Procedure for Reliability Analysis of Wheelchair Lifts

SNEHAMAY KHASNABIS, HALUK AKTAN, AMARNATH KAMBHATLA, AND QUN LIN

Transit experts are concerned that wheelchair lifts in transit buses often do not work. The exact nature of the problems related to these lifts is not documented in the literature, but it is generally believed that the problems are not the consequence of a single factor but are caused by a combination of factors encompassing the lifts' design, manufacturing, operation, and maintenance. The objective of a project being conducted at Wayne State University is to assess and identify the sources of failure of wheelchair lifts in transit buses. As a part of the project the framework of a reliability model was established using available repair data on wheelchair lifts. A procedure for analyzing reliability of wheelchair lifts on the basis of commonly available repair data is presented. Repair data for two types of lifts for a random sample of five from each category were collected for 5 years from the regional transit agency in southeast Michigan. These data were used to develop, test, and validate Weibull models for analyzing the reliability of the lifts. The results indicate that the distribution of repair data, measured either in miles between repair (MBR) or time between repair (TBR), follow Weibull distribution patterns. Furthermore, the consistency in the parameters (for similar lifts) suggests that it is possible to predict repair needs of lifts as a function of TBR and MBR.

Many consider the enactment of the Americans with Disabilities Act of 1990 (ADA) to be a major step toward ensuring access to public facilities for persons with disabilities. Public transportation agencies in the United States have made serious efforts to provide such access to buses through wheelchair lifts since 1985. The ADA is expected to strengthen the commitment of the transportation sector to this cause. The purpose of the act is to make sure that the United States becomes a nation with transportation options for all its citizens regardless of their mobility constraints. The act stipulates that publicly funded systems must purchase (or lease) only accessible bus and rail vehicles so that no one is discriminated against when using public transportation facilities.

There is a concern today that wheelchair lifts in transit buses are often not in working condition. Although the exact nature of the problems is not documented in the literature, it is generally believed that they are not the consequence of a single factor but are caused by a combination of factors encompassing the design, manufacturing, operation, and maintenance of the lifts. In addition, compatibility of the lift life span with the bus life span concerns all operators.

This paper is the result of a project conducted at the Department of Civil Engineering, Wayne State University, to investigate the design, operation, and maintenance aspects of wheelchair lifts. The objective of the multiphased project is to assess and identify the sources of wheelchair lift failures in transit buses. In Phase 1, a preliminary investigation of the design, operation, and maintenance of wheelchair lifts was conducted. Manufacturers and fleet managers were surveyed, and a finite element model was developed to analyze the structural components of the lift mechanism. The framework of a reliability model was established using available repair data on wheelchair lifts.

In Phase 2, the modeling work (both structural and reliability) was continued in an effort to refine the models and to calibrate the various model parameters. An experimental investigation of the operation of wheelchair lifts was conducted in Phase 3 to aid in the development of structural specifications to improve the operation of wheelchair lifts. The Phase 1 report from which this paper is developed addresses the problem identification process designed to examine the serviceability of wheelchair lifts by a combination of engineering and statistical analysis. A discussion of the results of the entire Phase 1 report is beyond the scope of the paper, which instead will focus on the statistical analysis of a random sample of lift repair data.

TERMINOLOGY

Wheelchair lifts used in transit buses are categorized with respect to their architecture as active (platform) or passive (folding). The following terminologies are adopted from the U.S. Department of Transportation (*1*):

- Lift or wheelchair lift: A level-change device used to help those with limited mobility use transit and paratransit services. The terms "lift" and "wheelchair lift" are interchangeable.
- Active lift: An active lift is one that when stowed may interfere with the use of the vehicle entrance at which the lift is located and that when being raised and lowered operates primarily outside the body of the vehicle. It is also called a platform lift.
- Passive lift: A passive lift is one that when stowed allows the unlimited use of the vehicle door in which the lift is located. It is also called a step lift.

PURPOSE

Several transit operators in Michigan were interviewed for their input to the problem identification process. A compre-

Department of Civil Engineering, Wayne State University, Detroit, Mich. 48202.

hensive list of survey questions was prepared addressing issues of design, manufacturing, maintenance, and operation of wheelchair lifts. The survey was conducted on site with personal visits to transit operators. During the visits the interviewers tried to determine the availability and quality of repair data for wheelchair lifts. It was clear from the discussion with the transit agencies that the larger operators were more likely to have a comprehensive data base on lift maintenance and repair. As such, it was decided to investigate the repair data on step lifts available from the largest operator in southeast Michigan, the Suburban Mobility Authority for Regional Transportation (SMART). The purpose of this paper is to present a procedure for analyzing the reliability of wheelchair lifts on the basis of commonly available repair data. The specific objectives of the analysis conducted with the repair data are as follows:

1. To determine if there is a statistical pattern in the frequency and distribution of repair needs of wheelchair lifts;
2. To develop a reliability model for predicting repair needs, assuming the existence of a pattern; and
3. To determine if there are significant differences among the distributions of repair needs of different types of lifts.

METHODOLOGY

Weibull distribution is a common tool for reliability analysis of machine components. Weibull distribution was originally proposed for interpreting fatigue data; later it was extended to a variety of engineering problems, particularly those dealing with service life phenomena (*2*). Past research has shown that the Weibull distribution well describes the characteristic life of individual machine components and that exponential distribution (which can be shown to be a special case of Weibull distribution) is better suited to explain levels of assemblies or systems. Maze and others have demonstrated the application of Weibull distribution in transit maintenance and repair data (*3–5*). A sample of the lift repair data retrieved from the SMART buses when plotted on Weibull probability paper suggested a linear relationship typically expected of Weibull distribution (explained later in this paper). It was decided to apply the Weibull distribution to explain mathematically the repair needs of wheelchair lifts.

Assumptions

Two major assumptions were made before Weibull testing was conducted:

1. Current literature suggests that Weibull distribution appears to explain failure of component data better than system data. This is not to say, however, that system data do not fit Weibull distribution. Whether a lift is a component or a system is a matter of opinion. If one considers the bus to be an integrated system comprising the wheelchair lift, engine, chassis, transmission, brakes, and so on, then each of these entities could be considered a component. On the other hand, each entity in its own right could be considered a subsystem with subcomponents. Thus, a lift could be considered a subsystem consisting of subcomponents such as the platform, lifting device, and control mechanism. For this research, the lift was assumed to be a component.
2. Ideally, Weibull distribution explains failure data when, after failure, a component is discarded and replaced by a new component. But generally a lift does not fail in its entirety, and generally it is not discarded. Instead, repairs are conducted when needed. For the statistical analysis, it was assumed that after a repair, the lift becomes functionally a new component.

A software called Qualitek-2 developed by NUTEK was donated to the Department of Civil Engineering, Wayne State University; the software was used for analyzing the lift repair data. Qualitek-2 is a comprehensive package used extensively for failure data analysis; it can develop the Weibull parameters (slope and characteristic life), given the appropriate failure and repair data (*6*). The software can also test the goodness of fit of the Weibull model developed and generate confidence ranges of expected life of the component for various levels of statistical significance.

Mathematical Basis

The Weibull density function is of the following form (*2*):

$$f(x) = \left[\left(\frac{b}{\Theta - x_0}\right)\left(\frac{x - x_0}{\Theta - x_0}\right)^{b-1}\right] \times \left\{\exp\left[-\left(\frac{x - x_0}{\Theta - x_0}\right)^{b}\right]\right\} \quad (1)$$

where

x_0, b, Θ = parameters determined empirically or experimentally;
x = random variable;
x_0 = expected minimum value of x, or location parameter;
b = Weibull slope, or shape parameter, and
Θ = characteristic life, or scale parameter.

The cumulative distribution function, derived by integrating Equation 1, is

$$f(x) = \int_{-\alpha}^{x} f(x)dx = \int_{x0}^{x} f(x)dx$$

$$f(x) = \int_{x0}^{x}\left(\frac{b}{\Theta - x_0}\right)\left(\frac{x - x_0}{\Theta - x_0}\right)^{b-1} \exp\left[-\left(\frac{x - x_0}{\Theta - x_0}\right)^{b}\right]dx$$

Now, suppose

$$y = \left(\frac{x - x_0}{\Theta - x_0}\right)^{b}$$

then

$$dy = b\left(\frac{x - x_0}{\Theta - x_0}\right)^{b-1}\left(\frac{1}{\Theta - x_0}\right)dx$$

or

$$f(x) = \int e^{-y}dy$$

yields

$$f(x) = 1 - \exp\left[-\left(\frac{x - x_0}{\Theta - x_0}\right)^b\right] \quad (2)$$

To simplify the model development process empirically, it is sometimes assumed that the lower bound of life x_0, the expected minimum of the population, is zero. This assumption reduces the Weibull cumulative distribution function specified in Equation 2 to

$$f(x) = 1 - \exp\left[-\left(\frac{x}{\Theta}\right)^b\right] \quad (3)$$

Equation 3 is a simplified version with two parameters, compared with the three-parameter function specified in Equation 2.

Equation 3 can be rewritten as

$$\left[\frac{1}{1 - f(x)}\right] = \exp\left(\frac{x}{\Theta}\right)^b$$

Taking natural logarithms on both sides,

$$\ln\left[\frac{1}{1 - f(x)}\right] = \left(\frac{x}{\Theta}\right)^b$$

$$\ln \ln\left[\frac{1}{1 - f(x)}\right] = b(\ln x) - b(\ln \Theta) \quad (4)$$

Equation 4 has a form

$$Y = bX + C$$

where

$$Y = \ln \ln \{1/[1 - f(x)]\}$$
$$X = \ln x$$
$$C = -b \ln \Theta$$

The equation $Y = bX + C$ represents a straight line with a slope and intercept C on the Cartesian X,Y coordinates. Hence, a plot of Y against X will also be a straight line with slope b. Thus, the parameter b in the Weibull function is referred to as the "slope parameter." Figure 1 demonstrates different numerical values of Weibull slope. It can be shown further that when b equals 1, the Weibull distribution becomes an exponential function and that when b equals 3.5, it becomes a normal distribution.

To determine the probability that a part will fail at the characteristic life or less, from Equation 3

$$f(x) = 1 - \exp\left[-\left(\frac{x}{\Theta}\right)^b\right] = 1 - \exp\left[-\left(\frac{\Theta}{\Theta}\right)^b\right]$$
$$= 1 - e^{-1} = 1 - \left(\frac{1}{e}\right)$$
$$= 1 - \left(\frac{1}{2.718}\right) = 0.632$$
$$= 63.2 \text{ percent} \quad \text{for } x = \Theta \quad (5)$$

Thus, the characteristic life is the life by which 63.2 percent of the parts will have failed. Last, as stated before, the plot of Y versus X is a straight line with a slope of b. A special coordinate paper known as the Weibull probability paper, with a logarithmic abscissa scale and an ordinate scale transforming $f(x)$ to Y, is generally used to plot the distribution. Hence, a Weibull variable x plotted versus $f(x)$ on the paper will be represented as a straight line with a slope b as demonstrated in Figure 2.

RESULTS

A brief description of the data base used and the results of the analysis are presented in the following.

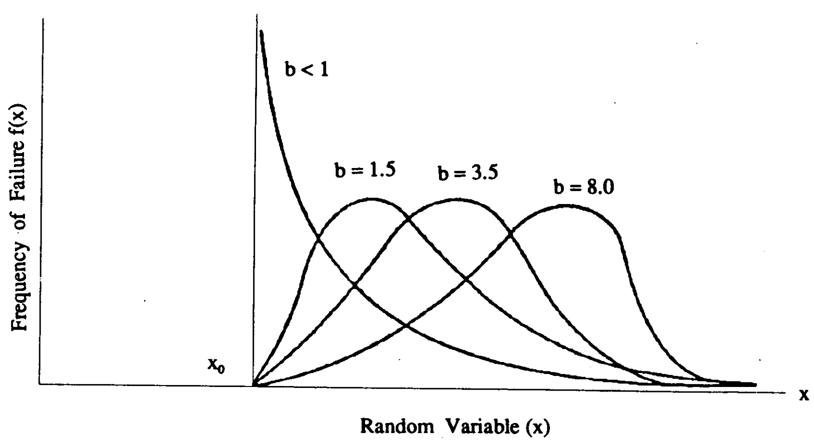

FIGURE 1 Density function of Weibull distribution (*2*).

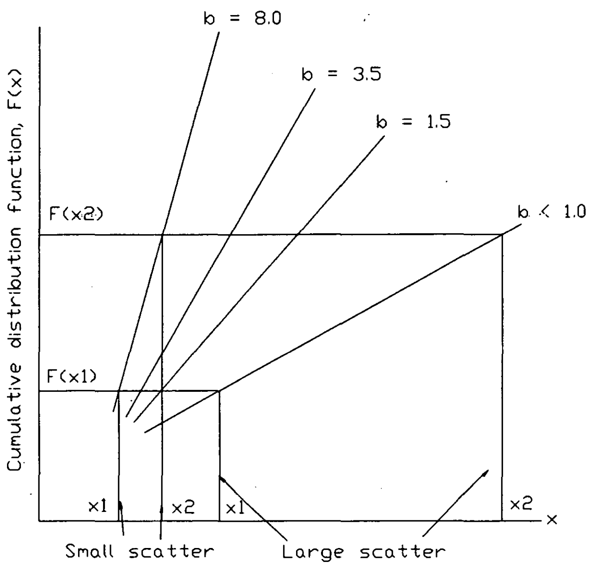

FIGURE 2 Weibull plots for various slopes on Weibull probability paper.

Data Base

The data base on lift repairs collected from SMART included the following:

- Period: 5 years (January 1, 1985, through December 31, 1989)
- Type of repair
  - General
  - Electrical
  - Mechanical
  - Body
  - Hydraulic
- Date of repair
- Mileage on day of repair
- Expenses incurred by labor hours and parts

These data were obtained from SMART for two types of step lift (A nd B), for five large transit buses for each type, making a total of 10 buses. The 10 buses were selected at random from more than 200 buses. Note that the repair data do not include the information on regular maintenance conducted at fixed intervals, usually every 3,000 mi. The data were then recast using the dBase III Plus software to depict information on the date of the repair, mileage, and expenses incurred in each of the five repair categories.

A review of the current literature indicates that for engineering analysis of repair data, two primary variables are used as the indicators of longevity of machine components: miles elapsed between successive repairs (MBR) and miles elapsed between successive repairs (TBR). For lifts, the number of cycles of operation is considered an ideal variable to depict longevity. Cycle data were not available, so MBR and TBR data were used in this study for lift reliability analysis. The repair cost data included in the data base were not used in the statistical analysis presented, primarily because of a wide variance in the distribution. An effort was made to segregate the MBR and TBR data by cost; however, this effort was discontinued because the resulting sample size became too small for statistical validity.

The MBR and TBR data were initially analyzed to conduct some basic statistical evaluation. Table 1 shows the means and standard deviations of the MBR and TBR distributions of the five lifts for Type A and B categories, for all repair codes considered together. The means of the two distributions are the mean time between repair (MTBR) and mean miles between repair (MMBR). Also included in Table 1 are beginning mileage and date, end mileage and date, number of repairs conducted during the 5-year period (*N*), and number of repairs per month (*n*). Finally, the grand mean values for the appropriate columns are also given in Table 1.

Table 1 indicates some trends that deserve attention. First, the consistency in the values of MTBR and MMBR and their corresponding variances is clearly noteworthy, despite the difference in the number of times that repair was needed (*N*-value). Second, Type A lifts appear to have greater longevity

TABLE 1 Summary of Repair Data for Type A and B Lifts (All Repairs Together)

Lift Type & number	Beginning		TBR (months)		MBR(miles)		N Number of Repairs	Repairs Per month	End	
	Date	Mileage	Mean	Std. Dev.	Mean	Std. Dev.			Date	Mileage
A-1	04-13-85	174,400	2.806	4.247	12,901	19,190	19	0.375	12-15-89	419,500
A-2	04-05-85	180,000	2.306	2.078	10,330	9,405	23	0.434	09-21-89	416,400
A-3	02-04-85	168,600	1.953	2.579	7,940	9,729	30	0.535	12-15-89	406,840
A-4	01-03-85	166,200	2.251	2.096	9,848	7,264	26	0.441	12-15-89	412,300
A-5	05-06-85	141,200	3.034	2.276	14,411	9,573	18	0.327	12-06-89	386,000
Grand Average			2.470	2.654	11,086	11,032	23.3	0.422		
B-1	01-08-85	91,700	1.245	1.388	6,508	6,508	49	0.881	12-04-89	291,690
B-2	01-02-85	86,700	1.820	1.675	8,176	8,176	33	0.559	12-13-89	296,500
B-3	12-27-84	86,300	1.353	1.429	6,998	6,998	45	0.717	12-18-89	295,300
B-4	01-24-85	92,800	1.415	1.710	8,401	8,401	41	0.695	12-13-89	297,500
B-5	01-28-85	117,100	1.455	1.213	6,259	6,259	41	0.695	12-19-89	301,600
Grand Average			1.457	1.483	7,268	7,268	41.8	0.710		

than Type B. A review of the grand mean values shows that on the average for Type A lifts, a repair was needed every 2.47 months or every 11,086 mi. The corresponding figures for a Type B lift were 1.46 months and 7,268 mi. Third, the number of repairs needed for the same 5-year period for Type A lifts was less than that for Type B. Type A lifts needed repair at the rate of 0.42 times per month; the corresponding figure for Type B was 0.71. Last, there was a strong correlation between MBR and TBR (correlation coefficient exceeding .90, not shown in the table). The ratio of MBR and TBR was an indicator of the number of miles driven per month for the bus equipped with the lift in question.

Analysis of MBR Data

Summarized versions of the Weibull test results of repair data of the MBR distribution for the 10 lifts (5 for Type A and 5 for Type B) are presented in Table 2. Figure 3 is adapted from the graphics output of Qualitek-2 representing the cumulative distribution function (CDF), as given in Equation 2, for Lift A1. The following observations from this table are in order:

1. Table 2 shows that in all 10 cases there is an excellent correlation between the dependant variable Y and the independent variable X in Equation 3 as indicated by high R^2-values (coefficient of correlation). The lowest R^2-value obtained is .928 for Lift A2, and the highest is .983 for Lift A1.
2. Table 2 also shows that the characteristic life (63.2 percentile value) for Type A lifts varies from 7,063 to 16,317 mi. The corresponding values for Type B lifts range from 5,485 to 8,801 mi. The composite averages of the characteristic values for Type A and B lifts are 11,034 and 7,254 mi, respectively. Furthermore, a closer examination of the characteristic life value shows that for Type A and B lifts, there are two outliers each in the distribution: A3, A5 and B1, B2. The characteristic life values in the other three cases, for Types A and B, are near the composite averages of 11,034 mi and 7,254 mi, respectively. Furthermore, a closer examination of the characteristic life value shows that for Type A and B lifts, there are two outliers each in the distribution: A3, A5 and B1, B2. The characteristic life values in the other three cases, for Types A and B, are near the composite averages of 11,034 mi and 7,254 mi, respectively.
3. The slope parameter b is within the proximity of unity, with 6 of the 10 values being less than 1 and the other 4 values exceeding 1.
4. In Table 2, the equations developed for the linear Weibull function (Equation 5) are also presented in the last column. The relationship between these equations and the parameter's slope and characteristic life are as follows:

From Equation 3,

$$Y = \ln \ln \left[\frac{1}{1 - f(x)}\right] X = \ln X C = -b \ln \Theta$$

so that $Y = bX + C$.

Referring to Lift A1 from Table 2,

$$b = 0.6505$$

$$C = -5.9961$$

since

$$C = -b \ln \Theta$$

$$-5{,}9961 = -0.6505 \ln \Theta$$

$$\ln \Theta = \left(\frac{5.9961}{0.6505}\right) \doteq 9.2176$$

so that

$$\Theta = e^{9.2176} = 10{,}073$$

Note that this value matches the calculated value of 10,075 as shown in Table 2.

TABLE 2 Weibull Parameters for MBR Distribution

Lift Type & number	R^2 Correlation Coefficient	Θ Characteristic life in miles	b slope	N Number of repairs	Equation Y=bX+c
A-1	0.9839	10075	0.65	19	Y=0.651X - 5.9961
A-2	0.9281	10811	1.09	23	Y=1.094X - 10.1562
A-3	0.9838	7063	0.76	30	Y=0.768X - 6.8052
A-4	0.9772	10904	1.41	25	Y=1.412X - 13.1255
A-5	0.9609	16317	1.62	17	Y=1.629X - 15.8052
Average		11034	1.10		
B-1	0.9518	5485	0.96	49	Y=0.962X - 8.2749
B-2	0.9558	8801	1.00	33	Y=1.003X - 9.1082
B-3	0.9776	6942	0.98	42	Y=0.981X - 8.6752
B-4	0.9789	7066	1.08	40	Y=1.086X - 9.6243
B-5	0.9679	7979	0.98	41	Y=0.989X - 8.8947
Average		7254	1.00		

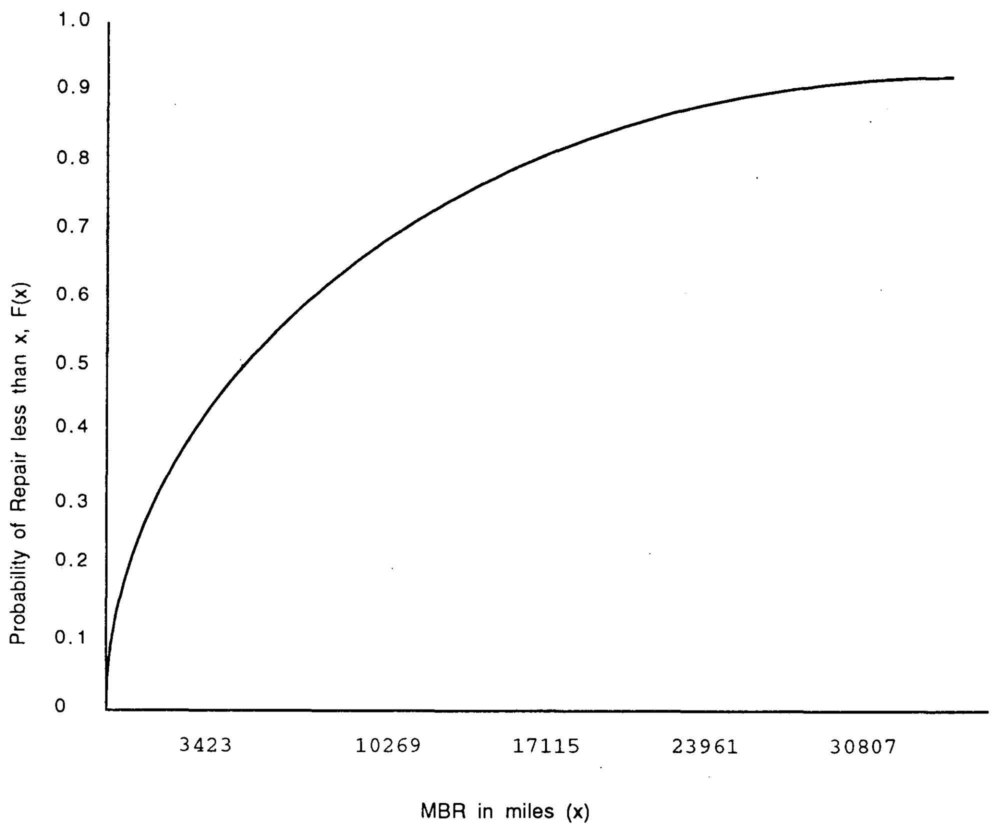

FIGURE 3 Weibull cumulative MBR distribution function for Lift A1 (Θ = 10,075 mi, b = 0.65).

Analysis of TBR Data

Table 3 shows the Weibull parameters for TBR distribution for the same 10 lifts. These tables can be interpreted the same way as explained for the MBR distribution in the preceding section. As with the MBR distribution, the characteristic life for the TBR distribution (63rd-percentile value of the time elapsed in months between successive repairs) is higher for Type A than for Type B lifts. This would seem to further support the idea that the longevity of Type A lifts is greater than for Type B. The following observations on the TBR Weibull function can be noted:

1. The consistency in the characteristic-life values within the same type of lift is worth noting, notwithstanding the difference between Type A and B lifts. For Type A lifts, the

TABLE 3 Weibull Parameters for TBR Distribution

Lift Type & number	R^2 Correlation Coefficient	Θ Characteristic life in months	b Slope	N Number of Repairs	Equation Y = bX + c
A-1	0.956042	2.08926	0.700	19	Y = 0.70X - 0.5191
A-2	0.848980	2.45072	1.060	23	Y = 1.06X - 0.9565
A-3	0.963278	1.67867	0.820	30	Y = 0.82X - 0.4282
A-4	0.973360	2.40805	1.110	25	Y = 1.11X - 0.9774
A-5	0.958320	3.44458	1.180	17	Y = 1.18X - 1.4659
Average	0.939996	2.41430	0.974	22.8	
B-1	0.9773260	1.55440	0.758	49	Y = 0.76X - 0.4791
B-2	0.9377720	1.86181	1.050	33	Y = 1.06X - 0.6562
B-3	0.9837175	1.35523	0.960	42	Y = 0.96X - 0.2948
B-4	0.9498300	1.39313	1.170	40	Y = 1.17X - 0.3899
B-5	0.9826970	1.57874	1.160	41	Y = 1.16X - 0.5310
Average	0.9662685	1.548662	1.019	41	

composite average characteristic life is 2.4143, indicating that 63 percent of the time a repair is likely to be warranted within 2.414 months. The corresponding figure for Type B lifts is 1.548662.

2. The slope parameter b for TBR distribution is close to unity, with 4 of the 10 observations being less than 1 and the remaining values exceeding 1.

3. In Table 3, the equation developed for the Weibull function is also presented in the last column. The relationship between these equations and the parameters b and characteristic life are the same as those explained for the MBR distribution.

Model Validation

The R^2-values presented in Tables 2 and 3 exceeding .90 in all the cases analyzed indicate an excellent correspondence between the model output and the observed data. Another validation effort was made by developing the parameters from a group of three lifts and applying these parameters on the remaining two lifts. The following three-step process was followed:

1. The mean values of the two parameters (slope and characteristic life) were computed for Lifts A1, A3, A5, B1, B3, and B5 (i.e., every other lift).
2. These parameters were applied to compute the CDF $f(x)$ for the remaining lifts—A2, A4, B2, and B4—as

$$f(x) = 1 - e^{-\left(\frac{x}{\Theta}\right)^b}$$

where b and Θ are the mean parameters and x is the random variable (i.e., MBR or TBR).

3. The computed CDF (using the preceding parameters) were compared with the actual observations for Lifts A2, A4, B2, and B4.

The results of this comparison are presented in Tables 4 and 5 for A2 and B2 lifts for MBR and TBR distributions, respectively. A visual comparison of these two distributions is presented in Figures 4 and 5. The tables and figures are self-explanatory and indicative of the very close correspondence between the observed data and the model output. For example, Table 4 indicates that according to the model, there is a 55.3 percent probability that a Type A lift will require a repair within 9,000 mi. For Lift A2, a repair was needed within 9,000 mi 52.3 percent of the time. Similarly, the model predicts that there is a 43.2 percent chance that a Type B lift will need a repair within 0.77 months. For Lift B2, 45.6 percent of the repairs were warranted within 0.77 months. Similar validation conducted for Lifts A4 and B4 (not shown in this paper) showed excellent correspondence between the model output and the observed data.

CONCLUSIONS

This paper aims to present a statistical approach for analyzing reliability of wheelchair lifts. Repair data for two types of lifts for a random sample of five from each category were collected for 5 years from the regional transit agency in southeast Michigan. These data were used to develop, test, and validate Weibull models for analyzing the reliability of the lifts. The procedure presented requires the availability of repair data

TABLE 4 Comparison of Weibull Model Output $f(x)$ with Actual MBR Values for Lift A2 (N = 23)

MBR (miles)	Frequency	Percent	Percentile	Model
0-2000	3	13.1	13.1	16.1
2000-3000	3	13.1	26.2	23.2
3000-3600	4	17.4	43.6	27.2
3600-9000	2	8.7	52.3	55.3
9000-13000	5	21.7	74.0	68.7
13000-18000	3	13.1	87.1	80.2
18000-+	3	13.1	100.0	100.0

TABLE 5 Comparison of Weibull Model Output $f(x)$ with Actual TBR Values for Lift B2 (N = 33)

TBR (months)	Frequency	Percent	Percentile	Model
0-0.2	4	12.2	12.2	16.8
0.21-0.47	5	15.2	27.4	31.2
0.48-0.77	6	18.2	45.6	43.2
0.78-1.70	5	15.2	60.8	66.3
1.71-2.90	5	15.2	76.0	81.6
2.91-3.84	5	15.2	91.2	88.3
3.84- +	3	9.1	100.0	100.0

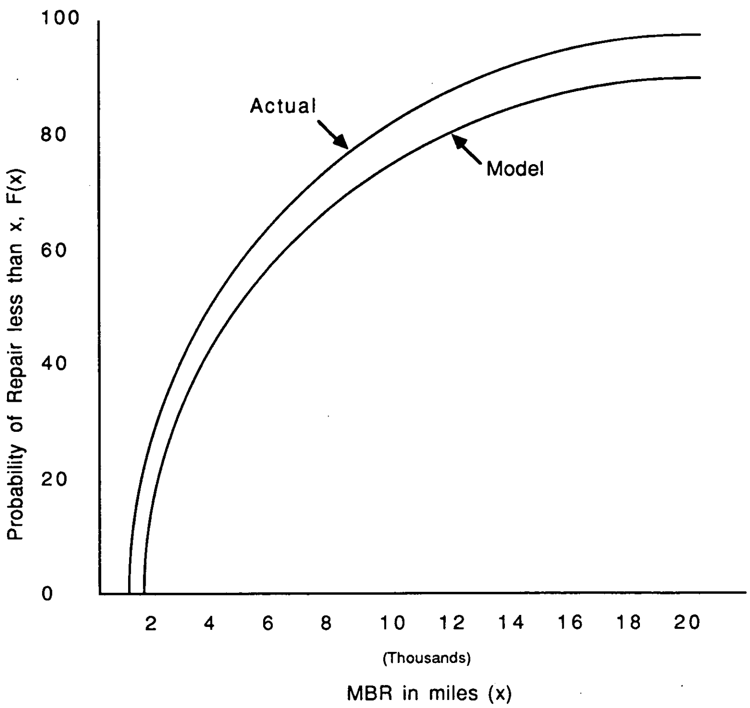

FIGURE 4 Comparison of actual data with model output for Lift A2.

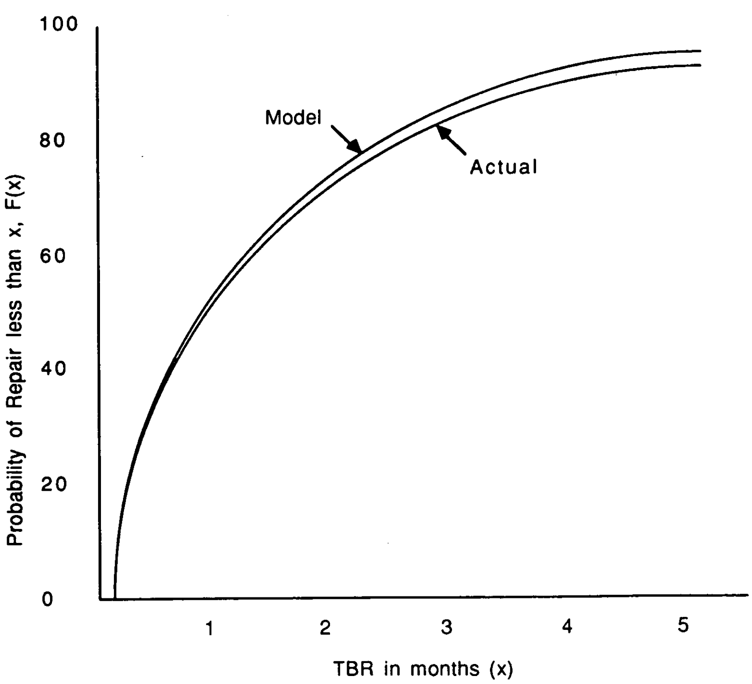

FIGURE 5 Comparison of actual data with model output for Lift B2.

likely to be collected by most large transit operators. The conclusions of this study follow:

- There is strong correlation between MBR (in thousands of miles) and TBR (in months) for wheelchair lifts.
- The statistical analysis of a 5-year repair data base of two types of lift for 10 lifts indicates that the distribution of repair data, measured either in MBR or TBR, follows Weibull distribution patterns.
- On the basis of the consistency in the values of the model parameters (slope and characteristic life), it is possible to predict repair needs of wheelchair lifts as a function of the distribution of MBR or TBR.
- From the distribution of TBR and MBR, it is possible to determine if there are significant differences between the repair needs of different types of lifts.
- Further studies should be conducted to incorporate cost factors in the reliability analysis of wheelchair lifts. The procedure presented in this paper is based entirely on the distributions of TBR or MBR.

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