Risk/Benefit Assessment of Delayed Action Concept for Rail Inspection

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Administration**

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13. ABSTRACT (Maximum 200 words)

A Monte Carlo simulation of certain aspects of rail inspection is presented. The simulation is used to investigate alternative practices in railroad rail inspection programs. Results are presented to compare the present practice of immediately repairing every detected defect with an alternative practice under which repair can be delayed for defects not exceeding a specified size. The sensitivities of inspection vehicle utilization and rail failure rate to variations of inspection frequency, repair gang capacity, and traffic tonnage are presented. A risk/benefit assessment of delayed action, relative to present practice, is developed and carried out to compare the risk of rail failure due to incorrect classification of defect size with the benefit of rail failure prevention due to increased opportunity to detect large defects.

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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 (km)	=	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 (ha) = 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

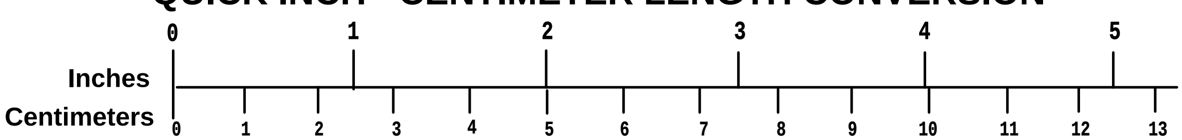
VOLUME (APPROXIMATE)

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

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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PREFACE

In 1993, the Track Safety Research Division, Office of Research and Development, Federal Railroad Administration (FRA), asked the Volpe National Transportation Systems Center to begin exploring the application of risk/benefit models to assess the procedures regulated by the Track Safety Standards (49 CFR 213). This report summarizes a project carried out by the Volpe Center, in response to the FRA request, on comparative assessment of two alternative procedures for scheduling repair of detected rail defects. One procedure (an existing practice) requires immediate repair of every defect and thus limits rail inspection to the pace of the repair gang. Under the other procedure, certain small size defects can be left for a follow-up gang, and the inspection proceeds more or less at its own pace. The project objective was to develop and apply models of the inspection process to quantitatively assess the delayed action procedure in terms of the potentials for: (1) improving the pace of inspection; (2) reducing the rate of rail breaks from undetected defects, via increased detection opportunity provided by faster pace; and (3) increasing the rate of rail breaks due to delay in repairing detected defects.

To quantitatively model such inspection processes makes it necessary to deal with input variables that are difficult to characterize. For example, earlier research has shown that rail defect formation and growth rates depend strongly on traffic tonnage and ambient temperature (the latter effect arising through tension induced in the rail); both tonnage and temperature experience daily fluctuations that are not readily predictable. Other significant and equally unpredictable inputs are the locations of individual defects, e.g. by track milepost, and the performance of inspection equipment. Moreover, the relations between these inputs and the desired outputs are nonlinear and discontinuous.

To model the process under such circumstances requires a numerical simulation based on the well-known Monte Carlo method. A digital computer program encompassing the input-output relations is run repeatedly, each execution being based on random selections of input values. One can imagine each outcome as the result of a series of coin flips or rolls of the dice (hence the name of the method). Each difficult-to-predict input is assumed to behave as an idealized random variable, characterized by a probability distribution with a specified average and standard deviation. Random values are obtained when standard library software is used to repeatedly sample the probability distribution.

The convenience and power of the Monte Carlo method can tempt the unwary to over-elaborate a risk/benefit model, simply because it is as easy to deal with more random variables as with fewer. More superficially equals better because each decision to treat an input as a random variable means one less chance to bias the model. However, this overlooks the facts that: (1) risk/benefit assessments depend on the differential input-output relations (how much does a change of an input value change the output); and (2) the differential results are usually quite sensitive to the input values. In practice, this means that the input-output results must reasonably agree with actual observations, or the risk/benefit results will be unrealistic. Therefore, it is essential to constrain any Monte Carlo model by calibrating the inputs against actual data, and to avoid the temptation to extrapolate risk/benefit conclusions.

Also, there is often a practical limit on the kind and quantity of available data (as is the situation in the present case). Under such circumstances, the need to constrain the model conflicts with the desire to enlarge the roster of random variables. The present authors have chosen to constrain their model, reducing the Monte Carlo portion to the two least predictable inputs (defect location and the detection/non-detection event per inspection opportunity). Other inputs which might have been treated as random variables have instead been characterized in terms of average quantities. In the authors' judgment, however, the potential bias thus introduced is far outweighed by calibration of the model to input-output results based on field experience.

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EXECUTIVE SUMMARY

This report covers the development and application of a risk/benefit model for comparative evaluation of two alternative procedures for managing rail inspection and defect repair. The work was carried out by the Volpe National Transportation Systems Center (Volpe Center), at the request of the Federal Railroad Administration (FRA) Office of Research and Development, to provide technical support to the FRA Office of Safety.

The Track Safety Standards require railroads to periodically inspect rail on lines where operating speeds exceed 40 mph (49 CFR §213.237) and to take immediate action to preserve operational safety whenever a rail defect is discovered (49 CFR §213.113). The immediate action may be a speed restriction, temporary repair, or permanent repair. Railroads generally make immediate repairs on heavy haul lines, in order to minimize disruption of revenue traffic, by organizing a chase gang to follow the inspection vehicle ("detector car"). Since the number of repairs per day is limited by chase gang work rules and access to track between trains, the practice of immediate repair has led to the restriction of detector car operations through territories with high concentrations of rail defects.

In 1993, the Union Pacific Railroad, reviewing its inspection records for the preceding three years, noted a decreasing trend in average daily track miles inspected. The railroad also noted a corresponding trend toward greater percentages of rail defects being discovered by means other than scheduled detector car operations. These "service defects", especially internal defects in the railhead, are often discovered as a result of a complete break, and such rail failures increase the risk of train derailment.

The railroad proposed to the FRA an alternative practice to reverse these trends without disrupting revenue traffic. For defects not exceeding a specified size ("non-critical" defects), deferral of repair or other action would be permitted, provided that a follow-up gang completed the delayed action within a specified grace period. This would enable the detector car and chase gang to continue the inspection, thereby increasing the opportunity to find and repair larger defects. The proposal was consistent with earlier research results developed by the Volpe Center; namely, that rail defects tend to grow slowly and steadily under the influence of train loads, and that larger defects pose greater risks of rail failure than small defects. As the FRA Office of Safety began its evaluation of the railroad's proposal, the Volpe Center started a technical support project to develop a computer simulation of the rail inspection process, for the purpose of comparing the present practice of immediate repair with the proposed practice of delayed action on small defects. The simulation is referred to as the rail flaw detection (RFD) model.

In 1994, the FRA granted the Union Pacific Railroad a test waiver for trial of delayed action on two heavy haul line segments crossing southern Wyoming and western Nebraska. The initial trial was conducted over six months of warm weather (June to November). The waiver was subsequently modified and extended to allow the railroad to conduct a system-wide trial of delayed action. Field data from the initial trial was furnished to the FRA and used by the Volpe Center to calibrate the RFD model.

Sections 2 and 3 of this report document the model development and calibration. The RFD model simulates a hypothetical single-track subdivision with uniform traffic, rail age, and seasonal weather. Hypothetical rail defects are then generated in quantities and at times consistent with these characteristics. Each defect is randomly assigned to a milepost on the subdivision, and its increasing size is tracked as time and traffic pass.

Inspection is simulated by following the progress of a hypothetical detector car across the subdivision. As the car encounters each defect, a detection or non-detection event is generated from an assumed equipment performance characteristic that assigns chance of detection in accordance with defect size at the time of the encounter. Defects that go undetected until they become large enough to cause a rail failure under normal operating conditions are counted as service defects.

The detector car is allowed to inspect 30 miles per day, unless restricted by a repair gang capacity. For present practice, the restriction comes into effect if the number of detected defects reaches the daily capacity of the chase gang. For delayed action, non-critical detected defects are omitted from the daily count but are accumulated in a backlog file. The detector car is then restricted only if the daily count of critical defects reaches the chase gang capacity, or if the backlog of non-critical defects reaches the capacity of the follow-up gang for repair within the grace period.

A single inspection is defined to be complete when the detector car has covered the entire subdivision. Two or more inspections per year are simulated, as specified in an input, and the simulation computes annualized statistics for the inspection program. Ten replicates of each analysis are executed and averaged to smooth out fluctuations.

The calibration demonstrates that the RFD model results are consistent with the field statistics derived from the Union Pacific Railroad inspection program. In the initial trial, the railroad applied delayed action on two lines carrying 60 and 160 million gross tons with two and four annual inspections, respectively. Of the defects detected during this trial, 55% were reported as exceeding the originally specified size limit for delayed action. For the same annual tonnage and inspection frequencies, simulations of the two lines produced corresponding figures of 50% and 63%, respectively. Also, the simulation computed service defect rates from 2% to 7% of detected defects, when the rate of detections was in the range of 0.25 to 0.7 defect per track mile per year. These figures are reasonably consistent with the railroad's system-wide statistics: a service defect rate of 5% and detections at 0.25 defect per track mile per year.

RFD model simulations incorporating seasonal weather and the terms of the modified waiver (Section 4) led to the following conclusions:

- In comparison with present practice, delayed action increases average detector car miles per day, thus increasing the opportunity to find critical defects, in territories with high detection rates (i.e., 0.5 to 0.7 defect per track mile per year).

- Delayed action can reduce the service defect rate, relative to the rate under present practice, in territories with very high detection rates (i.e., exceeding 0.7 defect per track mile per year).

- More frequent inspection can reduce the service defect rate.

- Keeping the number of annual inspections fixed, but scheduling the program to emphasize the colder months of the year can also reduce the service defect rate, relative to the rate with equal intervals between inspections. (The Union Pacific and other railroads generally try to follow this practice.)

A supplemental risk/benefit model was also developed and applied to the cases analyzed by the RFD model (Section 5). The purpose of the new model was to evaluate the risk of rail failures from non-critical defects, during the grace period, in comparison with the benefit of rail failures prevented via increased opportunity to detect critical defects. The risk was estimated by deriving, from results of a laboratory examination of defects, a formula for the probability that a critical defect might be incorrectly classified as non-critical, due to measurement error in the field. The risk was quantified by assuming that all such incorrectly classified defects would cause rail failures. (This assumption over-estimates the risk, but is the only basis for an unbiased numerical estimate.) The benefit was estimated from the extra miles inspected under delayed action, relative to present practice, for an equal number of days of detector car operation. In the extra miles, it was assumed that the detector car would find a number of defects in proportion to the average detection rate, and that a small fixed percentage of these defects would have been large enough to have caused rail failures, had the detector car not been given the extra opportunity.

Risk benefit calculations were carried out for the hypothetical subdivisions carrying 60 and 160 million gross tons annually and for detection rates from 0.25 to 1.0 defect per track mile per year. The results varied with both tonnage and detection rate, from a net risk of about 13% more rail failures to a net benefit of about 27% fewer rail failures. Net benefits were predicted at detection rates above 0.3 and 0.8 defects per track mile per year for the 60 and 160 million gross ton subdivisions, respectively.

The following conclusions were drawn from the results of the RFD model and risk/benefit model analyses. Assuming continued inspection of rail at current frequencies, including cold weather scheduling practice, and continued performance of detection and defect size estimation at current levels:

- Delayed action on non-critical defects is a worthwhile concept from the viewpoint of railroad safety.

- Delayed action can help to keep the overall service defect rate at a low level and is likely, in the long run, to avert more rail failures by providing increased detection opportunity than the number of rail failures that might be caused by incorrectly classified critical defects.

1. INTRODUCTION

This report summarizes a risk/benefit assessment of a concept for delayed remedial action on certain kinds of rail defects detected during scheduled rail inspections. The concept was developed by the Union Pacific Railroad (UPRR) and is being field tested by the UPRR under test waivers granted by the Federal Railroad Administration (FRA). This assessment is based on a Rail Flaw Detection (RFD) model developed earlier by the Volpe Center [1]. The RFD 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 [2,3]. The model is extensively based on the detail fracture (DF) because this is the most common type of rail defect in continuous welded rail (CWR) carrying heavy freight traffic, and also because the DF is the principal defect type for which delayed action is permitted under the test waivers.

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 delays. 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 workday.

Under the most recent test waiver, a grace period of five days is allowed before an action must be taken on DF defects not exceeding 25 percent of the rail head area (%HA). In the cold season, defined as November 15 to March 15, the grace period is restricted to four days above 0°F for defects not exceeding 20% HA. 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 of the concept 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 risk of rail failure from a delayed-action defect can be minimized but not totally eliminated. The earlier research [2] has been used to estimate the remaining safe life of a rail assumed (1) to contain a DF of size equal to the non-critical limit; and (2) to continue carrying loaded traffic combined with tension induced by cold weather. The calendar-day grace periods in the current test waiver are based on such estimates, together with a figure for average daily tonnage on the most heavily used line in the United States. These precautions make it extremely unlikely that a defect reserved for delayed action in accordance with the waiver would cause a rail failure. However, the possibility of such a rail failure cannot be denied because the research results do not describe DF defect behavior with absolute precision. In the present report, the risk is quantified by estimating the percentage of adversely misclassified DF defects and assuming that all such defects cause rail failures.

The safety benefit associated with delayed action results directly from the economic benefit of improved detector car utilization. Better car utilization increases the opportunity to find defects that have already grown to exceed 25% HA, i.e., defects posing the greatest risk of rail failure. The additional mileage inspected per day (as compared with existing practice under 49 CFR §213.113) is combined with the average defect rate (defects per track mile per year) and the percentage of high-risk defects to quantify the benefit of rail failures prevented.

2. RAIL FLAW DETECTION

The RFD model simulates a hypothetical 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 [2,3]. 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 Technology Center's Facility for Accelerated Service Testing (FAST) and on several segments of revenue track studied by the Association of American Railroads (AAR):

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

where T is the rail age in cumulative million gross tons (MGT) of traffic, 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: β = 1000 MGT on FAST, $\beta \geq$ 1500 MGT on 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 ($\Delta T << T$), 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:

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

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

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

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 about 0.5% 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 Technology Center [4]. 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 [2]. This model was calibrated from the original detail fracture growth test on FAST tangent track [5,6] 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 [4]. 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 DF growth curves used in the simulation model. These curves are simplified representations of the DF growth model results, intended to approximate the seasonal influence of thermal stress in CWR. Based on comparison with DF growth model calculations, the curve with the slowest growth rate represents rail at service temperatures within ±5°F of the CWR neutral temperature, whereas the curve with the fastest rate represents rail at service temperatures from 10 to 35 °F below the CWR neutral temperature. These bounding curves represent typical summer and winter conditions, respectively. In the simulation model, defect growth per MGT is projected from a seasonally adjusted rate, based on one of the curves shown in Figure 1, for each calendar month.

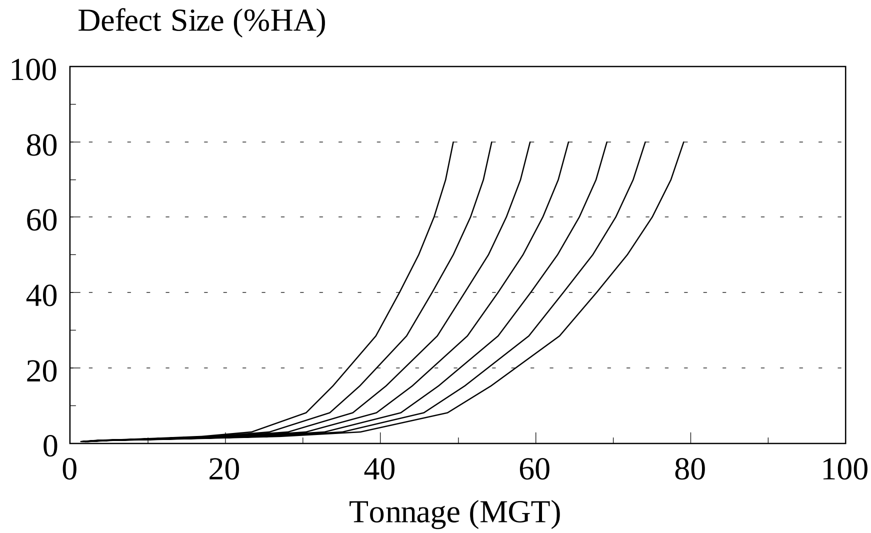


Figure 1. Detail fracture growth curves with varying service temperature.

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 (when inspected) will be detected.

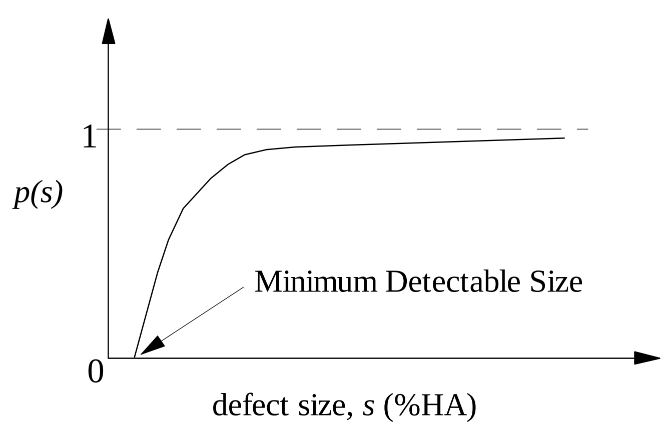


Figure 2. Detection probability curve.

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 any 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 give by [3]:

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

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° sensors per probe wheel. As an initial estimate for modeling of technology currently used by UPRR, the following curve has been adopted:

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

where s is greater than or equal to a minimum detectable size of 3% HA. The difference is that the newer equipment has an array of three 70° sensors per probe wheel to extend coverage toward the gage and field corners of the railhead. 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 [1]. 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. In particular, 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 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 are 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 AND CALIBRATION

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 unit uniform distribution). 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 1500 MGT for low to medium annual tonnages or 5000 MGT for high annual tonnage. 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 [7]. 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 about 0.5% HA as of its occurrence date. The defect growth rate depends on both the size of the crack and the season. The size of each defect is increased each day by linear interpolation of the growth rate curve for the appropriate calendar month (Figure 1), based on 1/365 of the annual tonnage.

The detection process is simulated by 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 defined if the random value is greater than $p(s)$, where $p(s)$ is the detection probability defined by equation (5) (see Section 2.3). If a defect grows to 80% HA before detection, it is assumed to cause a rail failure and is counted as a service defect.

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.

Three limits are placed on the number of miles inspected per day. First, an absolute limit of 30 miles per day is enforced to represent the best achievable track occupancy for the detector car. The 30-mile figure reflects a typical constraint resulting from conflicts with revenue traffic on heavy haul freight lines. 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 six critical defects per day is used as the baseline. Third, a baseline limit of six non-critical defects per day is imposed for repairs by the second gang. In this case, however, the limit does not affect the detector car unless the allowable backlog (6 defects per day times number of grace days) is exceeded. The simulation keeps a running tally of the backlog by adding the number of non-critical defects detected and subtracting the number (up to 6) repaired each day.

The RFD model was calibrated by adjusting the defect detection probability and growth rate parameters to bring the simulated defect statistics into agreement with field experience. The comparison was based on the UPRR system-wide averages of 0.25 defect per track mile per year and service defects at 5% of detected defects, together with a breakdown by size of defects detected by the railroad during the initial field trial of delayed action.

The initial trial was conducted during June to 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. From the reports of detected defects, some 455 transverse internal railhead defects[1] for which size estimates in %HA were reported. Of the total, 252 defects or 55% were classified as exceeding 15% HA, and 143 or 31% were classified as exceeding 25% HA. With RFD model parameters as given in Section 2, the simulation produced the comparable statistics summarized in Table 2.

[1] UPRR reports defects in the following classifications: DIW (defective in-track flash butt weld), DFW (defective field weld), DPW (defective plant weld), and TD (transverse defect). Most of the reported detections were classified TD, a nomenclature used by the railroad to indicate detail fractures (DF).

Table 2. Comparison of RFD Model with UPRR Experience.

Track	Annual Tonnage (MGT)	Inspections per Year	Percentage of Defects Exceeding		Defects per Track Mile per Year	Service Defects (% of Detected Defects)
			15% HA	25% HA		
UPRR	60 160	2 4	} 55	} 31	} 0.25 [a]	} 5 [a]
RFD model [b]	60 160	2 4	50 63	28 45	} 0.25 - 0.7	2 7

[a] System-wide average [b] Using slowest (summer season) defect growth rate

4. SIMULATION RESULTS

Selected results from the RFD model analyses are presented below. Since the β factor for defect formation rate (Section 2.1) and the model calendar scale are idealized, the results have been cross-plotted to avoid the difficulty of attempting to interpret the meaning of these parameters with respect to actual track environments. The RFD model results of most interest are the service defect rate (as a percentage of detected defects) and detector car utilization (average miles per day). The annual data for each quantity has been averaged and cross-plotted versus detected defects per track mile per year.

4.1 SEASONAL EFFECT

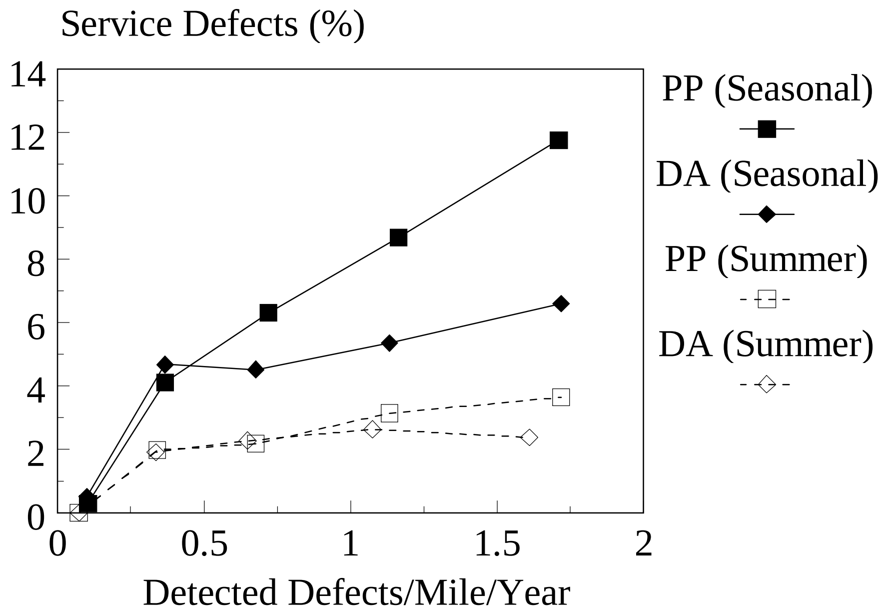
A hypothetical track carrying 60 MGT per year with two inspections annually was analyzed to illustrate the recently developed seasonally varying defect growth rate feature. The four plots in each graph (Figure 3) compare the effect of seasonal (solid lines) versus slowest summer (dashed lines) defect growth rate for both the present practice of immediate repair (PP, square symbol) and the delayed action practice under the current waiver (DA, diamond symbol).

The seasonal effect is manifested as a higher percentage of service defects, relative to the percentage obtained when the slowest summer growth rate is used. Detector car utilization is not affected by the defect growth rate, but delayed action preserves near-maximum car miles per day for defect rates up to 0.7 defect per track mile per year. Conversely, the rapid decline in car miles per day under present practice reflects the restrictive effect of repair gang limits. When the seasonal variation of defect growth rate is accounted for, delayed action also exhibits a benefit of reduced service defect percentage for detected defect rates exceeding 0.7 per track mile per year.

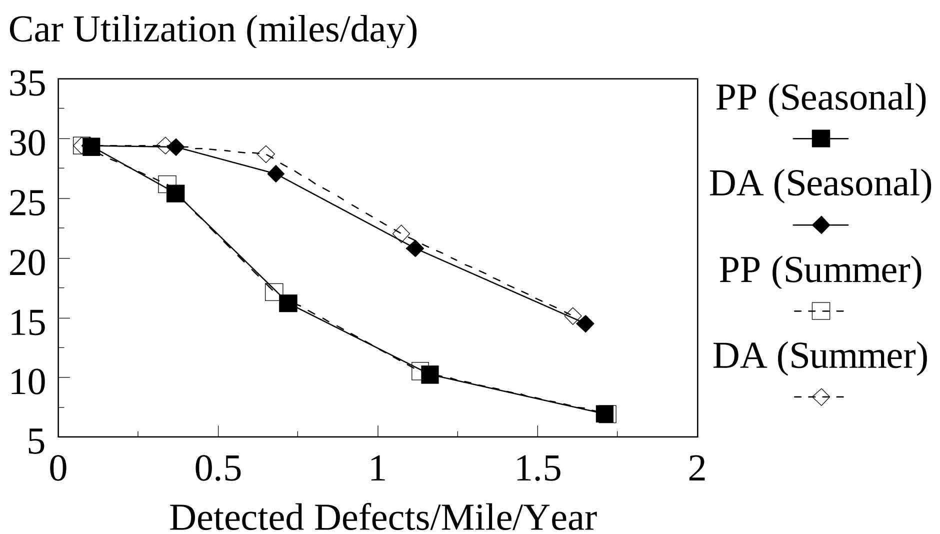
4.2 ILLUSTRATION OF SENSITIVITIES

Several additional cases of the hypothetical line carrying 60 MGT per year were analyzed to demonstrate the extent to which inspection program performance might be altered by changing schedule or capacity. In all of the following cases, the RFD model was run with seasonal adjustment of the defect growth rate.

Figure 4 illustrates the effect of increased inspection frequency. The previous case of two inspections per year (solid lines) is compared with a case of three inspections per year (dashed lines). The more frequent inspection enables present practice to maintain the same service defect percentage as delayed action, at a level much lower than the service defect percentage with two inspections per year.

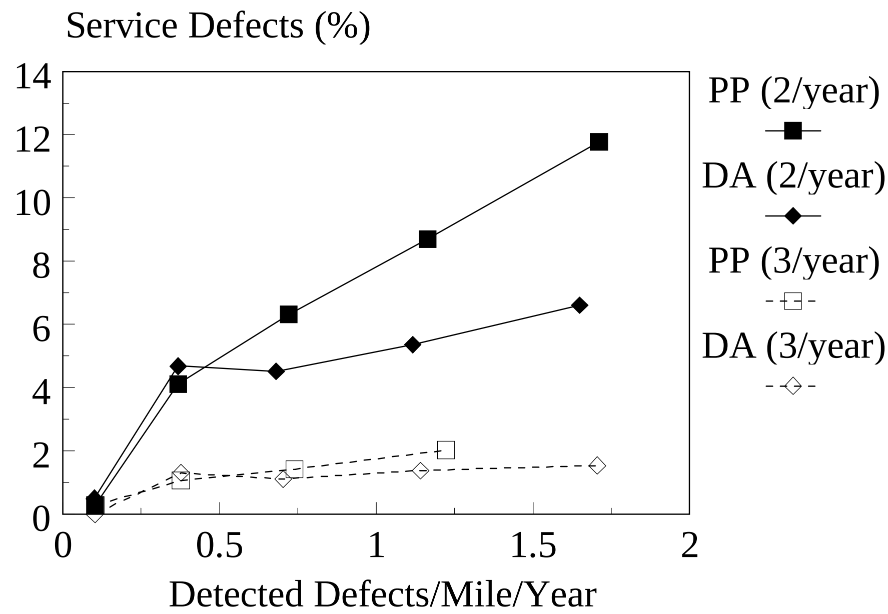


(a) Service defect rate.

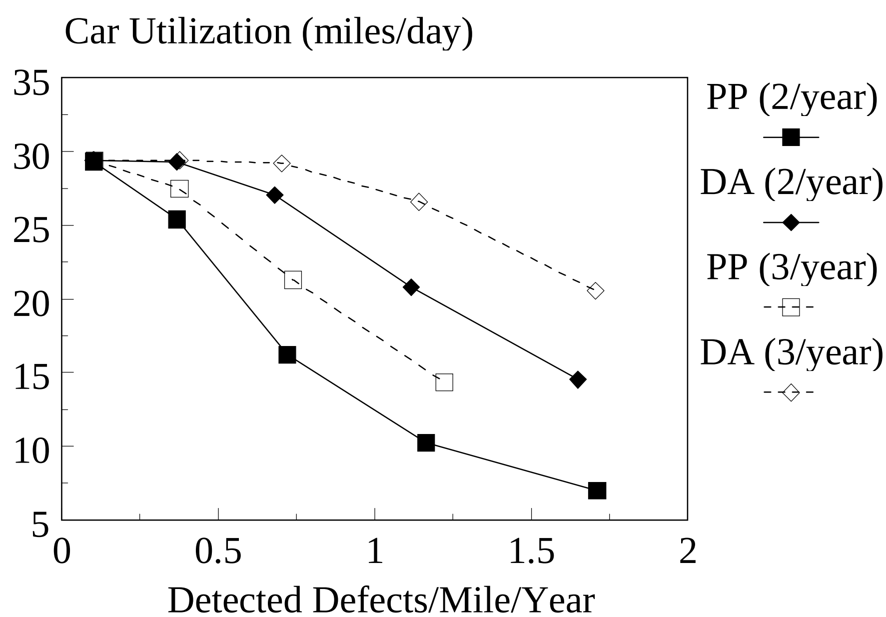


(b) Detector car utilization.

Figure 3. Seasonal effect for 60 MGT/year traffic density.



(a) Service defect rate.



(b) Detector car utilization.

Figure 4. Inspection interval effect for 60 MGT/year traffic density.

The higher inspection frequency also leads to about 50% more car miles per day if present practice is followed. Since there is also 50% more inspection, this result implies no net change in the total number of car days required to complete the annual inspection program. Conversely, the higher inspection frequency leads to somewhat less than 50% extra car miles per day if delayed action is followed, i.e., a modest increase of car days to complete the annual program.

Figure 5 shows the effect of increasing capacity for immediate repair. The normal circumstance of up to 6 repairs per day is compared with a hypothetical organization, in which two chase gangs leapfrog each other to increase the immediate repair capacity to 12 defects per day. A doubled chase gang operating under present practice has the same effects on service defect percentage and car miles per day as a single chase gang operating under delayed action. Doubling the gang in combination with delayed action produces no further decrease of service defect percentage, but does increase detector car miles per day.

When the delayed action practice is followed, a second gang is organized to repair non-critical defects within the allowed grace period. Detector car operation is not restricted by the second gang, unless the backlog of non-critical defects becomes large enough to consume the entire grace period. The potential effect was tested by means of a case in which the second gang capacity was doubled from 6 to 12 repairs per day. Comparison with the baseline case shows no effect on either service defect percentage or car miles (Figure 6), indicating that the normal capacity of 6 repairs per day has not restricted detector car inspection conducted twice annually on a line carrying 60 MGT per year.

4.3 EFFECT OF INSPECTION FREQUENCY ON HIGH-DENSITY LINE

Several additional cases were analyzed to investigate the effect of changing inspection frequency on a line with high traffic density. Annual tonnage of 160 MGT was assumed in these cases, and a baseline frequency of 4 inspections per year was established to reflect the UPRR policy. Simulations were also run for 5 and 8 inspections per year.[2]

Figure 7 presents the simulation results. A trend of decreasing service defect percentage with increasing frequency of inspection is evident, but there appears to be no significant difference between present practice (immediate repair) and delayed action. Conversely, delayed action increases car miles per day in comparison with present practice. Also, at detected defect rates exceeding 0.7 per track mile per year, it appears that increasing the inspection frequency tends to increase the number of car days required to complete the annual program.

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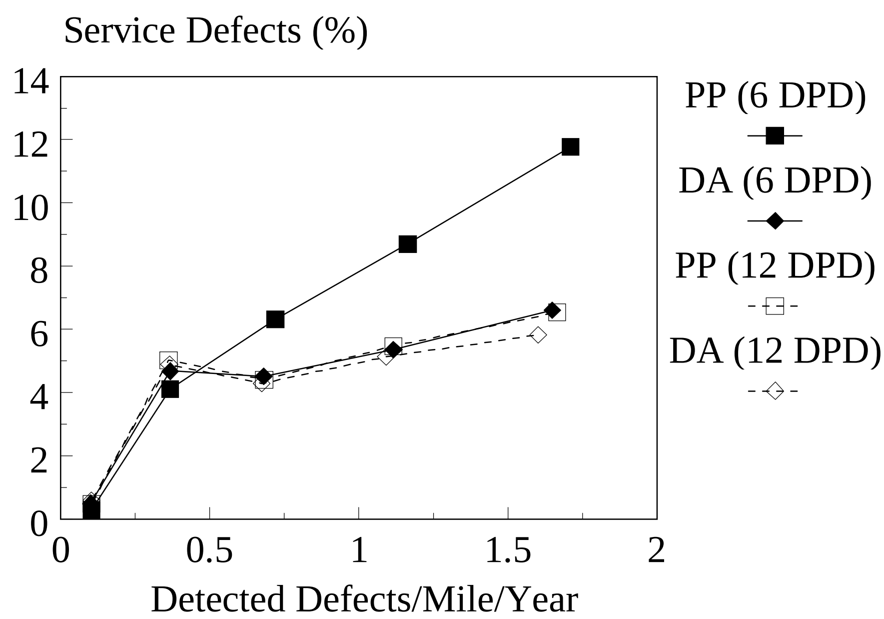
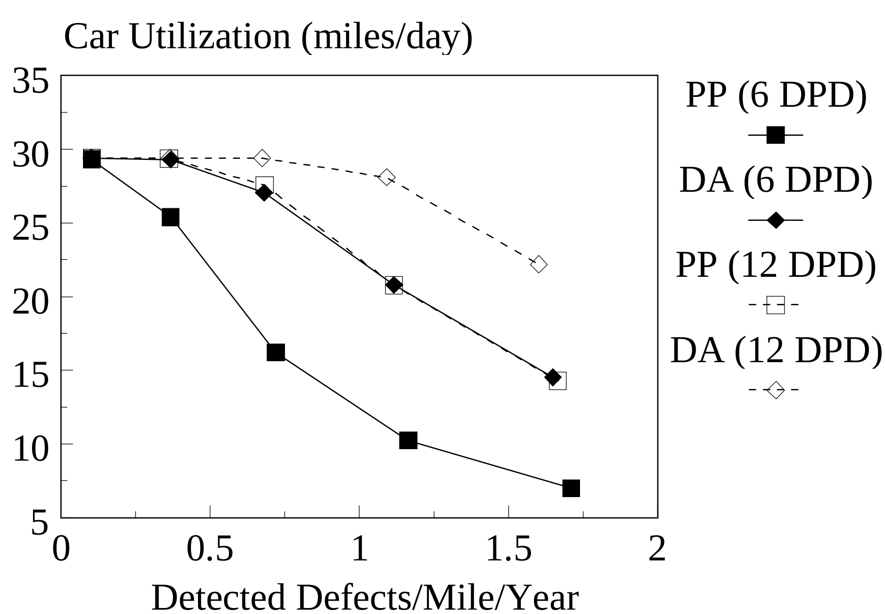
[2] According to the railroad, the actual practice on the high density line is usually 4 but sometimes 5 inspections per year.

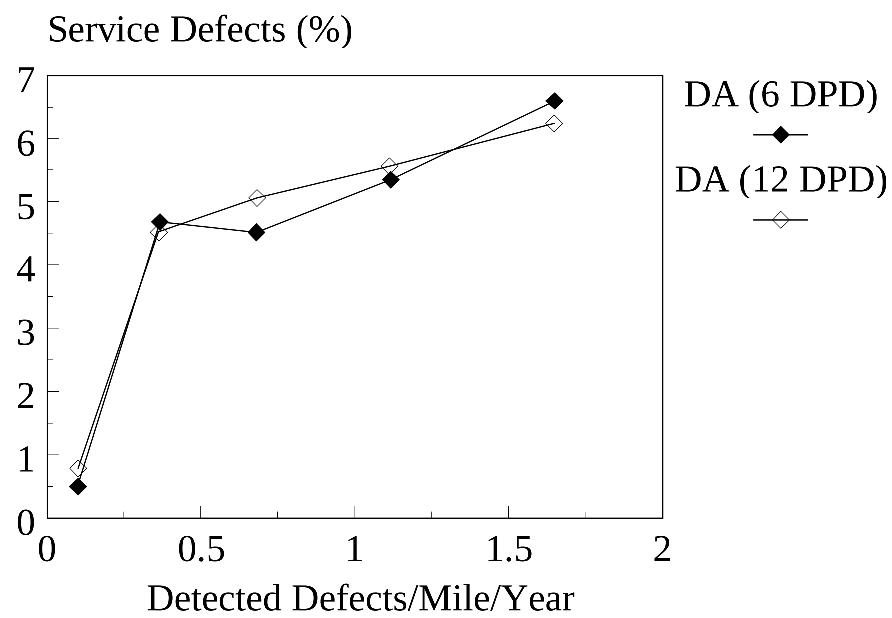


(a) Service defect rate.

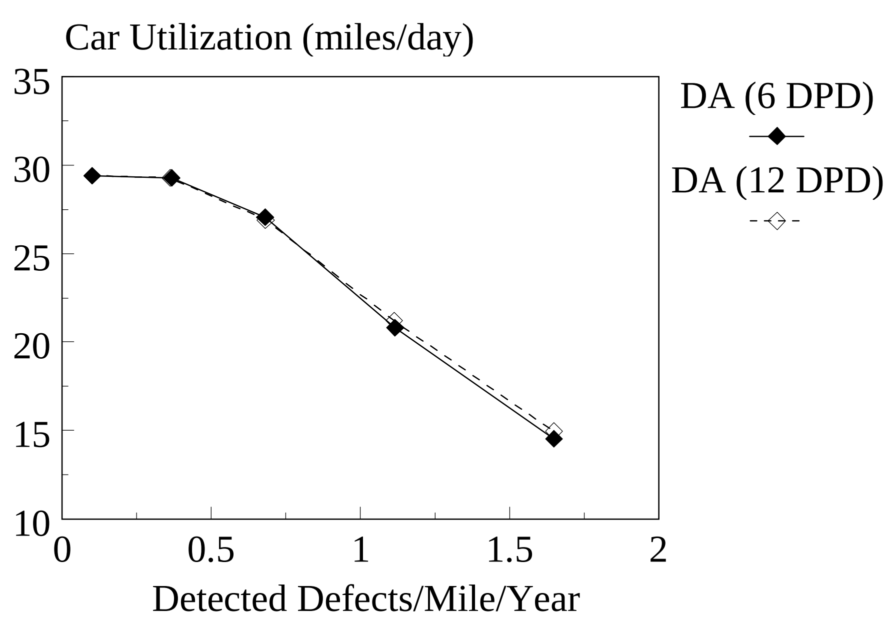


(b) Detector car utilization.

Figure 5. Effect of repair gang limit for 60 MGT/year traffic density.

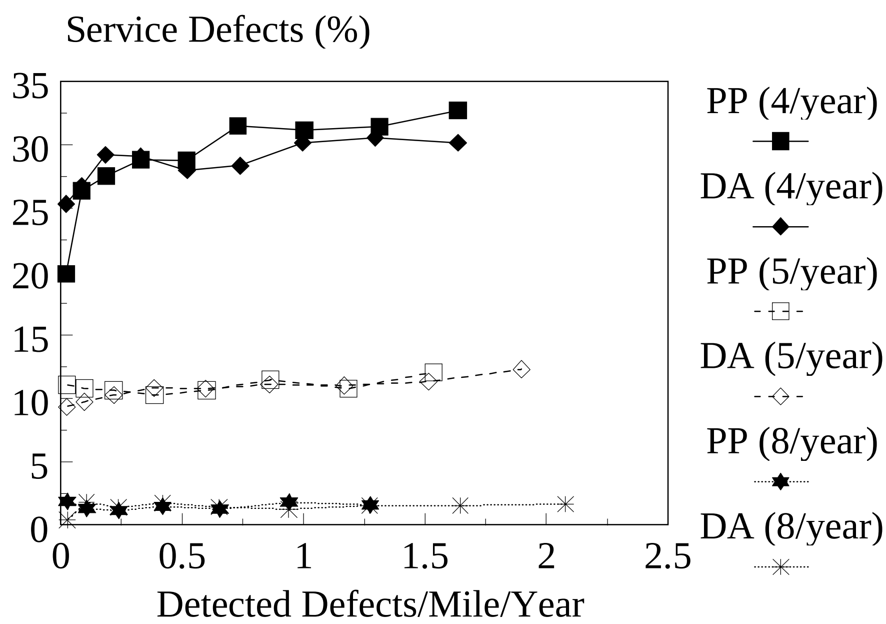


(a) Service defect rate.

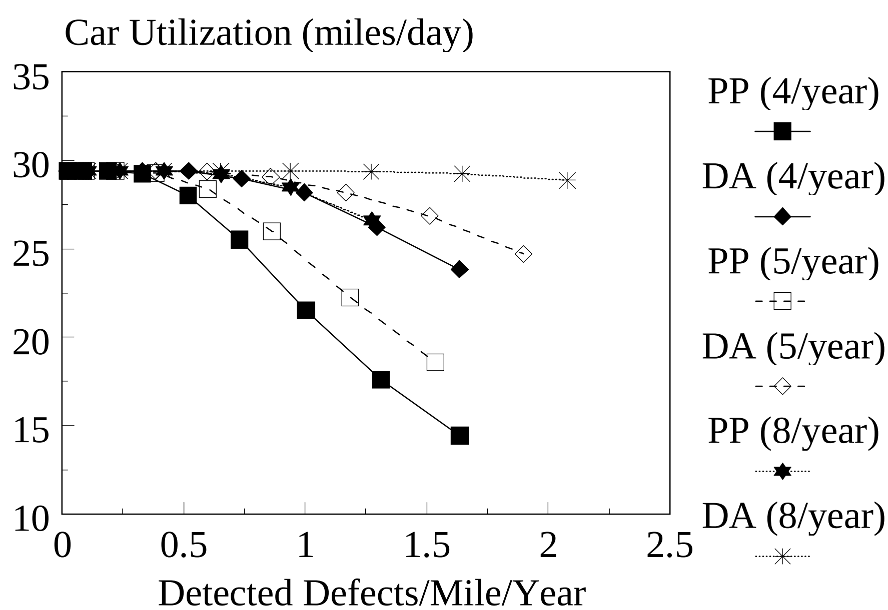


(b) Detector car utilization.

Figure 6. Effect of second gang limit for 60 MGT/year traffic density.



(a) Service defect rate.



(b) Detector car utilization.

Figure 7. Inspection interval effect for 160 MGT/year traffic density.

5. RISK/BENEFIT ASSESSMENT

In comparison with present practice, the greater average of detector car miles per day under delayed action (Section 4) is an obvious economic benefit. Better detector car utilization should also provide more opportunities to detect defects on the verge of rail failure. However, this implied safety benefit cannot be properly evaluated without consideration of the associated risk, viz.: how many rail failures might be caused by defects for which repair action has been delayed.

Delayed action should not trigger rail failures, provided that repairs are completed within the prescribed grace period. For example, the cold weather conditions of the current UPRR waiver allow a four-day grace period for transverse defects not exceeding 20% HA, except that action must be taken before the effective time of a weather forecast of temperature below 0 °F.[3]

Despite these precautions, the slow growth safety margin can be eroded by error in the estimation of defect size. In particular, it is possible that a defect exceeding the established size limit but incorrectly classified as non-critical might grow enough to cause a rail failure within the grace period. The probable distribution of size estimation error, based on experimental data, is developed (Section 5.1) and combined with a defect size distribution based on field data (Section 5.2) to formulate a quantitative assessment of this risk (Section 5.3). The defect distribution is also used to estimate savings of rail failures through better detector car utilization, and the net safety benefit is estimated (Section 5.4).

5.1 PROBABILITY MODEL FOR ERROR IN DEFECT SIZE ESTIMATION

The size of a transverse defect (TD) in a railhead is estimated by means of portable ultrasonic equipment. The general procedure is described as follows. A single 70°-angle probe is calibrated and then swept near the defect to: (1) estimate the lateral position of the defect center by maximizing the signal return; (2) refine the maximum by an axial sweep; (3) estimate the most shallow depth of the upper edge and the deepest point of the lower edge by finding the axial probe positions along the center plane for half signal strength; and (4) estimate the maximum defect width by finding the lateral probe position for half signal strength. Figure 8 summarizes the procedure.

[3] Low temperature induces tension in the rail; tension accelerates the defect growth rate and can also reduce the defect size at which rail failure under the next train must be expected.

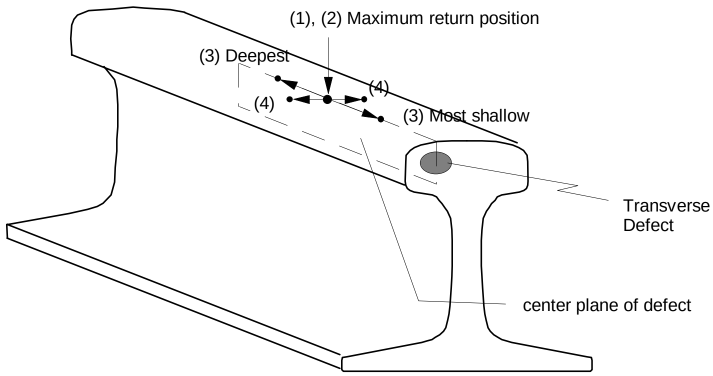


Figure 8. Schematic of size measurement for internal transverse defect.

The area of the rectangle thus determined (height × width) is then multiplied by an empirical constant to estimate the area of an inscribed oval or ellipse, which is assumed to be the defect shape. For transverse defects in the range of 20% HA to 40% HA, examinations of defects broken open in the laboratory show that the shape closely approximates an ellipse with an aspect ratio (ratio of semi-minor to semi-major axes, b/a) of 0.7 (Figure 9).

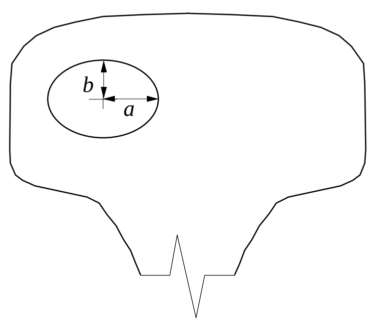


Figure 9. Transverse defect approximated as an elliptical flaw.

If the ultrasonic beam were to behave ideally (uniform density of signal strength) and to reflect ideally up to a sharp edge (no transmission across touching crack surfaces) of an idealized rectangular-shape defect, then the half-power points would precisely locate the defect edges and the measurement error would be negligible. In reality, however, the combination of non-uniform signal strength density, partial transmissibility when there is crack closure, and curved crack edges will create measurement error. Variability in operator technique and field conditions (e.g., rail surface) provide additional sources of error. Thus, the defect area estimated from the measurement procedure may in general be either greater than or less than the true area.

In order to assess the risk associated with misclassifications of defect size (e.g., where the size is compared with a criterion for allowance of delayed action), a probability model of the estimation error is needed. The objective of the model is to facilitate the interpretation of data on measurement errors. Such data are obtained when defects classified in the field are broken open in the laboratory to provide a comparison between the field measurement, A^*, and the true area, A.

The probability model should also be consistent with the physics of the measurement process. In the present case, physical considerations suggest that the most logical basis of the model is a linear dimensional error. In other words, the physical measurement deviates from the actual defect size by its relative locations from the edges at the top, bottom, and sides of the defect. As a first approximation, we can adopt the working hypothesis that errors at all four of these locations are described by the same random variable, defined mathematically as x. The statistics of this random variable will be sought from comparative data. We shall also adopt the convention that positive x corresponds to a measurement that underestimates the true size (Figure 10).

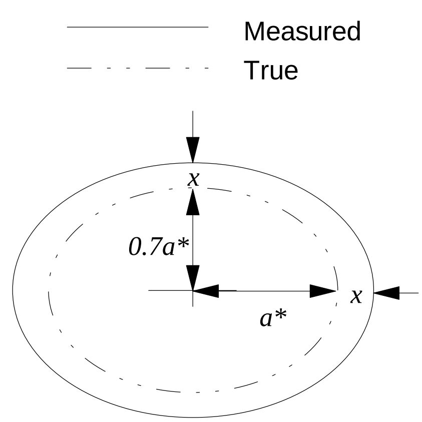


Figure 10. Schematic representation of measured versus true defect size.

Assuming that the area of the internal defect can be represented by an ellipse with an aspect ratio of 0.7, the model can be formulated in terms of the following equations:

<u>Measured size:</u>

$$A^* = \pi a^* b^* = 0.7\pi (a^*)^2 \tag{6}$$

<u>True size</u>:

$$A = \pi (a^* + x)(b^* + x) = A^* + 1.7\pi a^* x + \pi x^2 \tag{7}$$

An additional assumption is made that $x << a^*$, so that the term in x^2 can be neglected. Thus, the true defect size is approximated by:

$$A \cong A^* + 1.7\pi a^* x \tag{8}$$

Substituting from equation (6) into equation (8) to eliminate the parameter a^* then leads to:

$$A \cong A^* + 1.7\sqrt{\frac{\pi}{0.7}}\sqrt{A^*}\,x = A^* + C\sqrt{A^*}\,x \tag{9}$$

where C =3.6. Now let (A_i^*, A_i) be pairs of measured and true defect areas where i =1,2, …N. Each pair is used to imply a result for the random error variable, from equation (9):

$$x_i = \frac{A_i - A_i^*}{C\sqrt{A_i^*}} \tag{10}$$

where the physical areas (not the percent rail head area, %HA) are to be used. Furthermore, we assume that the random variable x follows a Gaussian distribution:

$$\phi(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \tag{11}$$

where μ is the mean value of x and σ is the standard deviation of x. These statistics can be estimated from comparative data using the following formulas:

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad\qquad \sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \tag{12}$$

At this point, a brief digression on two points is in order. First, a strict statistical analysis, where N is not large, would require the results from equation (12) to be treated as expectations requiring bounds established by confidence interval estimates based on Student's t-distribution [10]. However, the use of worst-case bounds is not appropriate for a practical assessment of risk. Instead, additional data should be sought to enlarge N. Second, the Gaussian distribution as given by equation (11) is unbounded. In other words, a finite probability in the model exists for negative values of A_i. This probability, however, is small enough to be of no practical concern as long as μ, σ << a^*.

Before the UPRR was granted the original delayed action test waiver, the FRA requested a demonstration of the railroad's ability to non-destructively measure and classify the size of detected detail fractures (DFs). This demonstration consisted of finding DFs in service, ultrasonically estimating the size of the defects, removing the rails containing the defects from service, and breaking the rails open in the laboratory to measure the true sizes. Data were collected for eleven defects, with measured DF sizes ranging between

4% HA and 15% HA. Comparisons between measured and true DF sizes (in terms of %HA) are listed in Table 3.

Table 3. Comparison Between Measured and Actual DF Sizes.*

Measured Size (%HA)	True Size (%HA)
11.0	17.5
5.0	20.0
10.0	26.0
15.0	15.0
14.0	13.5
6.0	11.0
9.0	8.0
4.5	4.0
7.5	3.5
12.0	6.0
10.5	7.0

* Based on 132 RE section; rail head area = 4.42 in^2.

The data listed in Table 3 were used to estimate the mean and standard deviation of the error distribution. From equation (12) these statistics were calculated to be:

$$\mu = -0.013 \text{ inch} \qquad \sigma = 0.103 \text{ inch} \tag{13}$$

The negative value of μ indicates that the field measurements overestimated the defect size, on average; the relatively large value of σ implies significant variability.

5.2 MODEL OF DEFECT SIZE DISTRIBUTION

Analysis of UPRR field data from the first waiver period showed that 55% of the detected TDs exceeded 15% HA and 31% exceeded 25% HA (see Table 2 in Section 3). Although the analysis is based on measured sizes, the sample of 455 defects is deemed large enough to justify an assumption that the measurement errors tend to cancel, and the above statistics will be taken to represent the true size distribution.

For the purpose of the risk/benefit assessment, it will be convenient to fit a Weibull distribution to the field data, in order to have a mathematical description of the percentage of defects as a function of size:

$$f(\overline{A}) = \frac{\alpha \overline{A}^{\alpha-1}}{\beta^{\alpha}} \cdot e^{-(\overline{A}/\beta)^{\alpha}} \tag{14}$$

where $\overline{A}$ is the defect size variable and α, β are the distribution parameters. The meaning of equation (14) is that, for any given time (e.g., a day of inspection), $f(\overline{A}) \cdot d\overline{A}$ is the fraction of the defect population having sizes between $\overline{A}$ and $\overline{A} + d\overline{A}$ at that time. The corresponding cumulative function is:

$$F(\overline{A}) = 1 - e^{-(\overline{A}/\beta)^{\alpha}} \tag{15}$$

and $1 - F(\overline{A})$ is the fraction of defects exceeding the size $\overline{A}$.

Substitution of the field data points into equation (15) leads, after some manipulation, to the following equations that can be solved to find the parameter values:

$$\left[-\ln(-0.31)\right]^{1/\alpha} - \frac{25}{15}\left[-\ln(-0.55)\right]^{1/\alpha} = 0 \tag{16}$$

$$\beta = \frac{25}{\left[-\ln(-0.31)\right]^{1/\alpha}} \tag{17}$$

The parameters are thus found to be:

$$\begin{aligned} \alpha &= 1.316 \\ \beta &= 22.17 \quad \%\mathrm{HA} \end{aligned} \tag{18}$$

5.3 MISCLASSIFICATION RISK

We now address the question of how many critical defects can be misclassified as non-critical. In order to do so, it will be convenient to first convert the relation between measurement error and physical defect size (Section 5.1) to defect size expressed in %HA. From equations (6) and (8) the edge error x can be expressed as:

$$x = \frac{A - A^*}{1.7\pi a^*} \tag{19}$$

where a^* is the measured semi-major axis and A^*, A are the measured and true physical sizes, respectively. In particular, we shall need an expression for the amount of edge error x_o that is just enough to misclassify a defect of size A as being exactly at the non-critical limit $A_o = 0.7\pi a_o^2$. Keeping the semi-major axis value a_o as the limit parameter and substituting the relation between physical size, A and percent rail head area (%HA), $\overline{A}$:

$$A = \frac{\overline{A} \cdot A_H}{100} \tag{20}$$

where A_H is the specified rail head area, leads after simplification to:

$$x_o(\overline{A}) = \frac{0.7}{1.7}\left(\frac{\frac{\overline{A} \cdot A_H}{70\pi} - a_o^2}{a_o} \right) \tag{21}$$

The probability that a defect of size $\overline{A}$ will be misclassified as a defect of size $\overline{A_o}$ is $\phi(x_o)$, where $\phi(x_o)$ is the edge error distribution (Section 5.1). To properly estimate the misclassification risk, however, requires that the entire range of possible adverse errors $x \geq x_o$ be accounted for. Thus, the total probability is expressed as:

$$P(\overline{A}) = \int_{x_o(\overline{A})}^{x_o(\overline{A}_{\max})} \phi(x)\, dx \tag{22}$$

where $\overline{A}_{\max}$ represents the largest possible size that a defect might reach without rail failure.[4] Equation (22) represents the probability that a defect of true size $\overline{A} > \overline{A_o}$ will be classified as non-critical. The fraction of total detected defects expected to be truly critical but misclassified as non-critical is then obtained by summing over the defect size distribution, as weighted by $P(\overline{A})$:

$$R = \int_{\overline{A}_o}^{\overline{A}_{max}} f(\overline{A}) \cdot P(\overline{A})\; d\overline{A} = \int_{\overline{A}_o}^{\overline{A}_{max}} f(\overline{A}) \cdot \int_{x_o(\overline{A})}^{x_o(\overline{A}_{max})} \phi(x)\, dx\, d\overline{A} \tag{23}$$

Figure 11 illustrates the probability of misclassification as a function of defect size, based on the edge location error distribution $\phi(x)$ determined from the rail breaking examination (Section 5.1), for the specified cold weather limit of 20% HA for non-critical defects. Note the rapid decrease as the true defect size increases. For example, the expectation is that roughly eight of every hundred 30% HA defects will be misclassified as not exceeding 20% HA.

[4] Based on earlier research [2], $\overline{A}_{max}$ = 80 %HA.

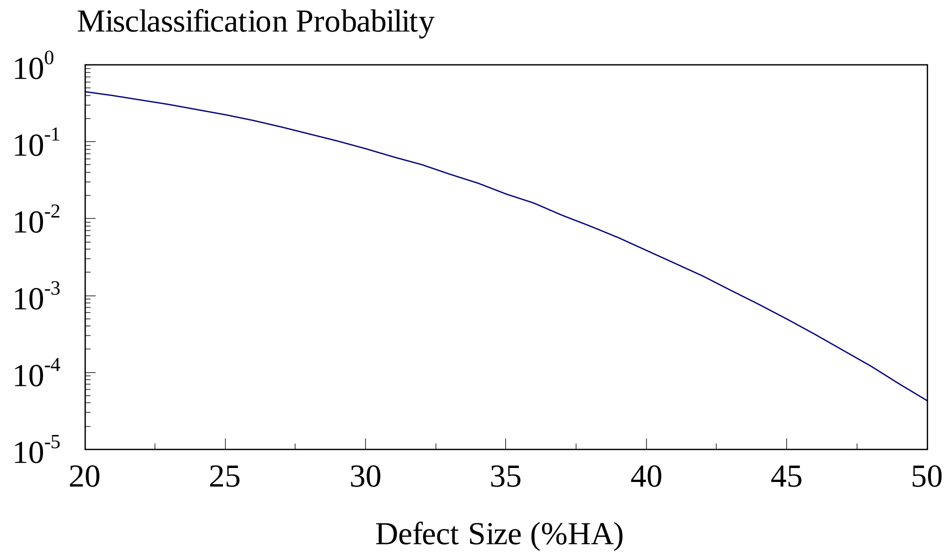


Figure 11. Probability of misclassification versus defect size for a non-critical size limit equal to 20% HA.

When these results are combined with the model of defect size distribution (Section 5.2) in equation (23), the numerical value R = 0.052 is obtained for the fraction of misclassified defects. In other words, if 1000 defects of all sizes (non-critical as well as critical) are detected, the expectation is that 52 defects exceeding 20% HA will be misclassified as non-critical.

5.4 MODEL APPLICATION

The risk/benefit analysis is carried out with respect to a baseline of 1000 track miles[5] inspected under present practice. For a selected defect rate (e.g. 0.25 defects per track mile per year), the equivalent number of track miles inspected under delayed action is the product of the baseline and the ratio (delayed action / present practice) of average detector car miles per day (see Sections 4.2 and 4.3).

The benefit is calculated as the product of three factors: (1) the selected defect rate; (2) a factor representing the percentage of defects that would cause rail failures if not detected quickly; and (3) the extra track miles inspected. Item 2 is taken as 0.05, representing the 5% of the defect population projected by the size distribution model (Section 5.2) to exceed 50% HA. The choice of 50% HA for this purpose reflects a general observation from field experience that defects exceeding this size leave the rail with little or no margin of strength to carry expected train loads.

The risk is also calculated as the product of three factors: (1) the selected defect rate; (2) a part of the fraction of defects that are both critical and misclassified as non-critical;

[5] The number of miles is chosen for convenience.

and (3) the total track miles inspected under delayed action. Item 2 is taken as the fraction *R*, defined by equation (23), but with a modified integration limit based on the following logic. Typical results from the RFD model analyses show that the average second gang repair backlog generally does not exceed one day's work (Figure 12). In addition, analysis based on the Detail Fracture Growth (DFG) model shows that defects as large as 27% HA still have a safe life somewhat longer than one day, assuming the maximum traffic density of 0.5 MGT per day and limiting winter temperature of 0 °F (Figure 13). Therefore, *R* has been evaluated by replacing $\overline{A_o}$ in equation (23) with 27% HA; i.e., by calculating the fraction of defects expected to be misclassified and large enough to cause rail failure within about 1.17 days under the stated conditions. The value thus defined is found to be $R = 0.009$. This choice still overstates the risk, since not all misclassified defects will necessarily cause rail failures and, in reality, traffic lower than 0.5 MGT per day and/or ambient temperatures above 0°F can be reasonably expected.

Calculations were carried out for 132RE rail ($A_H = 4.42$ in^2) and the cold weather limit $\overline{A}_o = 20\%$ HA (semi-major axis $a_o = 0.634$ inch). The following example is for the hypothetical track carrying 60 MGT with two inspections annually, assuming a rate of 0.5 detected defect per track mile per year:

<u>Average detector car miles per day</u>

28.35 (delayed action) / 21.92 (present practice) = 1.29 (ratio)

<u>Miles inspected under delayed action</u>

1290 (total) 290 (extra)

<u>Rail failures prevented by extra opportunity</u>

$0.5 \times 0.05 \times 290 = 7.25$

<u>Rail failures caused by misclassification</u>

$0.5 \times 0.009 \times 1290 = 5.81$

<u>Net safety benefit</u>

$$\frac{7.25 - 5.81}{1.29} = 1.12$$

Note that the net saving is divided by the car miles per day ratio (1.29) to produce a normalized result (in this case 1.12) of net rail failures prevented per 1000 track miles inspected. Normalizing in this way allows comparison of net benefits for different defect rates.

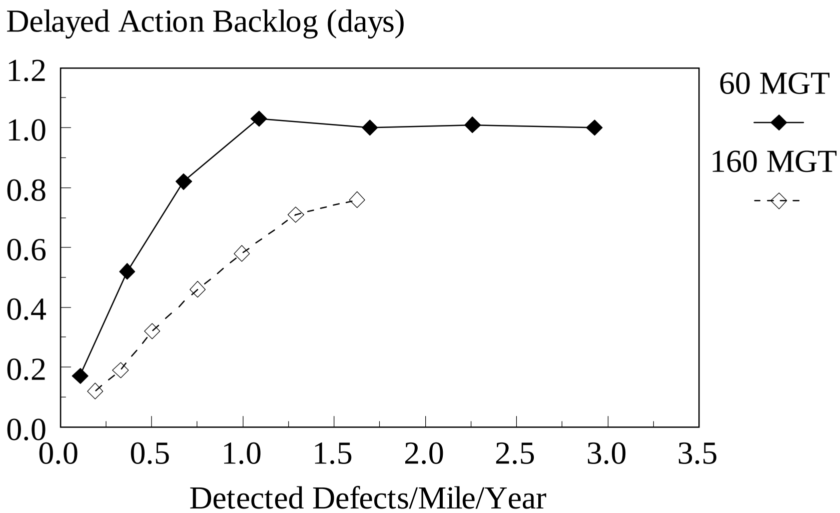


Figure 12. Second gang backlog versus detected defect rate.

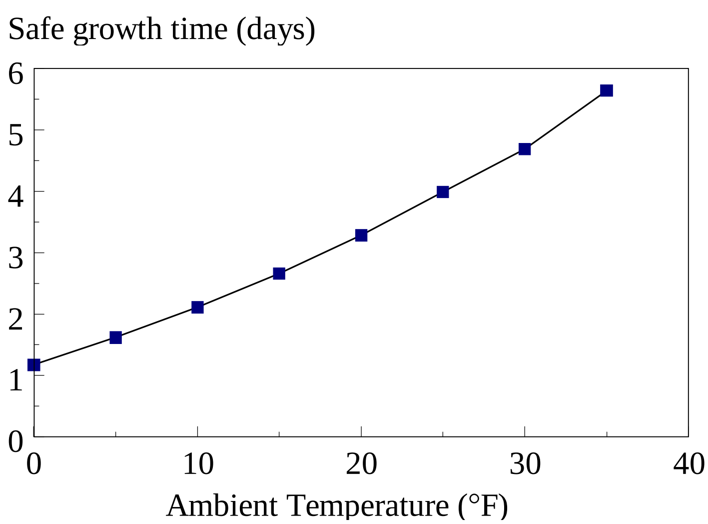


Figure 13. Safe growth time versus ambient temperature for 27% HA defect (traffic density 0.5 MGT per day).

Figure 14 summarizes additional results for both medium and high traffic densities. Delayed action apparently becomes more favorable as the defect rate increases. Note also the negative values for the 60 MGT track below about 0.3 defect per track mile per year and for the 160 MGT track below about 0.8 defect per track mile per year. Negative values indicate net risk. However, two points are worth emphasizing to place these results in perspective. First, is the previously mentioned observation that the basis of the calculation intentionally over-estimates the risk of misclassifying critical defects. Second, the increased risk is small in comparison with existing rates of rail failure.[6]

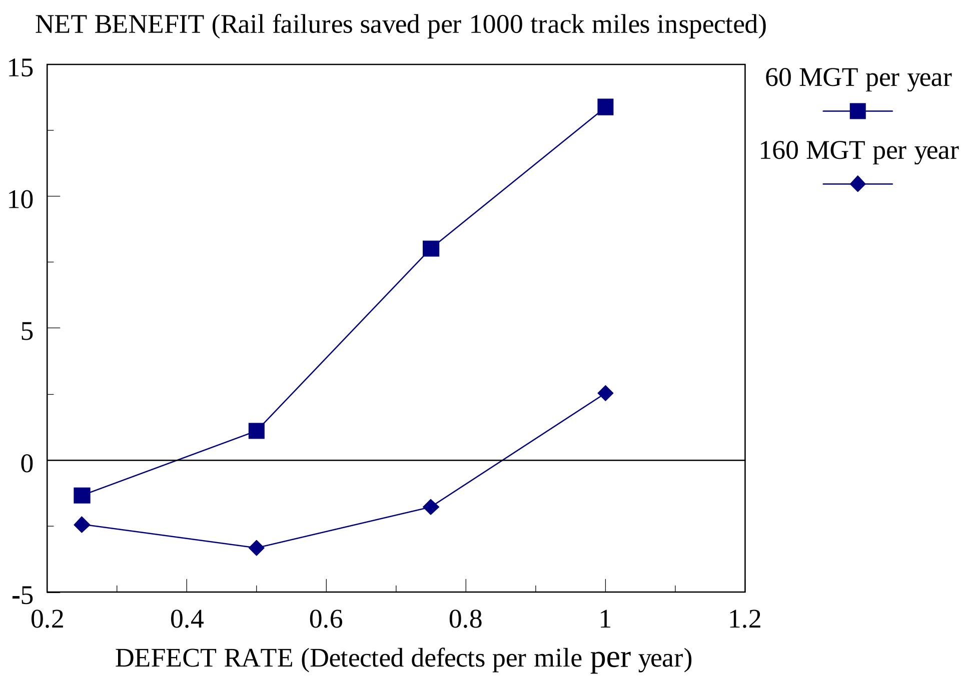


Figure 14. Net safety benefit versus detected defect rate.

[6] Per 1000 track miles inspected, the increased risk is in the range of 1 to 3 rail failures, whereas 12.5 to 37.5 rail failures would be expected for defect rates between 0.25 and 0.75 per track mile per year with a service rate of 5 % of detected defects.

6. SUMMARY AND CONCLUSIONS

This report summarizes an assessment of risk versus benefit associated with repair of detected rail defects under a delayed action protocol. The concept of delayed action allows a rail flaw detector car and its chase gang to continue the search for additional defects without stopping to repair certain defects (called “non-critical”) smaller than a specified size. Since rail defects tend to grow slowly and steadily under passage of trains, the remaining safe life of the largest non-critical defect can be estimated with reasonable accuracy, and a grace period can be established for repairs by a follow-up gang. Inspection of rail under a delayed action protocol thus trades a calculated risk (rail failure caused by a non-critical defect due to unusual circumstances) for the benefit of increased opportunity to find and repair larger defects that might otherwise cause rail failures just ahead of the detector car. The Union Pacific Railroad formulated the delayed action concept and is evaluating its effectiveness in a field trial under a waiver granted by the Federal Railroad Administration.

The assessment reported here is based on numerical simulation conducted by means of several related models developed by the Volpe Center in support of FRA track safety research. The two most elaborate are the detail fracture growth (DFG) model and the rail flaw detection (RFD) model. The DFG model correlates expected detail fracture growth rates with field conditions (track structure, traffic type and density, weather) and has been calibrated to reality by comparison with defect growth rate experiments conducted at the Transportation Technology Center [2,4]. The RFD model (Sections 2 to 4) combines seasonally adjusted defect growth rates, based on the DFG model and average traffic type, with a detection probability curve and Monte Carlo simulations of defect occurrence and detection or non-detection to evaluate detector car utilization (car miles per day) and inspection effectiveness (service defects as a percentage of detected defects) versus defect occurrence rate. For the purposes of the assessment, all service defects are assumed to be rail failures.[7] A preliminary version of the RFD model has been calibrated to Union Pacific Railroad field experience [1].

The RFD model addresses delayed action only in terms of the economic benefit of better detector car utilization and the safety benefit of reduced rail failure rate due to increased opportunity for detection of large defects. Additional models for estimation of the risk associated with delayed action (Section 5) characterize the distribution of defect sizes and the probability that a critical defect might be misclassified as non-critical. These models have been combined to estimate the safety risk, i.e., the percentage of detected defects expected to be of critical size but also to be misclassified as non-critical. For the purposes of the assessment, all such defects are assumed to cause rail failures. The size distribution represents the percentages of defects of various sizes that a detector car is expected to encounter, on average, in a typical day’s inspection. The misclassification probability is derived from a model of measurement error in the non-destructive

[7] Field reports of service defects may include large detail fractures, with cracking exposed on the gage face and/or running surface, detected by visual inspection during a 49 CFR 213.233 track patrol.

procedure used by detector car operators to estimate defect size. Both models have been calibrated to data provided by the Union Pacific Railroad.

Under typical conditions of medium to high traffic density, seasonal variation of defect growth rates, and rail age on main line track, annual detections of 0.25 to 1.0 defect per track mile are common, and service defects tend to occur in the proportion of about 5% to 10% of detected defects on lines subjected to well managed inspection programs. For these conditions, the RFD model predicts better detector car utilization for delayed action, as compared with the present practice of immediately repairing every detected defect regardless of size. This prediction appears to be consistent with field experience from the trial now being conducted by the Union Pacific Railroad.

Beyond the issue of car utilization, the assessment described in this report provides answers to two important safety questions. First, what frequencies of inspection are appropriate for maintaining a low overall rate of service defects? Second, in comparison with present practice, can delayed action on repair of non-critical defects be expected to increase or decrease the service defect rate?

Regarding the first question, the RFD model indicates that the most effective means of decreasing the service defect rate is to increase the number of inspections per year (Figures 4 and 7), although delayed action can also have some degree of favorable effect. However, raising the inspection frequency creates operational and economic burdens that a railroad cannot ignore. Furthermore, the RFD model has been simplified in a way that does not truly represent actual railroad practices. In the model, inspections are assumed to be scheduled uniformly over the calendar year. In practice, however, railroads tend to schedule their rail inspections in the colder half of the year, thereby increasing the effective frequency in the period of higher defect growth rates. The RFD model is indirectly consistent with this practice, in that it indicates a lower service defect rate for warm as opposed to seasonally varying weather (Figure 3). Also, the modest increases of inspection frequency suggested by the model, in order to maintain low service defect percentages (Figures 4 and 7), are easily achieved by means of the present scheduling practice.

Regarding the second question of risk versus benefit associated with delayed action, the numerical assessment produced results varying from slight additional risk (about 1 to 3 additional rail failures per thousand track miles inspected) to significant benefit (up to about 13 fewer rail failures per thousand track miles inspected). The net risk was found to increase generally with increasing annual tonnage and decreasing rate of detected defects. In the worst of the computed cases (160 million gross tons annually, four inspections per year, and 0.5 detected defect per track mile per year), the net risk was found to be 3.3 additional rail failures per thousand track miles inspected. To place this result in perspective, the same thousand miles of inspection would be expected to produce 500 detected defects, and a 5% service defect rate (a low figure) would imply 25 service defects, most of which would be rail failures, due to lost inspection opportunity. Furthermore, the numerical analysis over-estimates the risk, as explained in Section 5.4.

Assuming continued inspection of rail at current frequencies, including cold weather scheduling practice, and continued performance at current levels for transverse defect detection and size estimation, the foregoing results suggest that delayed action is a worthwhile concept from the railroad safety viewpoint. This study has highlighted two important benefits. First, delayed action increases the average day's track mileage inspected, thus providing more opportunity to detect large defects ahead of rail failure. This promotes reduction of service defect rates, relative to the present practice of restricting detector car movement to stay within the daily repair capacity of a chase gang. Second, delayed action can help to keep the overall service defect rate at a low level, when combined with the existing practice of scheduling more of the annual inspection program in the colder months of the year. This includes the likelihood of a significant benefit at the margin, i.e., more rail failures averted due to increased detection opportunity than rail failures caused by misclassified defects.

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APPENDIX - COMPUTER PROGRAM LISTING FOR MONTE CARLO SIMULATION

```fortran
      program mcrail
c
c     Monte Carlo Analysis of Subdivision Rail Test
c     Main (March 10, 1994)
c     bp edit May-june, 1994
c     yt edit November 1996
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     csize1     - critical crack size for colder monthes (%ha)
c     csize2     - critical crack size for warmer monthes (%ha)
c     cracki     - initial defect size (%ha)
c     icount     - number of critical defects removed per day
c     iday       - day counter for the entire analysis
c     imile      - mile post counter for inspection
c     iyear      -
c     ltrack     - length of track for the analysis (mile)
c     m1day      -
c     mcday      - day counter for updating the month in a year
c     mday       - number of repairing days for each year
c     mi2day     - counter for mile inspected per day
c     mipd       - number of miles inspected per day
c     month      - month of year to start analysis
c     mstart     - start of colder monthes
c     mend       - end of colder monthes
c     nday       - analysis duration in days
c     ndef       - defect counter at each mile post
c     nfix       - number of defects acted upon per day
c     nnfix      - number of non-critical defects acted upon per day
c     raila      - rail age in MGT (million gross tons)
c     raili      -
c     tonpd      - acummulated tonnage (MGT) per day
c
c     begin      - flag for the start of inspection
c     debug      -
c     inspct     - flag for end of inspection period
c     outpt      -
c     quit       -
c     quit1      -
c     quit2      -
c     quit3      -
c     report     -
c     season     -
c
      integer nday, ltrack, nfix, nnfix, mipd
      real    raili, tonpd, csize1, csize2, beta
c
      integer mday, m1day, iyear, mi2day
c
      logical inspct, begin,  report, season, quit, quit1, quit2,
     +         quit3, outpt, debug
c----67--1---------2---------3---------4---------5---------6---------7--
c  number of days per year (assume there are 30 days per months)
      ndpy  = 360
c  get external data from files
      call getinp (nday,ltrack,raili,tonpd,nfix,mipd,beta,nipy
```

```
     1              ,ndpy,month,mstart,mend,nnfix)
c
c  rdgrow is an entry in GROWTH
      call rdgrow
c  seed the random number generator
C      CALL RANDOM_SEED ()
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
      mcday  = 0
      ifflag = 0
      nnfound  = 0
      nndet = 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',3x,
     1        '<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
c
c  adjust month for every 30 days
      if (mcday.eq.30) then
          mcday=1
          if (month.eq.12) then
              month = 1
          else
              month = month + 1
          endif
      else
          mcday = mcday + 1
      endif
```

```
c
      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
        ndef = 1
        inspct = .true.
        lcount = 0
      end if
C write yearly report as soon as inspection is complete
      if (outpt) report = .true.
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,month)
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
     1            ,mstart,mend,nnfix,ifflag,month,nnfound,nndet)
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)
        endif
        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
            ndef = 1
            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)
c
            nspct=nspct+1
            inspct = .false.
            imile = 1
            ndef = 1
            icount = 0
          end if
c end of miles checks
        end if
c update days inspected
        mday = mday + 1
        if (mday.gt.ndpy) go to 110
      endif
c second gang fix non-critical defects
      if (nnfound.gt.0) call fixnc (ifflag,nnfix,nndet,nnfound)
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(quit1) m1day = m1day + 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,m1day,iday,iyear,debug)
        call opinit(iyear)
c  reset repair/inspection count
        mday  = 0
        m1day = 0
c
        report = .false.
      endif
c
c   accumulate tonnage for each day
c
      raila = raila + tonpd
c
100   continue
110   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,nipy
     1                  ,ndpy,month,mstart,mend,nnfix)
c
c  Monte Carlo Analysis of Subdivision Rail Test Data Input
c  14 variables
c  read, echoed & returned to main
c  yt edit May 1996
c  yt edit June 1996
c  yt edit July 1996
c
c----67--1---------2---------3---------4---------5---------6---------7--
      integer nday, ltrack, nfix, mipd
      real    raili, tonpd, csize1, csize2, 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 nyear, ndpy, noint, noday, inday, ncvday
      integer koday, knday, kcvday
      real tonpy, ainsp
      save nyear, tonpy, noint, noday, inday, ncvday
      save koday, knday, kcvday
c declarations for entry action
      integer iday
      integer iucpop, iudefs, iufail, iusum
      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
      inunit=25
c
      iucpop = 10
      iudefs = 11
      iufail = 13
      iusum = 14
c
c----67--1---------2---------3---------4---------5---------6---------7--
        open (unit=iucpop,file = 'fort.10')
        open (unit=iudefs,file = 'fort.11')
        open (unit=iufail,file = 'fort.13')
        open (unit=iusum,file = 'fort.14')
        open (unit=inunit,file = 'inp.dat')
        open (unit=15,file = 'fort.15')
        open (unit=30,file = 'fort.30',status = 'old')
        open (unit=31,file = 'fort.31')
```

```
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  Characteristic Life (MGT)
      read (inunit,*) beta
c  Month to Start Analysis
      read (inunit,*) month
c  Critical Crack Size for Colder Months (%ha)
      read (inunit,*) csize1
c  Critical Crack Size for Warmer Months (%ha)
      read (inunit,*) csize2
c  Start of Range for Colder Months
      read (inunit,*) mstart
c  End of Range for Colder Months
      read (inunit,*) mend
c  Minimum Detectable Crack Size (%ha,1.,3., or 5.)
      read (inunit,*) dsize
c  Number of Defects Act Upon per Day
      read (inunit,*) nfix
c  Maximum Number of Non-Critical Defects Act Upon per Day
      read (inunit,*) nnfix
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(10,241) month
      write (iudefs,241) month
      write (13,241) month
      write (14,241) month
241   format (1x,'month of year to start analysis = ',i2)
      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 (10,252) month
      write (iudefs,252) month
      write (13,252) month
      write (14,252) month
252   format (1x,'month which the analysis begin with =',i3)
      write (10,254) csize1
      write (iudefs,254) csize1
      write (13,254) csize1
      write (14,254) csize1
254   format (1x,'critical crack size for colder monthes =',f9.4,' %ha')
      write (10,256) csize2
      write (iudefs,256) csize2
      write (13,256) csize2
      write (14,256) csize2
256   format (1x,'critical crack size for warmer monthes =',f9.4,' %ha')
      write (10,258) mstart
      write (iudefs,258) mstart
      write (13,258) mstart
      write (14,258) mstart
258   format (1x,'start of colder monthes =',i3)
      write (10,259) mend
      write (iudefs,259) mend
      write (13,259) mend
      write (14,259) mend
259   format (1x,'end of colder monthes =',i3)
```

```
      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 (10,265) nnfix
      write (iudefs,265) nnfix
      write (13,265) nnfix
      write (14,265) nnfix
265   format (1x,'number of non-critical 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,csize1,csize2)
c
c  process return values
      nday  = nyear*ndpy
      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 defdet(imile,ndef,icount,n15,n25,ng25,
     1                  mstart,mend,nnfix,ifflag,month,nnfound,nndet)
c----67--1---------2---------3---------4---------5---------6---------7--
c     Monte Carlo Analysis of Subdivision Rail Test
c     Defect Detection Probability
c     yt edit June 1996
c     yt edit July 1996
c
      integer ndef,imile
      real amin, acrit1, acrit2, x, prob
c
c     double precision x, prob
      real dsize, csize1, csize2, ccsize
      real size, factor
      save dsize, csize1, csize2
c----67--1---------2---------3---------4---------5---------6---------7--
      if (ifflag.eq.0) then
          if (month.ge.mstart.or.month.le.mend) then
              ccsize = csize1
          else
              ccsize = csize2
          endif
      elseif (ifflag.eq.1) then
          ccsize = dsize
      endif
c     update day counter to fix noncritical defects
      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.)/.45)**.036
        end if
c
   10   continue
        call random_seed ()
        call random_number (x)
        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 .lt. ccsize) then
c   save noncritial counts in OUTPUT
            call svdet(imile, size, ndef, nnfix, ifflag, nnfound, nndet)
            ndef = ndef + 1
          else
c   increment removal and save critical counts in OUTPUT
            icount = icount + 1
            call svcdet(imile, size)
c   FIX decrements ndef to match flaw removal
            call fix (imile,ndef)
          endif
c
        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,acrit1,acrit2)
c----67--1---------2---------3---------4---------5---------6---------7--
c   get sizes for minimum detectable crack - dsize &
c   critical crack size                    - csize
      dsize = amin
      csize1 = acrit1
      csize2 = acrit2
c
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      end

      subroutine  growth (tonpd, ltrack, month)
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     yt edit June, 1996
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
      parameter (ntm = 1000, maxdpm = 500)
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, imile, ndef, ndir, jdir, jfail
      logical debug, grew
      integer nbig(5)
c  entry RDGROW declarations
      integer mpt
      parameter ( mpt = 14 )
      integer i, j, ii
      integer nump
      real a(mpt),dmgt(mpt),ddmgt(mpt)
c
      save nump,dmgt,a,cracki
c
      real cmgt(mpt),slope(mpt)
      parameter ( mxfail = 50000 )
      integer m(mxfail), ifail
      real    s(mxfail)
      save    ifail, m, s
c----67--1---------2---------3---------4---------5---------6---------7--
c
c  adjust crack growth rate (based on month of year)
      if (month.eq.1) factor=1.0
      if (month.eq.2.or.month.eq.12) factor=1.1
      if (month.eq.3.or.month.eq.11) factor=1.2
      if (month.eq.4.or.month.eq.10) factor=1.3
      if (month.eq.5.or.month.eq.9) factor=1.4
      if (month.eq.6.or.month.eq.8) factor=1.5
      if (month.eq.7) factor=1.6
c
      do 110 i = 1,nump
        ddmgt(i) = factor*dmgt(i)
110   continue
c
      cracki  = a(1)
      cmgt(1) = ddmgt(1)
c  find nump - 1 slopes
      do 120 i = 2, nump
        denom   = ddmgt(i)
        cmgt(i) = cmgt(i-1) + ddmgt(i)
        if (denom .eq. 0.0) then
          slope(i) = 0.0
        else
          slope(i) = ( a(i)-a(i-1) )/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
              if (crack .lt. a(ic) ) 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
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
c  read growth data
c
        open (unit=20,file='gcurv1.dat')
        rewind 20
        read (20,*) nump
        read (20,*) (a(i),dmgt(i),i=1,nump)
```

```
        close(20)
  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 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, x
c      double precision x
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
      call random_seed ()
      call random_number (x)
      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 reprt(ltrack,raila,mday,m1day,iday,iyear,debug)
c     yt edit July 1996
```

```
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,nndet,nnfound
c
      save    ndet, ncfound, nfound, nmade
c
      real    size, rate1, rate2
      integer mxfnd, i
c
      parameter ( mxfnd = 50000)
      integer mflag(mxfnd), mcflag(mxfnd), nmflag(mxfnd), nnflag(mxfnd)
      real    sflag(mxfnd), scflag(mxfnd), nsflag(mxfnd)

      save    mflag, sflag, mcflag, scflag, nmflag, nsflag, nnflag
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,i4,7x,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

        mflag(i)  = 0
c
        scflag(i) = 0.0
        mcflag(i) = 0
  400 continue
      nfound  = 0
      ncfound = 0
c
      ndet = 0
c
      return
c----67--1---------2---------3---------4---------5---------6---------7--
      entry svdet(imile, size, ndef, nnfix, ifflag, nnfound, nndet)
c  keep track of noncritical defects
c----67--1---------2---------3---------4---------5---------6---------7--
      ndet   = ndet +1
      nndet  = nndet + 1
      nfound = nfound + 1
      nnfound = nnfound + 1
      mflag(nfound) = imile
      sflag(nfound) = size
      nmflag(nnfound) = imile
      nnflag(nnfound) = ndef
      nsflag(nnfound) = size
c     allow five days to fix the non-critical defects
      mncrit = nnfix * 5
      if (nndet.ge.mncrit) then
         ifflag = 1
      else
         ifflag = 0
      end if
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
      end if
      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,i4,1x,f4.2,1x,i4,2x,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--
      entry fixnc (ifflag,nnfix,nndet,nnfound)
c     fix non-critical defects
c----67--1---------2---------3---------4---------5---------6---------7--
      jcount = 0
350   jcount = jcount + 1
      lmile = nmflag(jcount)
      ldef = nnflag(jcount)
      call fix (lmile,ldef)
      do 355 j = jcount+1,nnfound
         if (nmflag(j).eq.nmflag(jcount)) then
            nnflag(j) = nnflag(j) - 1
         endif
355   continue
      nndet = nndet - 1
      mncrit = nnfix * 5
      if (nndet.ge.mncrit) then
```

```
            ifflag = 1
         else
            ifflag = 0
         endif
         if (jcount.lt.nnfix.and.nnfound.gt.jcount) then
            go to 350
         else
            do 360 i = 1,nnfound-jcount
               nmflag(i)=nmflag(i+jcount)
               nnflag(i)=nnflag(i+jcount)
               nsflag(i)=nsflag(i+jcount)
360         continue
            nnfound = nnfound - jcount
         endif
370      continue
         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
```