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WEIBULL ANALYSIS OF COAL CAR WHEEL LIFE

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Summary

Transportation Technology Center, Inc. performed a statistical analysis on selected series of coal cars in the North American fleet. Coal cars were chosen for this analysis because of their dominance in the railway industry and their affect on maintenance and component usage. Over 25 percent of carloads and 44 percent of tons are originated from coal traffic on the U.S. Class I railroad system (Analysis of Class I Railroads, 2002).

The analysis showed three significant findings:

- Brake-related failures were found to reduce the life of wheelsets by more than 50 percent, from 393,006 miles on average to 195,406 miles. Using conservative assumptions, the net present value of the costs of brake-related wheel failures for this fleet was estimated in excess of \$8,100 per car, not including the value of out of service time.
- Life for wheels in service with standard three-piece trucks is 10 to 25 percent less than for more modern designs (trucks similar to those now being required under cars built for 286,000-pound gross rail load), depending on specific route and service characteristics. This finding is consistent with technological improvements.
- Wheel lives were not significantly different for cars with Frame Brace™ trucks with primary suspension pads removed; i.e., wheel life and the incidence of failure were not measurably changed from the standard three piece truck.*

Two North American railroads and two private car owners provided data for this analysis. Approximately 2,100 coal gondolas with mileages ranging from 90 to 110,000 per year were used as a sample group. The analysis was completed to better understand the relationship between component usage, modes of failure, and maintenance practices.

Car owners provided repair histories and monthly mileage records for periods of 8 to 12 years. The repair and mileage records for the cars were merged and estimates of the wheel failure parameters were made using a commercial statistical package. Wheel life parameters were analyzed by car owner and truck type. The size and completeness of the data made it possible to estimate statistical parameters within relatively tight confidence intervals.

This work was a part of the Association of American Railroads' Strategic Research Initiative Program in freight car maintenance and economics, component repair and usage. The results from analyzing the data may ultimately be used to drive a maintenance policy and cost model.

*Note: Cars equipped with Frame Brace™ in this study did not include primary suspension pads as recommended by the manufacturer. See the following digests for more information on studies that did include primary suspension pads: "Economics of Improved Suspension Trucks" (TD90-009) and "Warp Characteristics of Bulk Commodity Suspensions: Conventional and Frame Brace™ Trucks: Part 1 of 3" (TD03-023).



BACKGROUND

In economic terms, wheels are among the most significant components on freight cars. For example, Class I railroad and AAR car repair data indicates that the industry spends approximately 37 percent of its \$1.5 billion in car repair cost on wheels, constituting an expenditure of approximately \$555 million.¹ In addition, lost service time due to unplanned repairs of wheels significantly reduces asset utilization and availability figures for the national car fleet. Car owners and suppliers have conducted extensive research in the past several decades exploring modes of failure and means to increase wheel life.

Weibull Analysis

One of the most important tools available for understanding failure data is Weibull analysis. Essentially, Weibull analysis is fitting failure data to a particular statistical distribution and interpreting the results. Two parameters — scale and shape — typically characterize Weibull distribution. The *scale parameter*, or characteristic life, is the value at which approximately 63 percent of the components can be expected to have failed. The *shape parameter* indicates the pattern by which components fail. Shape parameters less than 1 means that the component improves with age (such as wear hardened steel), or is subject to infant mortality. Shape parameters equal to 1 means the component fails essentially randomly; e.g., by external environmental effects. Shape parameters greater than 1 means the component wears out with time or usage. Only components with shape parameters greater than 1 are candidates for planned replacement, and the higher the shape parameter, the more predictable the failures. Values higher than about 2.5 are particularly good candidates, if the cost of failure is greater than the value of foregone wear life. Weibull analysis requires large datasets that include cause and timing (or mileage) of failures. Once the data is collected and processed for completeness and consistency, the Weibull distribution can be estimated using commercial statistical packages.

Data Used in the Analysis

For this study, machine-readable records were provided for approximately 3,200 cars, including mileage from 1987-2001, repair records from 1989 to 2001, and UMLER² file data. The cars were J312 coal gondolas built between 1976 and 1991 and have been used in unit coal train service over their lifetimes. The cars average approximately 90,000 miles per year.

After cleaning the data for incomplete or defective records, there were usable repair histories for 2,924 cars. These cars provided 15,000 complete uncensored observations of wheel life.³

Results

The results of the Weibull analysis are summarized in Table 1 (page 4). For each car series, the results are presented by truck type and failure type. The results include the shape parameter, the scale (or characteristic life), the 95-percent confidence interval for each of these parameters, and the mean and median. For each truck type, the parameters are given for all types of failures and for wear only failures. The scale parameters for wear-related failures are necessarily longer than for all failures since brake-induced failures are treated as censored removals.

EFFECT OF TRUCK TYPE ON WHEEL LIFE

Because of the wide variety of operating conditions, maintenance practices and other factors outside the control of this analysis, caution should be exercised in interpreting the results, particularly in terms of forming judgments about the relative merits of particular technologies. Nevertheless, the wheel life parameter estimates appear to be consistent within new technology truck types (see Figure 1). For example, the scale parameter for wheels under new technology type-3 trucks for all failure types are all between 336,000 and 360,000 miles. Similarly, the scale parameters with new technology type-1 trucks are in the range of 336,000 to 386,000 miles. The scale parameters for wheels in service with standard three-piece trucks are much lower than for new technology designs, which is consistent with technological improvements. Interestingly, the parameters are consistent across truck types for some but not all car series. Car series 4, for example, showed very similar numbers for both the truck types used in their trains. Car Series 2, on the other hand showed a variation of almost 35 percent between the scale parameter for its shortest- and longest-lived wheels.

There is less uniformity in the shape parameters across the study series, which may be attributable to either variations in operating conditions, planned maintenance activities, or both.

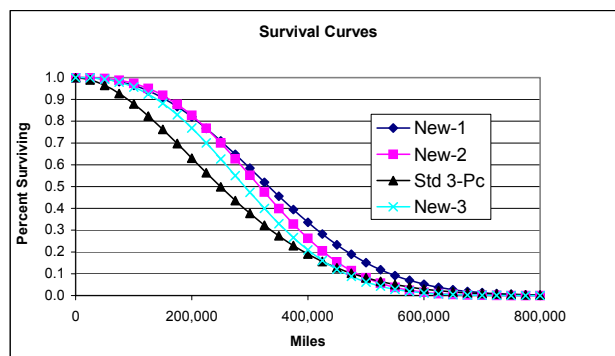


Figure 1. Survival Plot for Car Series 1

censored data. This is not an unusual situation when analyzing life data and standard statistical treatments could be applied. Fortunately, the size and quality of the data was such that the number of uncensored records was still very large, and accurate parameter estimates were obtainable.

¹ Class I Railroads Annual Report, Dec. 31, 2000

² Universal Machine Language Equipment Register

³ Because of the difference between car age, repair and mileage coverage, a significant number of the records were treated as

EFFECT OF BRAKES ON WHEEL LIFE

The medical community has long recognized that curing one ailment does not mean the patient will live forever. Indeed, patients are subject to many risks, and statistical techniques can be applied to determine how long a typical patient might have lived had they not suffered a particular fate. This approach is known as *competing risks* analysis. In this case, the question becomes: How long will wheels last if not subject to brake related failures? To explore this, the approach used was to include only wear-related failures in the failure data, treating all other failures as censored records and then to estimate the parameters. As a practical matter, almost all the non-wear failures were brake-related. For example, Why Made code 75 (tread shelled) is strongly related to the thermal loads placed on wheels during braking. In car series 1 data, this code accounted for 67 percent of the replacements in standard truck equipped cars and 59 percent in Frame Brace™ with the primary pads removed equipped cars.

After characterizing the non-wear failures as censored, Weibull parameters were estimated for all the fleets. In each case, the wear-related parameters are higher, which is to be expected. For some of the fleets, the increases are extremely high. For Car series 1, the scale parameter virtually doubled, and for Car series 4, the scale parameter increased by 95 percent for one truck set and 76 percent for the other. These results demonstrate the cost to car owners of brake-induced wheel failures as measured in foregone wheel life. Figures 2 and 3 show the Weibull plots for standard trucks.

A brief comment on interpretation of probability plots is in order. Because the scales are log-log, there is a tendency to focus excessively on the early failures (i.e., the lower left quadrant). This is misleading when samples are large, as in this case, when the relevant features are found in the upper right quadrant. The line marked 63rd percentile approximates the scale parameter when the corresponding mileage is read off the horizontal axis; the slope of the fitted line is the shape parameter. Components that are suited to preventive maintenance show a steep slope. Notice the dramatic increase in both the scale parameter value and the steepness in Figure 3. In almost every case, the competing risks analysis shows the shape parameter increasing, often dramatically, thus improving the ability to implement planned maintenance activities.

To estimate the economic effect of the current reduction in wheel life, a simple cost analysis was performed using the Railroad 1 parameters and the usage characteristics of this fleet. At 90,000 miles per year, a 10 percent discount rate, 20-year car life, and \$1000 cost per wheel set, the loss of wear life translates into a net present value of \$8,142 per car. In addition, because the shape parameter associated for wheelsets subject to brake-related failures is so much lower than for wear-only failures, the opportunities for predictive and preventive maintenance are significantly reduced. Given

a shape parameter greater than three, maintenance managers could easily direct the removal of wheelsets to be programmed to coincide with other maintenance activities.

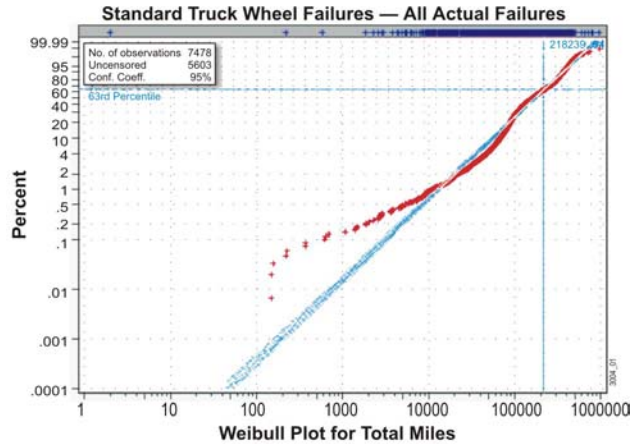


Figure 2. Weibull Plot for All Modes Wheel Failures

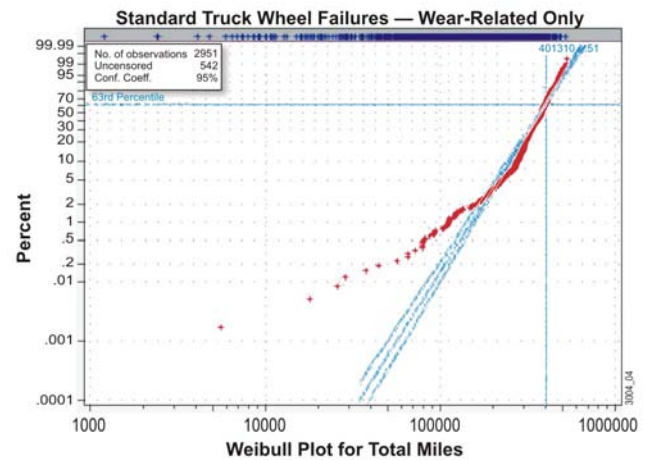


Figure 3. Weibull Plot for Wear-Related Wheel Life

WHEEL LIFE OF TRUCKS WITH PRIMARY PADS REMOVED

Because the fleet studied had a substantial number of cars with Frame Brace™ trucks with the primary suspension pads removed, it was possible to determine their effect on wheel life. The data included 352 cars without Frame Brace™ trucks, constituting 7,478 observations of wheel replacement. Of these, 5,603 observations were uncensored; i.e., complete life observations. The average annual mileage for cars without these trucks was 87,411 miles per year. The data also included 572 cars that were Frame Brace™ equipped and with the primary pads removed during the study period. These cars constituted 2,951 observations, of which 2,671 observations were uncensored, averaging 96,371 miles per year over the study period.

Weibull parameters were estimated for wheels used on both types of cars (Table 1). For cars with standard trucks, the scale parameter was 218,283 miles (with a 95% confidence interval of 214,764 – 221,860). The shape parameter was estimated as 1.628 (1.5958 – 1.6607). The mean life for wheels used with standard trucks was 195,408 miles. For Frame Brace™ trucks with primary pads removed, the scale parameter was estimated at 212,278 miles (207,151 – 217,531), the shape parameter at 1.603 (1.5568 – 1.6508), and the mean at 190,289 miles. There is no difference in wheel life between the standard three-piece trucks and the cross-braced trucks with the primary suspension pads removed. This suggests that removal of the primary suspension pads negates the wheel wear advantages made possible by the improved curving performance of trucks with primary pads.

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Table 1. Weibull Analysis Results

Car Series	Truck Type	Failure Type	Shape (β)	Scale (α) in Miles	95% LCI, Shape	95% UCI, Shape	95% LCI, Scale	95% UCI, Scale	Mean	Median
1	Standard 3-piece truck	All	1.63	218,284	1.60	1.66	214,765	221,861	195,408	174,279
		Wear Related	3.38	437,618	3.25	3.51	428,688	446,776	393,006	391,598
	Frame Brace™ without primary pads	All	1.60	212,278	1.56	1.65	207,152	217,531	190,289	168,894
		Wear Related	4.68	401,339	4.42	4.97	394,093	408,717	367,106	371,114
2	New Technology Type-1	All	1.62	342,901	1.47	1.78	316,974	370,950	307,136	273,378
		Wear Related	1.61	350,903	1.46	1.78	323,489	380,639	314,420	279,488
	New Technology Type-2	All	1.70	266,544	1.61	1.80	256,199	277,307	237,815	214,872
		Wear Related	1.79	282,117	1.69	1.89	270,794	293,915	250,986	229,756
	New Technology Type-3	All	1.12	359,735	1.03	1.22	326,045	396,096	344,937	259,470
		Wear Related	1.09	394,113	0.99	1.19	353,273	439,675	381,800	281,311
3	New Technology Type-1	All	2.46	386,191	2.21	2.71	366,282	407,183	342,520	332,709
		Wear Related	3.17	476,639	2.81	3.58	450,484	504,312	426,725	424,633
	New Technology Type-2	All	2.82	360,829	2.53	3.14	343,478	379,057	321,382	316,833
		Wear Related	3.50	415,330	3.07	3.98	394,911	436,804	373,663	373,981
	Standard 3-piece truck	All	1.85	304,262	1.70	2.01	286,730	322,867	270,271	249,483
		Wear Related	2.70	458,521	2.38	3.05	427,513	491,778	407,738	400,254
	New Technology Type-3	All	2.57	336,177	2.24	2.96	312,857	361,234	298,500	291,520
		Wear Related	4.71	450,190	3.81	5.83	419,851	482,723	411,917	416,480
4	New Technology Type-1	All	2.97	336,985	2.73	3.23	325,556	348,814	300,785	297,853
		Wear Related	2.40	660,250	1.98	2.91	553,159	788,073	585,314	566,853
	New Technology Type-3	All	2.33	345,861	2.17	2.50	332,003	360,297	306,455	295,540
		Wear Related	3.07	611,107	2.64	3.58	554,189	673,870	546,296	542,400

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