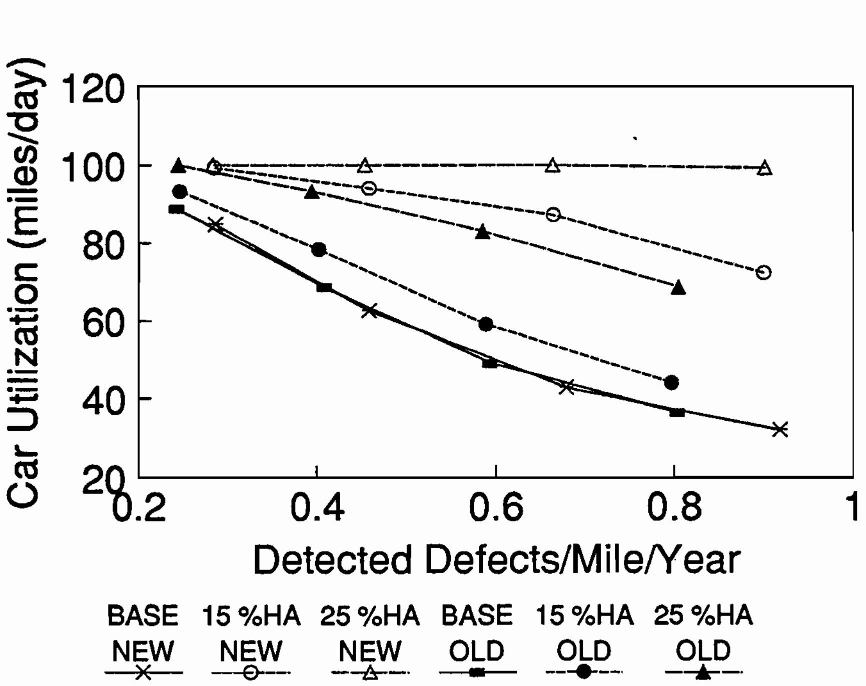

Figure 12. Effect of Equipment Performance on Car Utilization

Figures 13 and 14 summarize the effects of repair gang limit, i.e., the number of critical defects the car is allowed to detect before being shut down for the day. The results exhibit a weak tendency for the service defect rate to increase under the modified rules as the repair gang limit decreases (figure 13). Conversely, there is a strong effect on car utilization. The lower repair gang limit reduces car utilization by 20 to 30 percent under either present rules or modified rules with 15 %HA critical size but, with 25 %HA critical size, does not begin to reduce utilization until the detected defect rate exceeds 0.9 defect/mile/year (figure 14).

Figures 15 and 16 show that a 10 percent increase in crack growth rate does not affect either service defect rate or car utilization. However, much greater increases in the rate of DF growth are possible in different service environments, so the effect of this variable cannot be entirely dismissed.

Figures 17 and 18 show that the value assumed for characteristic fatigue life, β, affects neither service defect rate nor car utilization. By definition, β is the cumulative tonnage at which 63% of the rails in a population will have developed a defect, under the assumption that the defect formation rate for the entire population rises smoothly in accordance with a Weibull curve. At best, this model is no more than a rough approximation that might be usefully fitted to some short range of accumulated tonnage, based on field experience. When the simulation model results are plotted versus detected defect rate, as has been done here, the comparison of different β values is actually a test of the effect of the rate of increase of the defect formation rate. In particular, the variation $\beta = 3000$ MGT increases the formation rate at a slower pace than the baseline value of $\beta = 2000$ MGT.

Figures 19 and 20 illustrate the effects of inspection interval at the extreme traffic density of 160 MGT per year. The baseline value of 20 MGT and variations of 32 and 40 MGT correspond to 8, 5, and 4 inspections per year, respectively. The results presented in these plots are from Year 2, in which the detected defect rate was between 1.4 and 1.6 defects/mile/year. Unlike the preceding examples, inspection interval is used on the abscissa instead of detected defect rate. Nevertheless, these results can still be compared with the earlier results for inspection interval effect on 60 MGT/year track. In both cases, the service defect rate has a strong tendency to increase as the frequency of inspection is decreased (compare figures 9 and 19). Conversely, changing the inspection interval has little effect on car demand, as measured in total car days per year (figures 10 and 20).

In Figures 21 and 22, the baseline and illustrative example results have been combined to cross-plot service defect rate and total annual car effort as functions of annual tonnage, with the inspection interval kept constant at 20 MGT. The data used in these plots are from Years 15, 8, and 2, respectively, for 40, 60, and 160 MGT annual tonnage. In each case, the detected defect rate is between 1.4 and 1.6 defects/mile/year for the year mentioned. The service defect rate trend appears to be counter-intuitive (figure 21) but is actually a consequence of interaction between inspection frequency and seasonal crack growth rate. At the lower annual tonnages, most or all of the fall/winter season is encompassed in one inspection interval, thus reducing detection opportunities in the second half of each year. Figure 22 illustrates the effect of annual tonnage on car demand. There appears to be a weak trend toward less demand at lower annual tonnages, but the choice of critical defect size is the dominant influence.

4.3 COMPARISON OF MODEL PREDICTIONS WITH FIELD EXPERIENCE

The UPRR conducted rail inspections under test waiver H-94-1 from June through November 1994 on two lines, one carrying 55 to 60 MGT per year and the other carrying 210 MGT per year with 160 MGT on one track. Test records submitted to FRA included classification of detected defects by

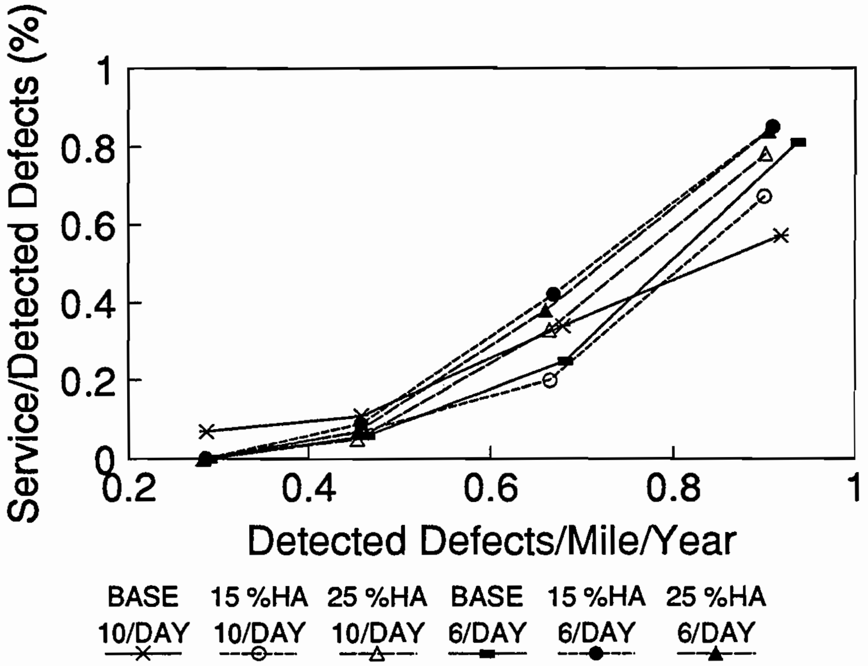

Figure 13. Effect of Repair Gang Limit on Service Defect Rate

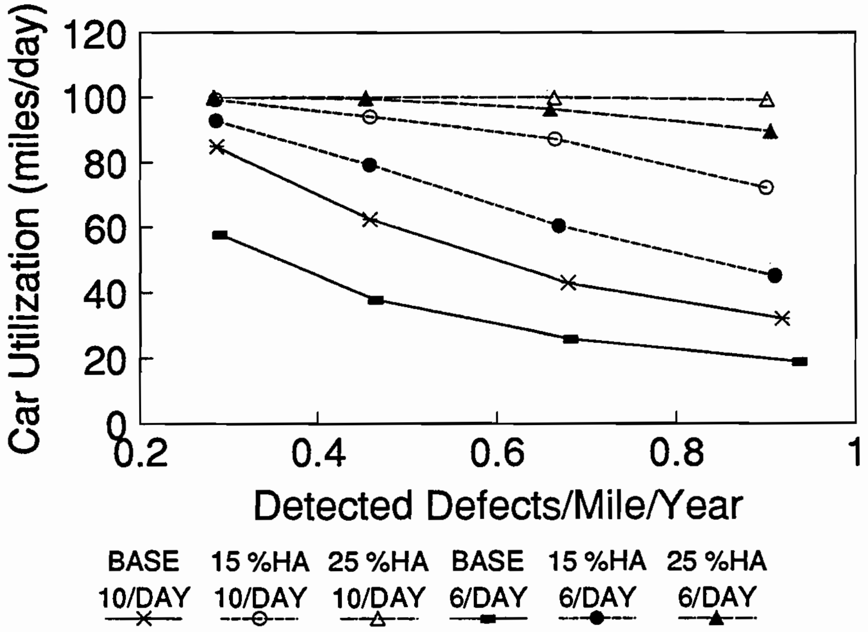

Figure 14. Effect of Repair Gang Limit on Car Utilization

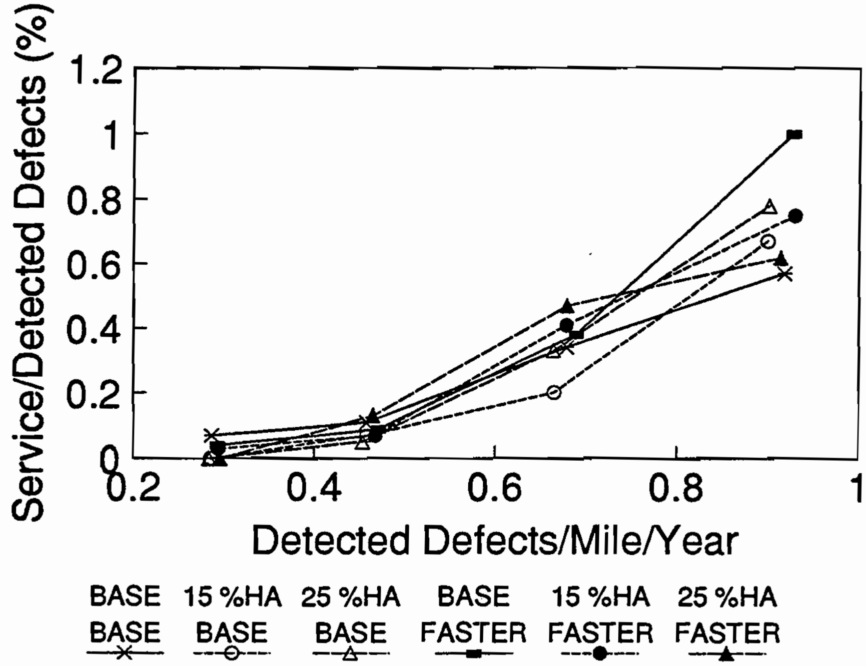

Figure 15. Effect of Defect Growth Rate on Service Defect Rate

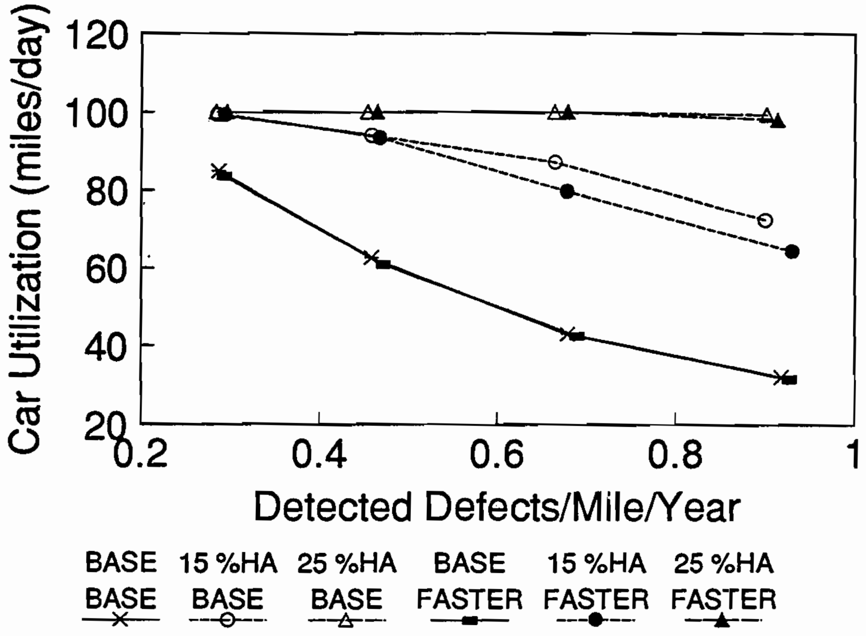

Figure 16. Effect of Defect Growth Rate on Car Utilization

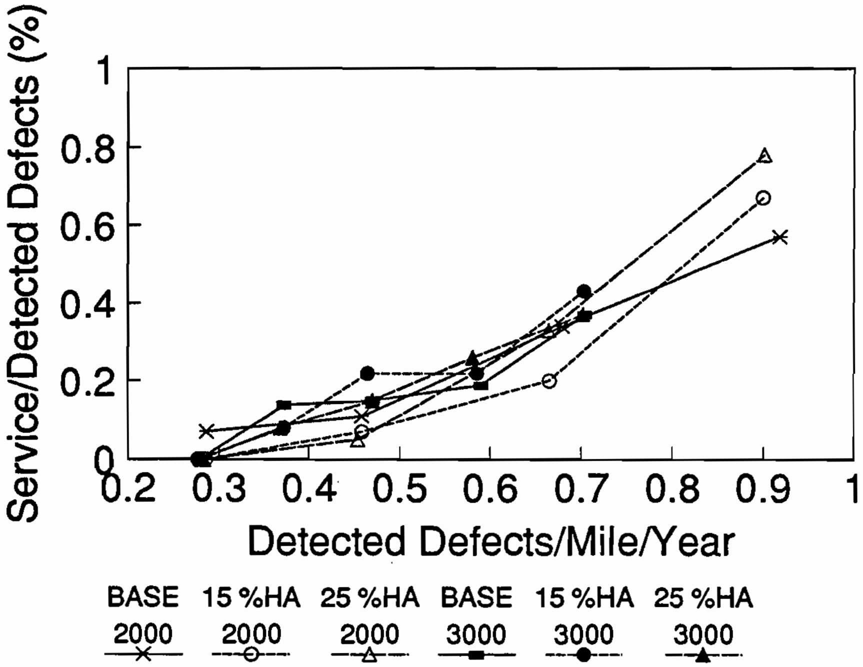

Figure 17. Effect of β on Service Defect Rate

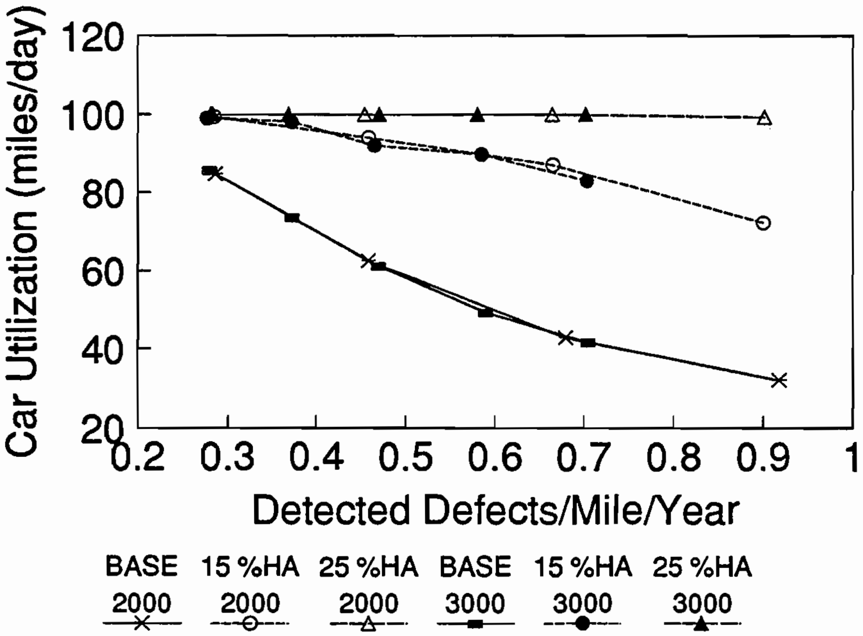

Figure 18. Effect of β on Car Utilization

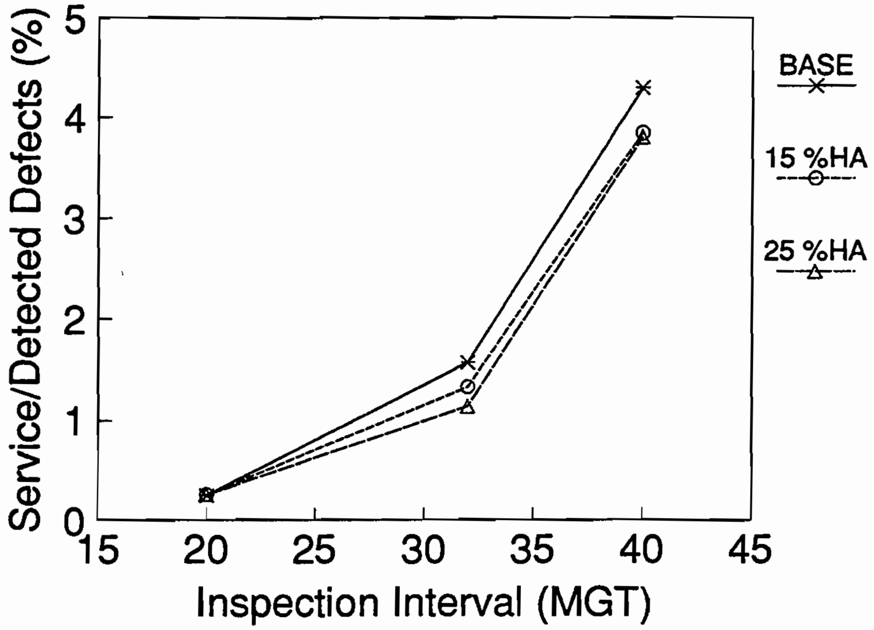

Figure 19. **Inspection Interval Effect on Service Defect Rate (Traffic Density 160 MGT per Year)**

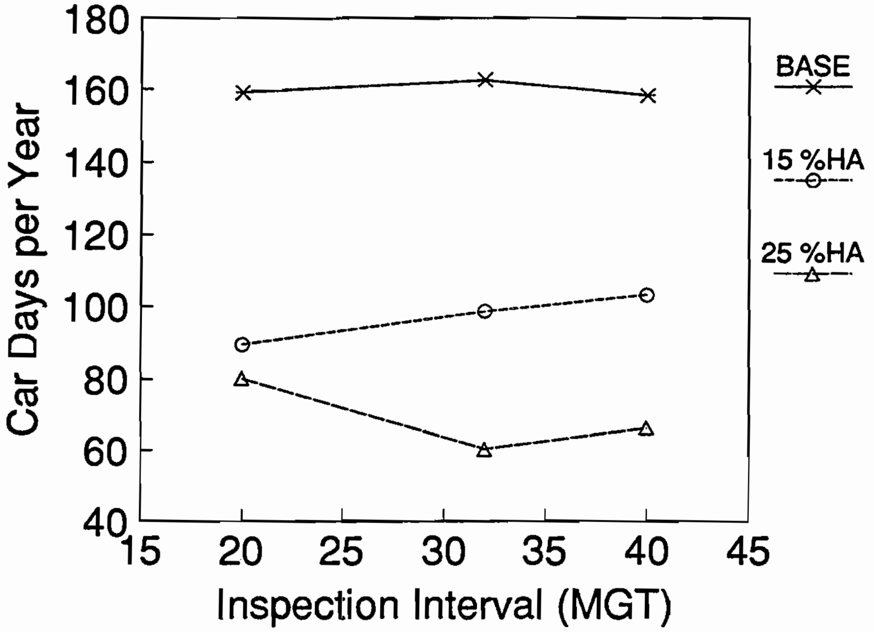

Figure 20. **Inspection Interval Effect on Car Demand (Traffic Density 160 MGT per Year)**

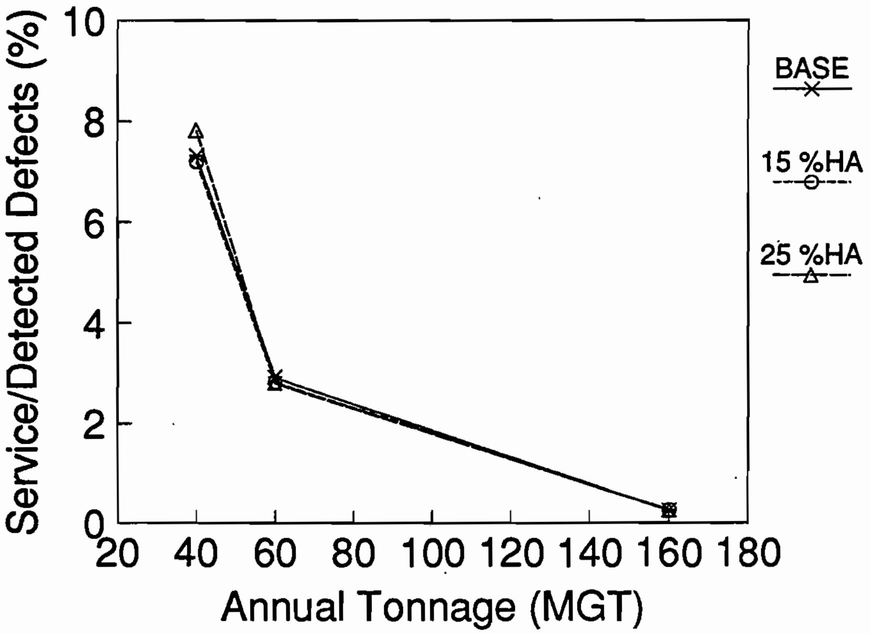

Figure 21. Effect of Annual Tonnage on Service Defect Rate for Track Inspected at 20 MGT Intervals

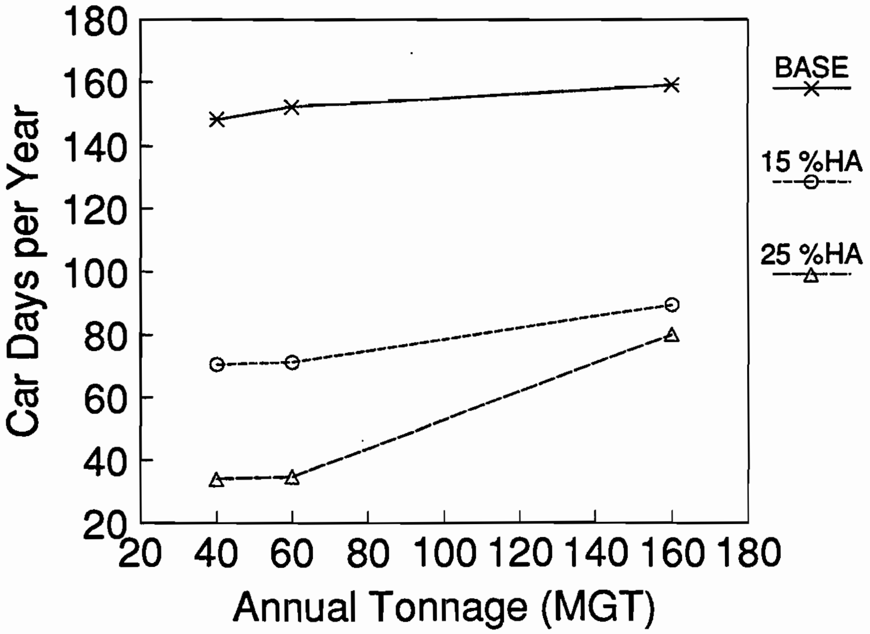

Figure 22. Effect of Annual Tonnage on Car Demand for Track Inspected at 20 MGT Intervals

type and size. From these records were identified some 455 transverse internal rail head defects[1] for which size estimates in %HA were reported. Of that total, 252 defects or 55% were classified as exceeding 15 %HA, and 143 or 31% were classified as exceeding 25 %HA. The percentage figures are useful measures of the potential for better car utilization as a function of critical defect size.[2]

The field experience was also used to calibrate the model. Trial simulations were conducted with the spring/summer defect growth curve and different combinations of detection probability curve parameters to arrive at equation (5) for the new equipment detection probability curve (section 2.3). For the given parameters, the simulation of a line carrying 60 MGT/year with two inspections per year produced averages of 58% of detected defects exceeding 15 %HA, and 26% exceeding 25% HA, in close agreement with the 55% and 31% figures from the field. (The simulated annual tonnage and inspection frequency closely represented the actual characteristics of the medium tonnage line.)

Additional results on the distribution of detected defect sizes were generated from the simulations to provide further confirmation of model validity and to illustrate the effects of the model variables. These results are compared with the field experience in the next several figures. The model-to-field comparison is not precise because the field statistics are based on ultrasonic test estimates of defect size and may, therefore, contain some measurement error. However, the error magnitude is believed to be small for the size classifications discussed here, and thus the comparison is still worthwhile.

The next five graphs summarize such comparisons from the results of the 60 MGT/year hypothetical track model sensitivity study. Each compares the baseline with a variation as outlined in table 2 (section 4.2).

Figure 23 illustrates the comparison with inspection interval as the model variable. The left and right bar groups show the percentages of defects exceeding 15 and 25 %HA, respectively. Each group contains seven bars showing: the UPRR field experience (solid black); the baseline simulation of 20 MGT inspection interval (narrow hatchings); the variation of 30 MGT inspection interval (wide hatchings). The legends also indicate the years which were taken from the simulation. Years 3 through 5 were selected for the comparison in order to obtain data from the range of 0.25 to 0.7 detected defect/mile/year. The model percentages were obtained by averaging over the different cases of critical defect size (present rules, 15 %HA, and 25 %HA), since the choice of critical size has no significant effect on the distribution of detected sizes.

The distribution of detected defect sizes predicted for the 30 MGT inspection interval closely matches the field experience. This case is similar to the calibration case discussed above, except that the seasonal effect on crack growth rate (section 2.2) has been re-introduced into the simulation. The comparison case shows that more frequent inspection dramatically reduces the percentages of defects exceeding either critical size.

Figure 24 compares new versus old equipment performance, showing that the improvement also dramatically reduces the percentages of detected defects exceeding critical size. Aside from a slight increase in the percentage exceeding 15 %HA when 10% faster defect growth rates are assumed, there are no effects of chase gang capability (figure 25), defect growth rate (figure 26), or characteristic rail fatigue life (figure 27).

---

[1] UPRR classifications DIW (defective in-track flash butt weld), DFW (defective field weld), DPW (defective plant weld), and TD (transverse defect).

[2] The interpretation of the percentage figures is that, whereas 100% of the detected defects would have required immediate action under 49 CFR §213.113, only 55% actually did require immediate action under test waiver H-94-1, and only 31% would have required immediate action if the waiver had allowed a 25 %HA critical defect size.

Similar statistics were extracted from the simulations of 160 MGT/year hypothetical track at different inspection intervals. Figure 28 compares these results with the UPRR field experience. The model projects somewhat higher percentages at the 40 MGT interval and agrees well with the field experience for the 32 MGT interval. These intervals represent 4 to 5 inspections per year, which bracket the UPRR practice on the high density test waiver line. Like the medium tonnage case, more frequent inspection dramatically reduces the percentages of detected defects exceeding either of the critical sizes.

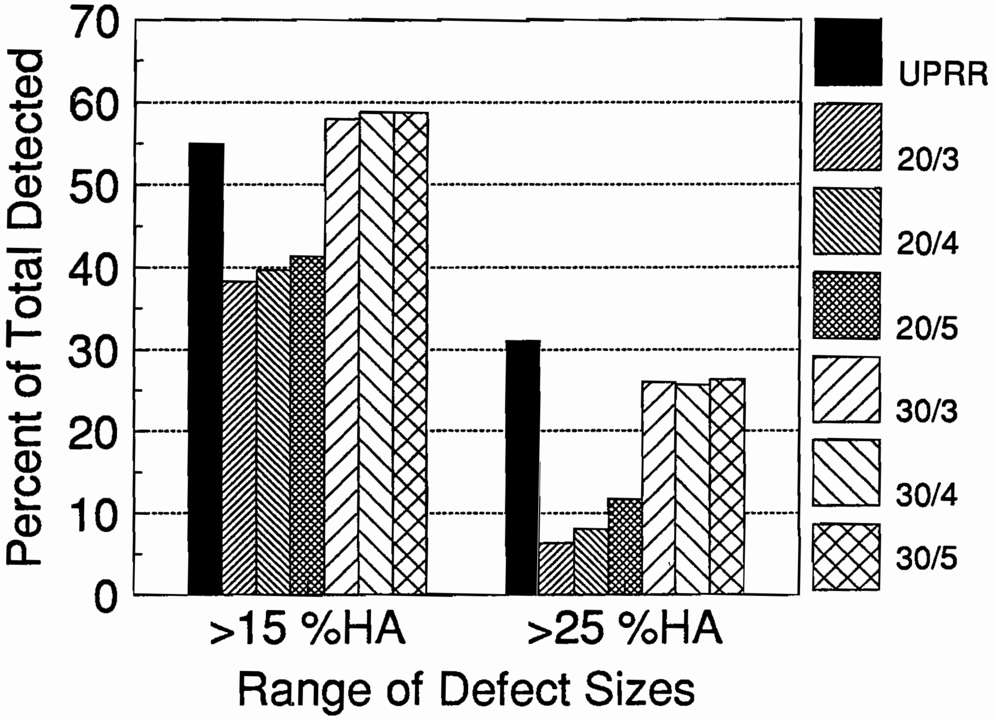

Figure 23. Inspection Interval Effect on Detected Defect Size

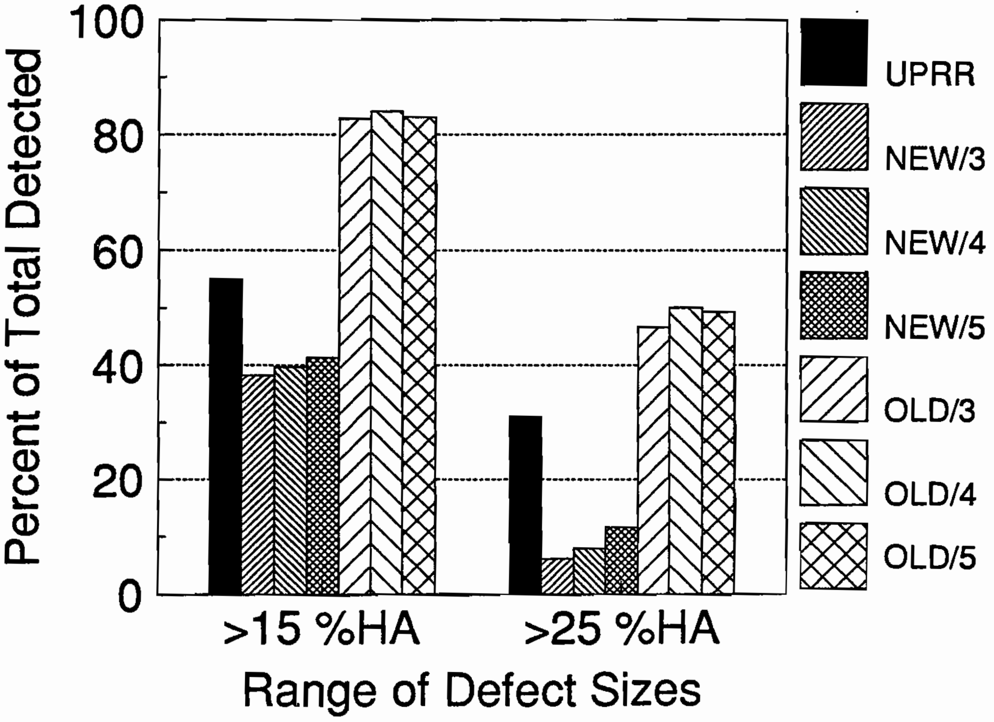

Figure 24. Equipment Performance Effect on Detected Defect Size

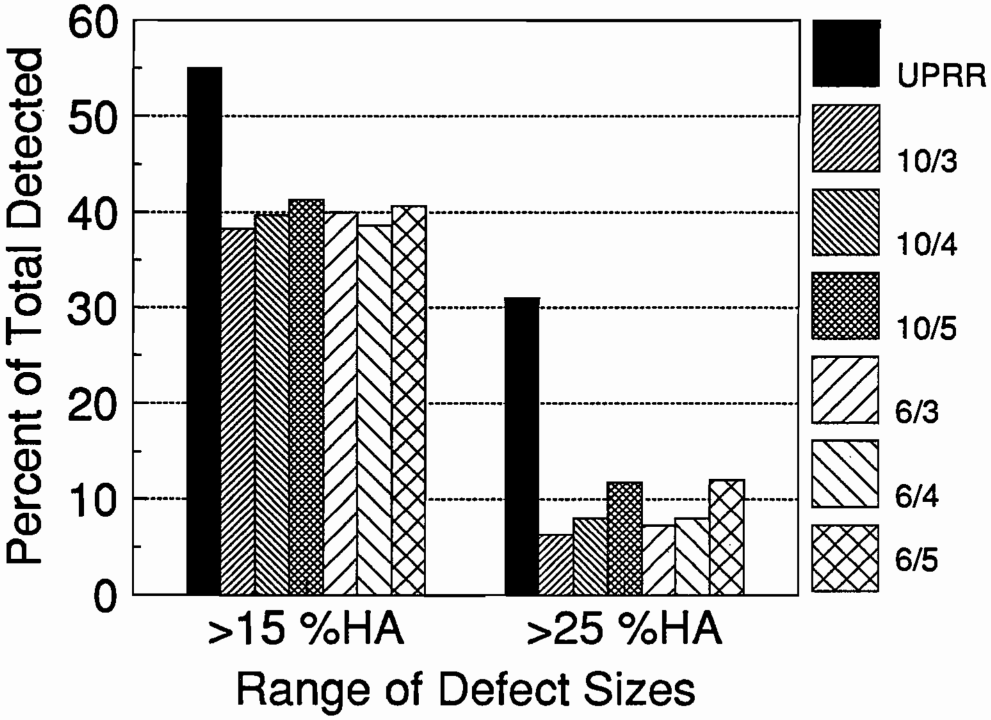

Figure 25. Chase Gang Limit Effect on Detected Defect Size

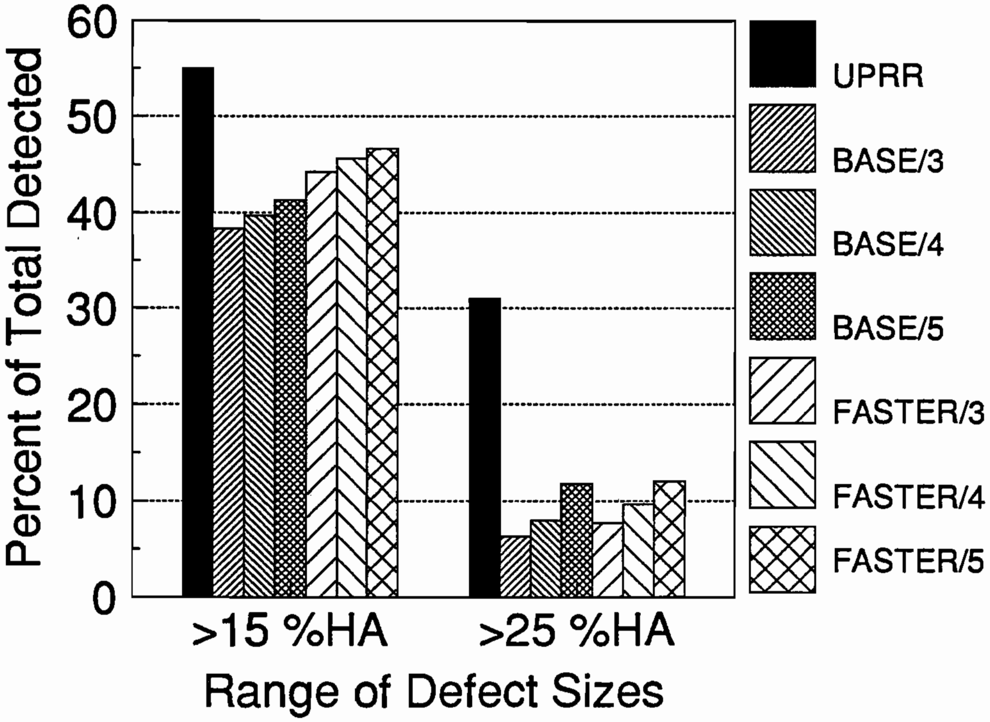

Figure 26. Crack Growth Rate Effect on Detected Defect Size

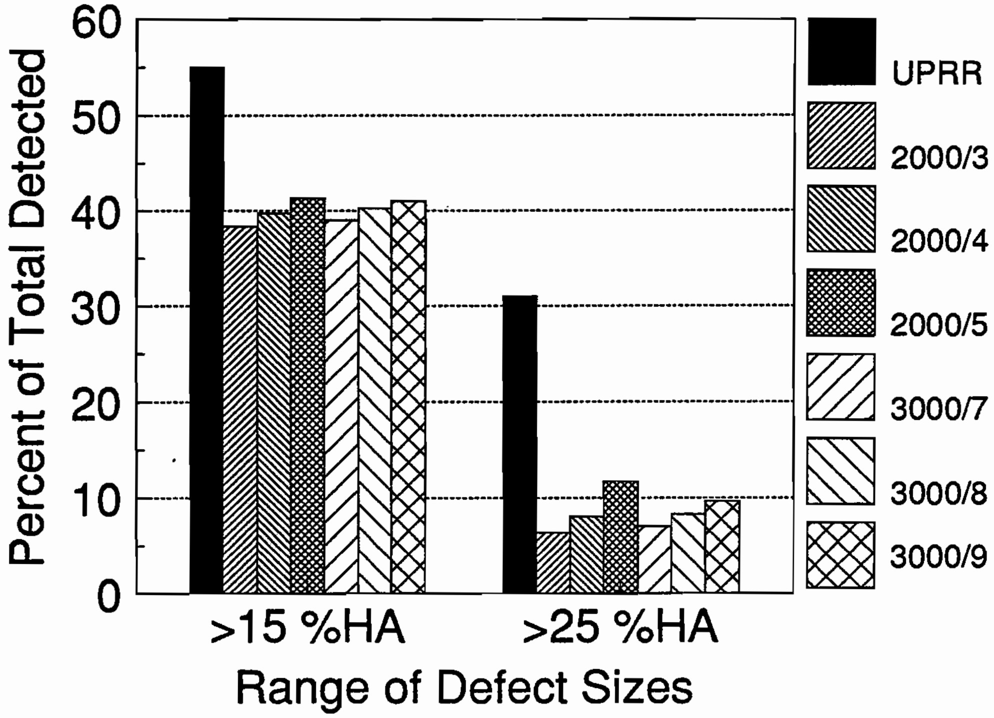

Figure 27. Effect of Characteristic Life β on Detected Crack Size

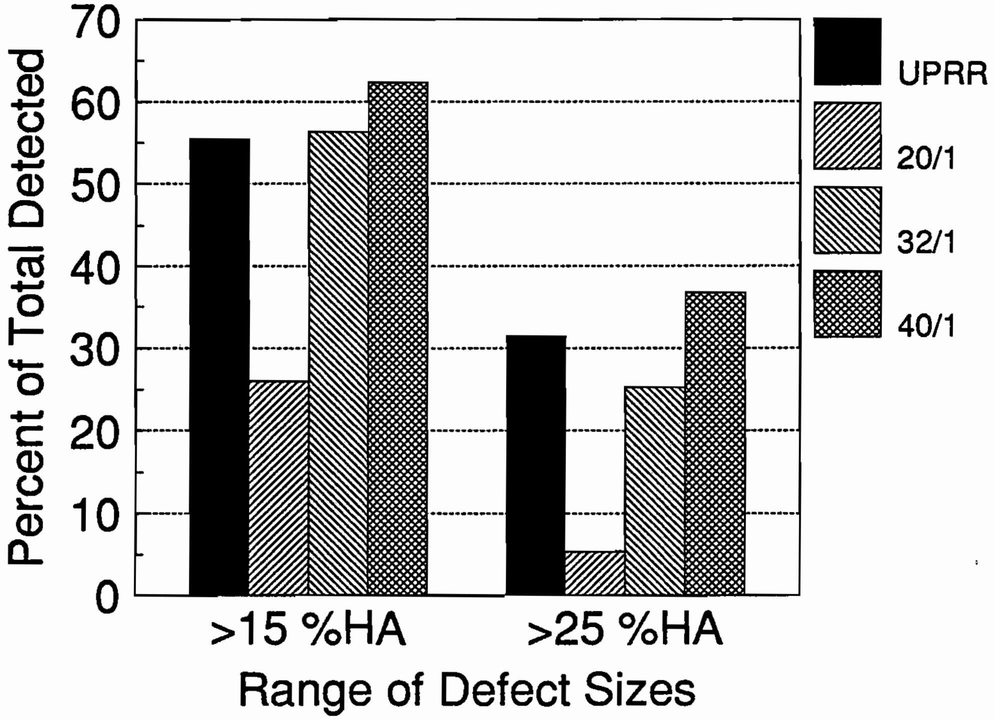

Figure 28. Inspection Interval Effect on Detected Defect Size (Traffic Density 160 MGT per Year)

5. CONCLUSIONS

With the present baseline parameters, the rail inspection simulation model produces results that match the UPRR field experience from the test waiver, so far as regards the percentages of detected detail fracture defects exceeding the proposed critical sizes of 15 or 25 %HA. However, the predictions for service/detected defect ratio are lower than the railroad's general field experience of 5%, as determined in a recent audit [8].

The model analyses were conducted under the assumption that the car would be able to inspect 100 track miles per day if not tied to the chase gang. This was done in order to get an idea of the best performance that might be realized under ideal conditions, with the detector car allowed unlimited track possession and thus able to run 6 to 7 hours per day. Since detector cars must often give way to revenue traffic, the best day's run is generally from 25 to 40 miles.

Despite the above differences, the following useful general conclusions about rail inspection programs can be drawn from the results of the model sensitivity study:

- Modifying the requirements of 49 CFR §213.113 to allow delayed action on defects not exceeding a specified critical size can improve detector car productivity without affecting the service defect rate. The modification does entail a risk of exposure to known subcritical defects, but that risk can be controlled by establishing a minimum ambient temperature below which no delayed actions are allowed.

- Increasing the specified critical defect size can further improve car productivity without affecting the service defect rate, provided that the specified minimum ambient temperature is also raised to keep subcritical defect exposure risk under control.

- Better detection equipment performance can produce simultaneous improvement of detector car utilization and reduction of service defect rate. Considerable gain has already been achieved by current equipment, relative to the systems that were deployed in the early 1980s.

- More frequent inspection can dramatically reduce the service defect rate.

- Increasing repair gang productivity improves detector car productivity but has no effect on service defect rate or subcritical defect exposure risk. However, equal or better improvement can be made by allowing 25 %HA, as opposed to 15 %HA, critical defect size.

- Detector car utilization can be improved when inspecting rail in areas of high defect occurrence rate (greater than 1 defect/mile/year) as long as sufficient track possession time is allowed for a practical day's run of at least 30 miles.

APPENDIX

```
      program mcrail
c
c     Monte Carlo Analysis of Subdivision Rail Test
c     Main (March 10, 1994)
c     bp edit May-june, 1994
c----67--1---------2---------3---------4---------5---------6---------7--
c     amgt        - tonnage interval expected to produce the next defect
c     aton        - accumulated tonnage between defect generation
c     beta        - characteristic life (MGT)
c     csize       - critical crack size (%ha)
c     cracki      - initial defect size (%ha)
c     icount      - number of defects removed per day
c     imile       - mile post counter for inspection
c     mi2day      - counter for mile inspected per day
c     mday        - number of repairing days for each year
c                   (for  all cracks
c     mipd        - number of miles inspected per day
c     ncurve      - number of growth curves (1 or 2)
c     nday        - analysis duration in days
c     ndef        - defect counter at each mile post
c     nfix        - number of defects acted upon per day
c     ninsp       - sequence of inspection (1 or 2, 1 - use crack
c                   growth curve 1, 2 - use crack growth curve 2)
c     raila       - rail age in MGT (million gross tons)
c     ltrack      - length of track for the analysis (mile)
c     tonpd       - acummulated tonnage (MGT) per day
c
c     begin       - flag for the start of inspection
c     inspct      - flag for end of inspection period
c
      integer nday, ltrack nfix, mipd, ncurve
      real    raili, tonpd, csize, dsize, beta
c
      real cracki
      integer ninsp, mday, m1day, iyear, mi2day, jstart, i, j
      integer ktime(3),lseed
c
      logical inspct, begin,  report, season, quit, quit1, quit2,
     +         quit3, outpt, debug
c----67--1---------2---------3---------4---------5---------6---------7--
c  get external data from files
      call getinp (nday,ltrack,raili,tonpd,nfix,mipd,beta,ncurve,nipy)
c
c  rdgrow is an entry in GROWTH
      call rdgrow (ncurve)
      ninsp = 1
c  seed the random number generator
      call itime(ktime)
      lseed =(ktime(1)+ktime(2)+ktime(3))/3
      write(*,*) ' Seed = ', lseed
      call srand(lseed)
c----67--1---------2---------3---------4---------5---------6---------7--
c  zero variables in OUTPUT entry
c  year in incremented in OUTPUT
```

```
      iyear  = 0
      call opinit(iyear)
c
      mday   = 0
      m1day  = 0
      ndef   = 1
      nspct  = 0
      n15    = 0
      n25    = 0
      ng25   = 0
c  age/tonnage is incremented at the end of the day loop
      raila = raili
c  target generation tonnage is set in OCCUR
      aton  = raili
c  init inspection, repair, report & season indicators
      inspct = .false.
      report = .false.
      season = .false.
      begin  = .false.
      outpt  = .false.
      debug   = .false.
c
      write (15,2)
2     format (1x,'Summary of Detected Detects History:',//)
      write (15,3)
3     format (1x,'year',3x,'insp #',5x,'<=15%ha',
     1        3x,'<15%ha and <=25%ha',3x,'>25%ha',/)
c
c----67--1---------2---------3---------4---------5---------6---------7--
c  start of main loop here
c----67--1---------2---------3---------4---------5---------6---------7--
      do 100 iday = 1, nday
        quit   = .false.
        quit1  = .false.
        quit2  = .false.
        quit3  = .false.
c  get agenda for the day
        call action(iday, begin, outpt, season)
C  begin, outpt and season are true only on due day
        if (begin) then
c start inspection
          imile  = 1
          inspct = .true.
        end if
C write yearly report as soon as inspection is complete
        if (outpt) report = .true.
C
        if (ncurve.eq.2) then
          if (season) then
            ninsp = 2
          else
            ninsp = 1
          endif
        endif
```

```
c  generation of defects for the day
        if (raila .ge. aton) then
c  initial crack size in GROWTH depends on ninsp  OCCUR
          call occur (raila,aton,ltrack,beta,tonpd)
        endif
c  update defect growth
        call growth (tonpd,ltrack,ninsp)
c----67--1---------2---------3---------4---------5---------6---------7--
c inspection for rail defect
c----67--1---------2---------3---------4---------5---------6---------7--
        if (inspct) then
c miles per day
          mi2day   = 1
c defects removed
          icount = 0
c start day
   5      continue
          call gtndef(imile,ndefm)
          if ( (ndefm .gt. 0) .and. (ndef .le. ndefm ) )then
c  find cracks: size is set in DEFDET
c  crack found: ndefm decremented
c     critical: icount incremented
c    not found: ndef incremented
            call defdet (imile, ndef, icount, n15, n25, ng25)
c get new defect count
            call gtndef(imile,ndefm)
C stop for day on crack fix limit; ndef will remain when we return tomorrow
            quit1 = (icount .ge. nfix)
          else
c make sure we start on first crack in the next mile
            ndef = 1
          endif
c
          if (.not.quit1) then
            if(ndef .le. ndefm ) then
C more cracks in the current mile
              go to 5
            else
c update to the next mile
              imile   = imile + 1
              mi2day = mi2day + 1
            end if
C check for mile limits
            quit2 = (mi2day .gt. mipd)
            quit3 =  (imile .gt. ltrack)
            if( .not.(quit2 .or. quit3) ) then
c do more miles
              go to 5
            else if (quit3) then
c no more cracks
              call dstdef(iyear,nspct,n15,n25,ng25)
              nspct=nspct+1
              inspct = .false.
              imile = 1
```

```
                icount = 0
              end if
c end of miles checks
            end if
c update days inspected
            mday = mday + 1
          end if
C----67--1---------2---------3---------4---------5---------6---------7--
C end of crack detection day
C----67--1---------2---------3---------4---------5---------6---------7--
          if(quitl) mlday = mlday + 1
c
c   output result
c
          if ( report .and. (.not. inspct ) ) then
c----67--1---------2---------3---------4---------5---------6---------7--
            call reprt(ltrack,raila,mday,mlday,iday,iyear,debug)
            call opinit(iyear)
c  reset repair/inspection count
            mday   = 0
            mlday  = 0
c
            report = .false.
          endif
c
c   accumulate tonnage for each day
c
          raila = raila + tonpd
c
100     continue
        iyear = iyear - 1
        call averg(ltrack,iyear,nipy)
c
        close (unit=10)
        close (unit=11)
        close (unit=13)
        close (unit=14)
        close (unit=15)
c
        stop
        end
```

```
      subroutine getinp(nday,ltrack,raili,tonpd,nfix,mipd,beta,ncurve
     1                  ,nipy)
c
c  Monte Carlo Analysis of Subdivision Rail Test Data Input
c  13 variables read, echoed & returned to main
c
c----67--1---------2---------3---------4---------5---------6---------7--
      integer nday, ltrack, nfix, mipd, ncurve
      real    raili, tonpd, csize, dsize, beta
c
c     nday        - analysis duration in days
c     ltrack      - length of track for the analysis (mile)
c     tonpd       - acummulated tonnage (MGT) per day
c
      integer i, iunit
      integer nyear, ndpy, noint, noday, inday, ncvday
      integer koday, knday, kcvday
      real tonpy, ainsp
      save nyear, ndpy, tonpy, noint, noday, inday, ncvday
      save koday, knday, kcvday
c declarations for entry action
      integer iday
      logical inspct, report, season
c
c     ainsp       - inspection interval in MGT (million grosss tons)
c     nyear       - analysis duration in years
c     ndpy        - number of days of operation per year
c     tonpy       - acummulated tonnage (MGT) per year
c     noint       - output intervals (year)
c     noday       - output intervals (day)
c
c  unit 10 is defects in rail
c  unit 11 is critical defects detected
c  unit 13 is service failures
c  unit 14 is summary
c
c  unit 25 is input
      parameter(inunit = 25)
c
      integer iucpop, iudefs, iufail, iusum
      parameter(iucpop = 10, iudefs = 11, iufail = 13, iusum = 14)
c----67--1---------2---------3---------4---------5---------6---------7--
        open (unit=iucpop,status = 'NEW')
        open (unit=iudefs,status = 'NEW')
        open (unit=iufail,status = 'NEW')
        open (unit=iusum,status = 'NEW')
        open (unit=inunit,status = 'OLD')
c
c     input parameters
c
c  Analysis Duration
      read (inunit,*) nyear
c  Length of Track (miles,i5)
      read (inunit,*) ltrack
```

```
c  Initial Rail Age (MGT,f9.3)
      read (inunit,*) raili
c  Inspection Interval in MGT
      read (inunit,*) ainsp
c  Maximum Number of Miles Inspected per Day
      read (inunit,*) mipd
c  Acummulated Tonnage (MGT) per Year
      read (inunit,*) tonpy
c  Number of Days of Operation per Year
      read (inunit,*) ndpy
c  Number of Growth Curves (1 or 2)
      read (inunit,*) ncurve
c  Characteristic Life (MGT)
      read (inunit,*) beta
c  Minimum Detectable Crack Size (%ha,1. or 5.'
      read (inunit,*) dsize
c  Critical Crack Size (%ha)
      read (inunit,*) csize
c  Number of Defects Act Upon per Day
      read (inunit,*) nfix
c  output intervals (year)
      read (inunit,*) noint
c
      close(inunit)
c
      write (10,160)
      write (iudefs,160)
      write (13,160)
      write (14,160)
160   format (1x,'Input Data :',/)
      write (10,170) nyear
      write (iudefs,170) nyear
      write (13,170) nyear
      write (14,170) nyear
170   format (1x,'analysis duration = ',i3,' years')
      write (10,180) ltrack
      write (iudefs,180) ltrack
      write (13,180) ltrack
      write (14,180) ltrack
180   format (1x,'track length = ',i5,' miles')
      write (10,190) raili
      write (iudefs,190) raili
      write (13,190) raili
      write (14,190) raili
190   format (1x,'initial rail age = ',f9.3,' mgt')
      write (10,200) ainsp
      write (iudefs,200) ainsp
      write (13,200) ainsp
      write (14,200) ainsp
200   format (1x,'inspection interval =',f9.3,' mgt')
      write (10,210) mipd
      write (iudefs,210) mipd
      write (13,210) mipd
      write (14,210) mipd
```

```
210   format (1x,'number of miles inspected per day = ',i3,' miles')
      write (10,220) tonpy
      write (iudefs,220) tonpy
      write (13,220) tonpy
      write (14,220) tonpy
220   format (1x,'acummulated tonnage per year = ',f9.3,' mgt')
      write (10,230) ndpy
      write (iudefs,230) ndpy
      write (13,230) ndpy
      write (14,230) ndpy
230   format (1x,'number of days of operation per year = ',i3,' days')
      write (10,240) ncurve
      write (iudefs,240) ncurve
      write (13,240) ncurve
      write (14,240) ncurve
240   format (1x,'number of growth curves = ',i3)
      write (10,242) beta
      write (iudefs,242) beta
      write (13,242) beta
      write (14,242) beta
242   format (1x,'characteristic life =',f9.3)
      write (10,244) dsize
      write (iudefs,244) dsize
      write (13,244) dsize
      write (14,244) dsize
244   format (1x,'minimum detectable crack size =',f9.3,' %ha')
      write (10,250) csize
      write (iudefs,250) csize
      write (13,250) csize
      write (14,250) csize
250   format (1x,'critical crack size =',f9.3,' %ha')
      write (10,260) nfix
      write (iudefs,260) nfix
      write (13,260) nfix
      write (14,260) nfix
260   format (1x,'number of defects act upon per day =',i3)
      write (10,270) noint
      write (iudefs,270) noint
      write (13,270) noint
      write (14,270) noint
270   format (1x,'output intervals =',i3,' years',//)
c
      call defsiz(dsize, csize)
c
c  process return values
      nday  = nyear*ndpy + 100
      tonpd = tonpy/ndpy
c  determine target day for next inspection, next report next season
      inday = ainsp/tonpy*ndpy
      nipy=tonpy/ainsp
      knday = inday
      noday = noint*ndpy
      koday = noday
      ncvday = ndpy/2 + 1
```

```
      kcvday = ncvday
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      entry action(iday, inspct, report, season)
c
      if(iday .lt. knday ) then
        inspct = .false.
      else
        inspct = .true.
        knday    = knday   + inday
      end if
c
      if( iday .lt. koday ) then
        report = .false.
      else
        report = .true.
        koday   = koday + noday
      end if
c
      if( iday .lt. kcvday ) then
        season = .false.
      else
        season = .true.
        kcvday   = kcvday + ncvday
      end if
c
      return
      end
```

```
      subroutine occur(raila,aton,ltrack,beta,tonpd)
c
c  Monte Carlo Analysis of Subdivision Rail Test
c     Defect Occurrence Rate; called once per day
c
c----67--1---------2---------3---------4---------5---------6---------7--
      integer ltrack
      real raila, aton, beta, tonpd
      double precision x,rand
c
      real amgt, bmgt
      integer k
c
c     amgt = tonnage interval expected to produce the next defect
c     bmgt = age accumulation for defect occurances per day
c  next day's mileage
      bmgt = raila + tonpd
c
c  set target for next defect
      amgt = (beta**3*exp((raila/beta)**3))/(810.*ltrack*raila**2)
c
c     call random generator to determine mile post location
c
   10 continue
      x = rand()
      if (x.eq.0.) go to 10
c  set the mile #
      k = int(ltrack*x) + 1
      if (k .gt. ltrack) ndmp = ltrack
c     update defect sizes and locations
      call stsize(k)
c  update target mileage
      aton = aton + amgt
c  check for more than one defect per day
      if (aton .lt. bmgt) go to 10
c
      return
      end
```

```
      subroutine  growth (tonpd, ltrack, ninsp)
c----67--1---------2---------3---------4---------5---------6---------7--
c   Monte Carlo Analysis of Subdivision Rail Test Defect Growth
c     bp edit May-july, 1994
c
c   this routine holds and processes the crack population
c        GROWTH - extends existing cracks for each days' traffic
c  ENTRY RDGROW - reads ncurve sets of crack growth data
c  ENTRY GTISIZ - returns initial (smallest) crack size
c  ENTRY FIX    - removes ALL detected cracks from detection population
c                 noncritical cracks are transferred to arrays for growth
c  ENTRY STSIZE - adds initial size crack #j at mile i
c  ENTRY GTSIZE - returns crack #j at mile i
c  ENTRY GTNDEf - returns # cracks at mile i
c  ENTRY REPTGR - output of crack population
c----67--1---------2---------3---------4---------5---------6---------7--
c     ifail      - service failure counter
c     ndir       - total number of defects in rail
c----67--1---------2---------3---------4---------5---------6---------7--
c  limits for # of miles; items per mile; items per interval
      integer ntm, maxdpm, maxdpi
      parameter (ntm = 1000, maxdpm = 100)
c  integer arrays
c     ndefm(i)    - total number of defects at the ith mile post
      integer   ndefm(ntm)
c  real arrays
c     sdef(i,j)  - size of defect for the jth defect and ith mile post
      real      sdef(ntm, maxdpm)
c
c     save ndefm, sdef
c
      real tonpd, cracki, size, ccmax, rate, sized, asize
      integer ltrack, ninsp, ncurve, imile, ndef, n2fix, ndir, jdir, jfail
      logical debug, grew
      integer nbig(5)
c  entry RDGROW declarations
      integer mpt, mcrv
      parameter ( mcrv = 2, mpt = 16 )
      integer ncurv, i, j, kfail, ii
      integer nump(mcrv)
      real a(mpt,mcrv),dmgt(mpt,mcrv)
c
      save nump,dmgt,a,ncurv,cracki
c
      real cmgt(mpt),slope(mpt-1)
      parameter ( mxfail = 90000 )
      integer m(mxfail), ifail
      real    s(mxfail)
      save    ifail, m, s
c----67--1---------2---------3---------4---------5---------6---------7--
      cracki  = a(1,ninsp)
      cmgt(1) = dmgt(1,ninsp)
c  find nump - 1 slopes
      do 120 i = 2, nump(ninsp)
```

```
        denom   = dmgt(i,ninsp)
        cmgt(i) = cmgt(i-1) + dmgt(i,ninsp)
        if (denom .eq. 0.0) then
          slope(i) = 0.0
        else
          slope(i) = ( a(i,ninsp)-a(i-1,ninsp) )/denom
        endif
120   continue
c
      do 200 i = 1, ltrack
        if (ndefm(i).gt.0) then
          do 150 j = 1, ndefm(i)
            crack = sdef(i,j)
            grew = .false.
c  find interval for each crack
c  no crack can be smaller than initial size
            do 130 ic = 2, nump(ninsp)
              if (crack .lt. a(ic,ninsp) ) then
                if (.not.grew) then
                  crack = crack + tonpd*slope(ic)
                  sdef(i,j) = crack
                  grew = .true.
                end if
              end if
130         continue
c  if crack has not grown => failure
            if (.not.grew) then
              ifail    = ifail + 1
              m(ifail) = i
              s(ifail) = crack
c
              if (ndefm(i).gt.1) then
c   move crack counters down; removes candidate crack
                do 140 ii = j, ndefm(i)-1
                  sdef(i,ii) = sdef(i,ii+1)
140             continue
              endif
c   fall through on only one crack; delete the highest one
              sdef(i,ndefm(i)) = 0.0
              ndefm(i) = ndefm(i) - 1
            end if
c  do the next defect
 150      continue
        endif
 200  continue
c
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      entry rdgrow(ncurve)
c----67--1---------2---------3---------4---------5---------6---------7--
c  init counters
      do 50 i = 1, ntm
        ndefm(i) = 0
        do 40 j = 1, maxdpm
```

```
          sdef(i,j) = 0.0
  40    continue
  50  continue
      ifail = 0
      do 70, i = 1, mxfail
        m(i) = 0
        s(i) = 0.0
  70  continue
c  read growth data
      ncurv = ncurve
      do 100 j = 1, ncurv
        junit = 19 + j
        open (unit=junit,'old')
        rewind junit
        read (junit,*) nump(j)
        read (junit,*) (a(i,j),dmgt(i,j),i=1,nump(j))
        close(junit)
  100 continue
c
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      entry fix (imile,ndef)
c----67--1---------2---------3---------4---------5---------6---------7--
      size = sdef(imile, ndef)
c  update crack population
      if (ndefm(imile) .gt. 1) then
        do 400 ii = ndef,ndefm(imile) - 1
          sdef(imile,ii) = sdef(imile,ii+1)
 400    continue
      endif
c  always decrement highest one
      sdef(imile, ndefm(imile)) = 0.0
      ndefm(imile) = ndefm(imile) - 1
c
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      entry gtsdef (imile,ndef,sized)
c----67--1---------2---------3---------4---------5---------6---------7--
      sized = sdef(imile,ndef)
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      entry stsize (imile)
c----67--1---------2---------3---------4---------5---------6---------7--
      ndefm(imile) = ndefm(imile) + 1
      sdef(imile,ndefm(imile) ) = cracki
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      entry gtndef (imile,ndef)
c----67--1---------2---------3---------4---------5---------6---------7--
      ndef = ndefm(imile)
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      entry reptgr(ltrack,jfail,jdir,debug)
c----67--1---------2---------3---------4---------5---------6---------7--
```

```
c   service failures output
c----67--1---------2---------3---------4---------5---------6---------7--
      write (13,1078) ifail
      write (10,1078) ifail
      if (ifail.eq.0) go to 550
      write (13,1090)
      do 500 ii=1,ifail
        write (13,1100) m(ii),s(ii)
  500 continue
  550 continue
c  prepare for a new year
      jfail = ifail
      ifail = 0
      do 600 i = 1, mxfail
        s(i) = 0.0
        m(i) = 0
  600 continue
c----67--1---------2---------3---------4---------5---------6---------7--
c    defects in rail output
c----67--1---------2---------3---------4---------5---------6---------7--
      ndir   = 0
      do 630 i=1, ltrack
        ndir = ndir + ndefm(i)
  630 continue
      jdir = ndir
      write (10,1114) ndir
c
      nclstr = 0
      do 635 i = 1, 5
        nbig(i)   = 0
  635 continue
      ccmax = 0.0
      asize = 0.0
c
      if(debug) write (10,1120)
      do 670 i=1, ltrack
        if (ndefm(i).gt.0) then
          do 650 j = 1, ndefm(i)
            if(ccmax .lt. sdef(i,j) ) ccmax = sdef(i,j)
            if(debug) write (10,1140) i,j,sdef(i,j)
            asize = asize + sdef(i,j)
            if(nclstr .lt. ndefm(i) ) nclstr = ndefm(i)
            if(sdef(i,j) .gt. 50.0 ) then
              nbig(5)   = nbig(5) + 1
            else if(sdef(i,j) .gt. 40.0 ) then
              nbig(4)   = nbig(4) + 1
            else if(sdef(i,j) .gt. 30.0 ) then
              nbig(3)   = nbig(3) + 1
            else if(sdef(i,j) .gt. 20.0 ) then
              nbig(2)   = nbig(2) + 1
            else if(sdef(i,j) .gt. 10.0 ) then
              nbig(1)   = nbig(1) + 1
            end if
  650     continue
```

```
          end if
   670 continue
        asize = asize/ndir
        write(10, 1130) ccmax
        write(10, 1150) asize
        rate = -1.*(asize - 1.)/16.
        rate = (1.- exp(rate))*100.
        write (10, 1145) rate
        write (10, 1135) nbig(1)
        write (10, 1136) nbig(2)
        write (10, 1137) nbig(3)
        write (10, 1138) nbig(4)
        write (10, 1139) nbig(5)
        write (10, 1125) nclstr
c
        return
c
 1078 format (/,1x,'number of service failure occurence = ',i5)
 1090 format (/,1x,'mile post #',12x,'crack sizes',/)
 1100 format (5x,i4,17x,f9.3)
c
 1114 format (/,1x,'defects still in rail = ',i3)
 1120 format (/,1x,'mile post # ',3x,'defect number',3x,
     +                  'defect size (%ha)')
 1140 format (5x,i4,10x,i3,10x,f9.3)
 1130 format (/1x, 'maximum defect left in rail = ',f9.3)
 1125 format (/,1x,'maximim defects per mile = ',i3)
 1135 format (/,1x,'# of flaws > 10% = ',i3)
 1136 format (/,1x,'# of flaws > 20% = ',i3)
 1137 format (/,1x,'# of flaws > 30% = ',i3)
 1138 format (/,1x,'# of flaws > 40% = ',i3)
 1139 format (/,1x,'# of flaws > 50% = ',i3)
 1150 format (/1x, 'average defect size = ',f9.3)
 1145 format (/1x, 'expected average detection rate = ',f9.3)
 1155 format (/1x, 'average  large defect size = ',f9.3)
 1165 format (/1x, 'expected large crack detection rate = ',f9.3)
c----67--1---------2---------3---------4---------5---------6---------7--
      end
```

```
      subroutine defdet(imile,ndef,icount,n15,n25,ng25)
c----67--1---------2---------3---------4---------5---------6---------7--
c     Monte Carlo Analysis of Subdivision Rail Test
c     Defect Detection Probability
c
      integer ndef,imile,ndre
      real amin,acrit
c
      double precision x, rand, prob
      real dsize,csize
      real size, factor
      save dsize, csize
c----67--1---------2---------3---------4---------5---------6---------7--
      call gtsdef(imile,ndef,size)
c  can crack be detected /
      if (size .ge. dsize) then
c
        if (dsize.eq.1.) then
          factor = -1.*(size - 1.)/16.
        else if (dsize.eq.5.) then
          factor = -1.*(size - 5.)/14.
        else if (dsize.eq.3.) then
          factor = -1.*((size - 3.)/.636)**.35
        end if
c
   10   continue
        x = rand()
        if (x .le. 0.) go to 10
c
        prob = 1.- exp(factor)
c
        if (x. gt. prob) then
c  go on to the next crack
          ndef = ndef + 1
        else
c  crack is detected
c
c   sort crack sizes into bins
c
          if (size.le.15.) n15=n15+1
          if (size.gt.15..and.size.le.25.) n25=n25+1
          if (size.gt.25.) ng25=ng25+1
c
          if (size .1t. csize) then
c   save noncritical counts in OUTPUT
            call svdet(imile, size)
          else
c   increment removal and save critical counts in OUTPUT
            icount = icount + 1
            call svcdet(imile, size)
          endif
c   FIX decrements ndef to match flaw removal
          call fix (imile,ndef)
        endif
```

```
      else
c  go on to the next crack; crack is too small to be detected
        ndef = ndef + 1
      endif
c
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      entry  defsiz(amin,acrit)
c----67--1---------2---------3---------4---------5---------6---------7--
c   get sizes for minimum detectable crack - dsize &
c   critical crack size                    - csize
      dsize = amin
      csize = acrit
c
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      end
```

```
      subroutine reprt(ltrack,raila,mday,m1day,iday,iyear,debug)
c
c     Monte Carlo Analysis of Subdivision Rail Test
c     Output Data
c
c----67--1---------2---------3---------4---------5---------6---------7--
c     ndet        - number of defects detected
c     ncfound     - number of critical defects detected
c     nfound      - number of defects detected per inspection interval
c     mcflag(i)   - mile post number for critical detected defect
c                   (per inspection interval)
c     mflag(i)    - mile post number for the detected defect
c                   (per inspection interval)
c     scflag(i)   - size of defects found (per inspection interval)
c     sflag(i)    - size of defects found (per inspection interval)
c
      integer ltrack, mday, m1day, iday, iyear
      logical debug
c
      integer ndet, ncfound, nfound, imile, ifail, ndir, nmade
c
      save    ndet, ncfound, nfound, nmade
c
      real    size, rate1, rate2
      integer mxfnd, i
c
      parameter ( mxfnd = 500000)
      integer mflag(mxfnd), mcflag(mxfnd)
      real    sflag(mxfnd), scflag(mxfnd)

      save    mflag, sflag, mcflag, scflag
c
      integer iucpop, iudefs, iufail, iusum
      parameter(iucpop = 10, iudefs = 11, iufail = 13, iusum = 14)
c----67--1---------2---------3---------4---------5---------6---------7--
c  population header
      write (iucpop,5)
      write (iucpop,10) iyear,iday
      write (iucpop,12) raila
c  defects detected header
      write (iudefs,5)
      write (iudefs,10) iyear,iday
      write (iudefs,12) raila
c  failures header
      write (iufail,5)
      write (iufail,10) iyear,iday
      write (iufail,12) raila
c
    5 format (///,1x,66(1h*))
   10 format (//,1x,'YEAR ',i3,',  DAY ',i5,/)
   12 format (1x,'accumulated tonnage = ',f9.3,' mgt')
c----67--1---------2---------3---------4---------5---------6---------7--
C   critical cracks detected(and removed) output
c----67--1---------2---------3---------4---------5---------6---------7--
```

```
      write (iudefs,71) ncfound
      if (ncfound.eq.0) go to 73
      write (iudefs,90)
      do 72 jj = 1,ncfound
        write (iudefs,100) mcflag(jj),scflag(jj)
72    continue
   71 format (/,1x,'number of critical defects detected = ',i4)
   90 format (/,1x,'mile post #',12x,'crack sizes',/)
  100 format (5x,i5,16x,f9.3)
c----67--1---------2---------3---------4---------5---------6---------7--
C   non-critical cracks detected output
c----67--1---------2---------3---------4---------5---------6---------7--
73    continue
      write (iudefs,74) nfound
      if (nfound.eq.0) go to 77
      write (iudefs,90)
      do 75 j=1,nfound
        write (iudefs,100) mflag(j),sflag(j)
75    continue
74    format (/,1x,'number of noncritical defects detected = ',i3)
c----67--1---------2---------3---------4---------5---------6---------7--
77    continue
c  write failure & defect population reports
      call reptgr(ltrack,ifail,ndir,debug)
c----67--1---------2---------3---------4---------5---------6---------7--
C   summary output
c----67--1---------2---------3---------4---------5---------6---------7--
      if (iyear.eq.1) then
c
         nmade = 0
c summary header
         write (iusum,1017)
         write (iusum,1020)
         write (iusum,1030)
         write (iusum,1031)
         write (iusum,1032)
c
         write (*,1030)
         write (*,1031)
         write (*,1032)
      endif
c  yearly results
      write (iusum,1040) iyear,ndir,ndet,ncfound,nfound,ifail,mday,m1day
      write (*,1040)     iyear,ndir,ndet,ncfound,nfound,ifail,mday,m1day
      write (31,1100)       iyear, ndet, ifail, mday
c
      nmade = ndir + ndet - nmade
c
      rate1 = float(ndet)*100./float(ndir + ndet)
      rate2 = float(ifail)*100./float(ndet)
c  diagnostic results
      write (iucpop,1045 ) m1day
      write (iucpop,1050 ) nmade
      write (iucpop,1060 ) rate1
```

```
      write (iucpop,1070 ) rate2
      return
 1017 format (1x,66(1h*))
 1020 format (/////,19x,'Summary of Rail Defects History')
 1030 format (//,'year ',
     +'defects total   critical noncritical service days     days')
 1031 format (5x,
     +'in rail defects defects  defects     failure repaired stopped')
 1032 format (5x,
     +'         found   detected detected',/)
 1040 format (i3,3x,i4,3x,i4,6x,i4,4x,i3,6x,i4,5x,i3,6x,i3)
c
 1045 format (/,1x, ' # of days stopped by repair limit =   ', i4 )
 1050 format (/,1x, ' # of cracks generated this year =  ', i4 )
 1060 format (/,1x, ' detection rate for this year    =  ', f5.1 ,' %')
 1070 format (/,1x, ' failure rate for this year      =  ', f5.1 ,' %')
 1100 format (4i4)
c----67--1---------2---------3---------4---------5---------6---------7--
      entry opinit(iyear)
c----67--1---------2---------3---------4---------5---------6---------7--
c   increment year (assumes report interval)
      iyear = iyear + 1
      do 400 i = 1, mxfnd
        sflag(i)  = 0.0
        mflag(i)  = 0
c
        scflag(i) = 0.0
        mcflag(i) = 0
  400 continue
      nfound  = 0
      ncfound = 0
c
      ndet = 0
c
      return
c
c----67--1---------2---------3---------4---------5---------6---------7--
      entry svdet(imile, size)
c  keep track of noncritical defects
c----67--1---------2---------3---------4---------5---------6---------7--
      ndet   = ndet +1
      nfound = nfound + 1
      mflag(nfound) = imile
      sflag(nfound) = size
c
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      entry svcdet(imile, size)
c  keep track of critical defects
c----67--1---------2---------3---------4---------5---------6---------7--
      ndet    = ndet + 1
      ncfound = ncfound + 1
      mcflag(ncfound) = imile
      scflag(ncfound) = size
```

```
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      entry dstdef(iyear,nspct,n15,n25,ng25)
      if (iyear.eq.1.and.nspct.eq.1) then
          write (15,110) iyear,nspct,n15,n25,ng25
110       format (3x,i2,4x,i2,7x,i5,10x,i5,11x,i5)
          nyear=iyear
      endif
      if(iyear.eq.nyear) then
         write (15,120) nspct,n15,n25,ng25
120      format (9x,i2,7x,i5,10x,i5,11x,i5)
      elseif(iyear.ne.nyear) then
         nspct=1
         if (iyear.ne.1)then
              ntot=nsum15+nsum25+nsumg25
              ntg15=nsum25+nsumg25
              pg15=float(ntg15)/float(ntot)
              pg25=float(nsumg25)/float(ntot)
              write (15,121)
121           format (75('-'))
              write (15,125) nsum15,nsum25,ntg15,pg15,nsumg25,pg25,ntot
125           format (18x,i5,12x,i3,2x,i3,2x,f4.2,2x,i3,2x,f4.2,2x,i4)
              write (15,121)
         endif
         write (15,110) iyear,nspct,n15,n25,ng25
         nyear=iyear
         nsum15=0
         nsum25=0
         nsumg25=0
      endif
      nsum15=nsum15+n15
      nsum25=nsum25+n25
      nsumg25=nsumg25+ng25
      ntotal=nsum15+nsum25+nsumg25
      ntg15=nsum25+nsumg25
      n15=0
      n25=0
      ng25=0
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      end
```

```
      subroutine averg(ltrack,iyear,nipy)
c----67--1---------2---------3---------4---------5---------6---------7--
      integer ltrack, iyear
c
      logical here
      integer nruns, nyear, n
      parameter( nyear = 20 )
      integer iy(nyear)
      real    andf(nyear), ansf(nyear), andr(nyear), psf, ampd
      integer iytmp, ndftmp, nsftmp, ndrtmp
c----67--1---------2---------3---------4---------5---------6---------7--
c
C      here = .false.
C      iunit = 30
C      inquire(unit = iunit, EXIST = here )
c  header
      write(*,1000)
c
C      if (here) then
         read (30, 1100) nruns
         if (nruns .gt. 0) then
           do 100 n = 1, iyear
             read (30, *) iy(n),andf(n),ansf(n),psf,andr(n),ampd
  100      continue
           do 200 n = 1, iyear
             andf(n) = nruns*andf(n)
             ansf(n) = nruns*ansf(n)
             andr(n) = nruns*andr(n)
  200      continue
         else
c  new file
          nruns = 0
          do 300 n = 1, iyear
            iy(n)   = n
            andf(n) = 0.
            ansf(n) = 0.
            andr(n) = 0.
  300     continue
        end if
c
      rewind(30)
      rewind(31)
c
      nruns = nruns + 1
      write(30,1100) nruns
c read new data
      do 400 n = 1, iyear
        read(31,1120) iytmp, ndftmp, nsftmp, ndrtmp
c calculate new averages
        andf(n) = (andf(n) + float(ndftmp))/nruns
        ansf(n) = (ansf(n) + float(nsftmp))/nruns
        andr(n) = (andr(n) + float(ndrtmp))/nruns
        psf     = (ansf(n)*100.)/andf(n)
        ampd    = float(ltrack*nipy)/andr(n)
```

```
        write (30, 1010) iy(n), andf(n), ansf(n), psf, andr(n), ampd
        write (*, 1010)iy(n), andf(n), ansf(n), psf, andr(n), ampd
  400 continue
c
      return
c----67--1---------2---------3---------4---------5---------6---------7--
 1000 format (/,1x,'year',5x,'defects',6x,'service',6x,'% service'
     1          ,6x,'days',6x,'miles/day',/,11x,'found',7x,'failure'
     1          ,7x,'failure',5x,'repaired',4x,'repaired',/)
 1010 format (1x,i3,5(6x,f7.2))
 1100 format (i4)
 1120 format (4i4)
 1110 format (i4, 5f10.3)
      end
```

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