COLLEGE OF
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Wayne State University

AN INVESTIGATION OF DESIGN, MAINTENANCE AND OPERATING PROCEDURES OF WHEELCHAIR LIFTS ON TRANSIT BUSES

FINAL REPORT
PHASE II

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(Phase - II)

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1. INTRODUCTION.

There is a concern today that wheelchair lifts installed in transit buses are sometimes not in working condition. While the exact nature of the problems related to these lifts is not documented in the literature, it is generally felt that these problems are not the consequence of a single factor. Rather, these are caused by a combination of factors encompassing the design, manufacturing, operation and maintenance of these lifts.

A project is currently being conducted at the Department of Civil Engineering, Wayne State University to investigate the design, operation and maintenance aspects of wheelchair lifts. The objective of this project is to assess the nature of the problems pertaining to any one or the combination of the design, manufacturing, operation, maintenance of wheelchair lifts of transit buses and to propose upgrade needs or operational changes to alleviate these problems. The project is conducted in three Phases over a three year period (1989-92). This report covers the work completed in the second year.

1.1 Terminology.

Wheelchair lifts that are used in transit buses are categorized with respect to its architecture as: Active Lifts (platform lifts). and Passive Lifts (folding lifts). The following terminologies defining the categories are adopted from the UMTA, USDOT [1].

Lift or Wheelchair Lift: A level change device used to assist those with limited mobility in the use of transit and paratransit services. The terms lift and wheelchair lift are used interchangeably.

Active Lift: An active Lift is one that when stowed may interfere with the use of the vehicle entrance where the lift is located and the when being raised and lowered operates primarily outside the body of the vehicle. (Commonly referred to as platform lifts.)

Passive Lift: A passive lift is one that when stowed allows the unlimited use of the vehicle door in which the lift is located. (Commonly referred to as step lifts.)

Other definitions used in this report are:

MBR: 'Miles Between Repairs' represents the number of miles that a bus equipped with a specific lift has traveled between two successive repairs of the lift in question.

TBR: 'Time Between Repairs' represents the amount of time measured in months that a bus equipped with a specific lift has traveled between two successive repairs of the lift in question.

1.2 Synopsis of Phase I Report.

The Phase I study completed during the 1989-90 can be categorized as a fact-finding mission designed to examine the serviceability of wheelchair lifts based upon an engineering analysis of the lift mechanisms. The approach taken to attain the Phase I objectives can be described as a series of sequential steps as follows:

Step 1 - Operator Survey: A number of transit operators (mostly rural operators) were interviewed for their input to the problem identification process. For this purpose, a comprehensive questionnaire survey was prepared addressing issues of design, manufacturing, maintenance, and operation of wheelchair lifts. The survey was conducted on site with personal visits to transit operator offices.

Step 2 - Compiling Technical Information: Through a formal library search process, a variety of technical information on wheelchair lifts was compiled. Much of the technical data thus compiled was used in the understanding of the behavior of the structural components and in the development of the finite element model.

Step 3 - Manufacturer Survey: A limited survey among the major wheelchair lift manufacturers in the U.S. was conducted. The survey was originally intended to be used to review the process of design and manufacturing of wheelchair lifts and their conformance to federal standards. Other objectives of this survey were to assess the manufacturer's perception on the probable causes of lift failure and to determine the possible impact of emerging technologies on the design and manufacturing process of these lifts. Unfortunately the survey results were of little consequence to the project because of a poor response.

Step 4 - Engineering Analysis of Structural/Mechanical Components: The purpose of this task was to identify specific operating components of the wheelchair lifts where failure/malfunctioning is likely to occur. The structural, mechanical and sensing components of the lift were analyzed. Also a computer- based finite element model was developed to analyze the structural components of the lift mechanism.

Step 5 - Analysis of Repair Data: Available data on maintenance/repair of wheelchair lifts was collected from two operating agencies in southeast Michigan. The data thus collected was analyzed to discern possible patterns in the maintenance needs of the wheelchair lifts. Also, the framework of a reliability model was established using available repair data on wheelchair lifts.

In Phase II, the modelling work (both structural and reliability) has been continued in an effort to refine the models and calibrate the various model parameters. Also an experimental investigation of the operation of wheelchair lifts was initiated to aid in the development of structural specifications to improve the operations of wheelchair lifts. Completion of the necessary experimental testing is expected during the Phase III of the project next year.

In summary, the completion of the Phase I study allowed the investigators to develop the foundation for assessing the nature of problems that affects lift performance. This was accomplished using two independent methodologies based on the following models:

Statistical Model for Lift Reliability: This model was based on lift repair data acquired from transit agencies. A preliminary methodology was developed with the objective of predicting failure rates of different lift models used in transit buses.

Structural Engineering Model for Lift Reliability: This model is based on a finite element description of the lift structural system. The model is formulated from engineering representations of the structural properties and topologies of various structural components in the fully deployed position. The model was used in Phase I for assessing the structural performance of the lift under specified demand conditions.

1.3 Scope of Phase II Study.

The primary purpose of the Phase II study was to continue the modeling work (both reliability and statistical) initiated in Phase I and to initiate the task of experimental testing of wheelchair lifts. The specific objectives of the Phase II study are:

i) To continue the development of the structural analysis model of rigid-platform lifts that will permit an in-depth analysis of stress-deformation of the components under various loading scenarios.

ii) To initiate structural analysis of folding platform lifts.

iii) To continue with calibration/refinement of lift reliability model.

iv) To initiate the experimental load testing of the two rigid-platform lifts most commonly used in buses procured by the Michigan Department of Transportation.

1.4 Specific Research Tasks.

Task 1. Literature Review:

An extensive literature survey was conducted to compile the specifications pertaining to not only to wheelchair lifts but to all lift systems for moving people. The literature provided a base line data in establishing allowable lift deformation, velocity, acceleration and jerk.

Task 2. Develop Realistic Load Demands:

The demands on lifts could vary widely depending on the type of use, environmental conditions and other factors. While normal loads are likely to prevail during much of the useful life of the lift, performance should also be specified under unusual loads. A set of realistic load demands and the lift performance expectations under a varying set of usage/load conditions was developed based upon information obtained from literature search and interview with transit agencies.

Task 3. Survey of Transit Agencies:

A set of surveys were conducted during Phase I among the transit agencies in Michigan (both rural and urban operators). The purpose of the survey was to obtain first hand information on issues related to the problems associated with wheelchair lifts. A number of other agencies identified in cooperation with the MDOT were visited during Phase II to increase the data base on wheelchair lift reliability.

Task 4. Structural Model Refinement:

The structural model developed in Phase I was further refined to ensure that: a) the various load demand conditions developed in task 2 can be accommodated in the model and b) the model output can be used to analyze the stress and deformations of the structural components of the lift.

Task 5. Structural Analysis Model of folding platform lift:

The model development describing the structural components of a typical folding platform lift was initiated in Phase II. The model thus developed can be utilized in identifying the possible weak links in the lift structure.

Task 6. Lift Reliability Statistical Model Refinements:

The reliability model was developed in Phase I for step lifts with limited data obtained from the regional transit operator in southeast Michigan, Suburban Mobility Authority for Regional Transportation (SMART). The model did provide a viable statistical approach towards analyzing repair data. In Phase II, the model was calibrated/refined with additional data and efforts were made to incorporate other pertinent variables. Additional data on lift repair from operators other than SMART were collected in order to refine the reliability model.

Task 7. Develop Experimental Procedure:

An experimental procedure was developed for assuring the compliance of the automatic rigid platform lifts with the structural specifications. The procedure development is to be completed in Phase III. The procedure may also be proposed as the certification procedure for the automatic rigid platform lifts prior to installation to MDOT buses.

Task 8. Preliminary Testing of Platform Lifts:

Two rigid-platform lifts that have completed the life cycle were procured through the assistance of MDOT as the specimens of the initial load testing. The lift brands are the most commonly used by rural transit agencies in Michigan. The primary purpose of the preliminary test is to ensure that the experimental procedure developed in task 7 can be implemented in a practicable manner. Testing on new lifts will be conducted in Phase III on completion of testing of the used lifts.

2. LITERATURE SURVEY.

2.1 Introduction.

The purpose of this chapter is to document the information gathered on different aspects of wheelchair lifts from manufacturers and , literature published. The following approach used to collect and assimilate the data concerning specifications of wheelchair lifts.

1) Identification of manufacturers from the trade magazines, transit industry directories and general industry directories.

2) Review of manufacturer's literature and brochures.

This review concerns guideline specifications of the active and passive wheelchair lifts. This review specially focused on the specifications related to structural, technical and design requirements , as well on testing and maintenance of the wheelchair lifts.

2.2 Technical Requirements.

The general technical requirements for wheelchair lifts can be described as follows:

i) Operating Environment: The lift should work in all the environments especially during the cold and hot temperatures ranging from -10° F to 115° F, and also at relative humidities 5 percent to 100 percent. Special hydraulic fluids and lubricants should be used to operate the lift for low/high temperature operating conditions.

ii) Weight: The weight of the lift should not adversely affect the legal axle loading, the maneuverability, structural integrity, or safe operation of the vehicle. Therefore lift system self-weight is limited to 1000 pounds for standard buses and 400 pounds for small buses. Operating design load is specified at 1000 pounds and the ultimate load is 2500 pounds for the initial yielding in any component.

iii) Operating Constraints: The lift should not operate when the bus is not on the level ground and the angle with the ground exceeds four degrees. Precaution should be taken that the lift be deployed on even ground surface to avoid any structural damage.

iv) Location of The Lift: The lift should be installed on the side of the vehicle opposite to the drivers seat or at the rear door of the bus so that the driver of the bus knows the safe deployment of the lift platform and passenger.

v) Protective Covering: All sharp edges or other hazardous protrusions on the wheelchair lift should be padded with energy absorbing materials to minimize injury in normal use.

vi) Operation of Counter: This optional provision is recommended to use counter that records each complete up and down cycle of the lift. These counters may provide data on lift use in statistical analysis.

vii) Platform Dimensions: The minimum clear width of the platform should be 30 to 32 inches. The minimum clear length of the lift platform as measured between the outer barrier and the inner edge or roll stop should be 40 inches. To accommodate the lift, the minimum height of the door opening at the wheelchair lift should be 56 inches.

viii) Platform Surface: The surface of the platform should be slip resistant for passenger safety. No protrusions on the platform should be greater than 0.25 inch or smooth rise greater than 0.5 inch, except for the stationary edge guards, inner roll stops, or outer barriers.

ix) Platform Deflections: The deflection of the platform should not be greater than 3 degrees in any direction.

3. SURVEY OF TRANSIT OPERATORS.

A list of survey questions was specially designed for transit operators in Michigan to elicit their viewpoints, comments on the operation of the wheelchair lifts, (Appendix A). A total of six operators with their fleet size varying between 10 to 224 were visited by the project team during Phase I. Additional three agencies were visited during Phase II. Table 1 shows the complete list of agencies visited, (Phase I and II combined) their respective bus fleet sizes and the type of lifts used for wheelchairs. The project team consisting of the two CO-PI's and the graduate research assistant visited these agencies and conducted a comprehensive interview with a representative of the agency that required two hours of meeting time. The object of the formal questionnaire survey was to maintain consistency among the operators in the nature and types of the questions. Table 2 shows a summarized version of the responses received from the operators. In addition to the results compiled in Table 2, the following additional observation are cited from Phase I report for continuity and relevance to the project :

(a) The operators expressed their concern about the needs of the handicapped, and appear to follow manufacturer-recommended maintenance procedures for the wheelchair lifts.

(b) The smaller operators with their constrained resources, and often with limited facilities face the prospect of serious service disruption in the event of a lift malfunction, because of the very little spare factor associated with their fleet.

(c) Larger operators are better equipped with manpower and maintenance/repair facilities and are not affected as adversely as the small operators in the event of lift malfunctions.

(d) The operators recognize the importance of proper training of the mechanics for the wheelchair lift maintenance and repair. This is evident from in-house training programs that they undertake and their participation in regional training programs offered by the MDOT during every summer, over and above the training usually recommended and sometimes provided by the lift manufacturer.

Table 1. Agencies Visited and Respective Fleet sizes, Common Lift Brands.

Agencies (Location)	Lift Type	Fleet Size (N)
SMART (Southeast Michigan)	TMC and LIFT-U (Large Buses) COLLINS (Small Buses)	224
LECT (Howell)	REB	10
EATRANS (Eaton County)	REB & COLLINS	15
SCTS (Sanilac County)	REB & COLLINS	10
HURON TRANS (Huron County)	REB & COLLINS	19
AATA (Ann Arbor)	ORION,TMC,LIFT-U,EEC	64
Jackson Transport Authority	REB,COLLINS,RTS(step)	42
Barry County Transit	REB	08
Prell Service (Alpena)	REB,COLLINS	22

Table 2. Operators Survey.

Name	Fleet Age	Procu-rement Specs.	Training Program	Lift Maintenance Schedule	Problems	CAUSES
1	10 Years	AMTMS	YES	Follows maintenance schedule well	No Serious problems.	NA
2	3 Years	SMART	YES	As and when needed.	Electrical system, Hydraulic pump cylinder system, Frame jerk & Swing.	Operation area is rural-dirt gravel.
3	3 Years	MDOT	YES	Follows maintenance schedule. Lifts. lubricated every two months or 3000 miles.	Electrical system, Pump oil link, Connecting pins, Frame jerk.	Inability of retraction mechanism to retain posi-tion during loading & insufficient shear strength of the pin connections
4	3 Years	MDOT	YES	NA	NA	NA
5	2 Years	MDOT	YES	Follows the maintenance manual. Lifts lubricated once in 3 months.	Electrical problems, Transmission flow Leaking.	NA
6	5 Years	MDOT	YES	Follows maintenance schedule well. Lifts lubricated every 3000 miles	Hydraulic, Electrical	Airlocks switches
7	6 Years	MDOT	NO	Same	Hydraulic, Electrical Welding	Under road Surface.
8	5 Years	MDOT	YES	Same	Hydraulic, Electrical Welding	Under road Surface.

(e) A number of the operators have a staffed maintenance/repair shop. However, the scope of the shop could vary from a full scale operation of major maintenance/repair service to a very basic repair facility. The latter case pertains to the smaller agency where, the operator either privately contracts for major repair services or seeks technical assistance from the regional transit agency, (if administratively possible). Staffing of maintenance/repair shop in most cases is inadequate.

(f) The extent of usage of the wheelchair lifts usually varies with the size of the population with impaired mobility. However, there appears to be some uniformity of usage over a period of a week for the same operator. For the smaller agency, many of whom operate on a para-transit mode, the lifts are used at least once per day. For the larger operator, with fixed route service, the usage rate varies with the specific route. In most cases, the lifts are 'cycled' at least once a day at the maintenance yard before the vehicle is dispatched for service. However, accurate data on lift usage per vehicle is not available.

(g) A number of operators expressed the opinion that the operating condition of lifts determinate quickly after a certain age. Age of lift rather than frequency of usage is a more important factor in this regard.

4. STATISTICAL ANALYSIS (OVERVIEW OF PHASE I).

A statistical analysis of repair data of two types of step lifts (type A and type B) was done. Repair data collected from the records of the regional transit operator SMART in south east Michigan was analyzed following formal statistical process to discern possible patterns in the maintenance needs of the wheelchair lifts. Also, the framework of a reliability model was established using available repair data on wheelchair lifts. The objective of the statistical analysis was (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 that can be used for predicting future repair needs. (3) to determine if there are significant differences between the distribution of repair needs of two types of lifts.

The repair data is retrieved from the individual repair records of the SMART data base on wheelchair lifts. The SMART data base consisted of 1) Five year time period 2) Two types of lifts, type A and type B, there being five buses in each category from a population of over 200 buses. 3) Different repair codes such as i) General Repair code-189 ii) Electrical repair code-190 iii) Mechanical repair code-191 iv) Body repair code-192 v) Hydraulic repair code-193. The repair data base also consisted of the date of the repair, mileage on the day of the repair and expenses incurred.

The repair data was collapsed into two subgroups; (1) for all repairs conducted under the 'general' category (2) those under all other categories. The statistical analysis conducted, was however, for all repairs considered together (first Subgroup). This is because of the fact that the sample size for the second subgroup became too small for statistical validity.

4.1 Mathematical Basis.

Weibull distribution, a common tool for reliability analysis of machine components, was originally proposed for interpretation of fatigue data, and later extended to a variety of engineering problems, particularly those dealing with service life phenomena [2]. Past research has shown that the Weibull distribution describes well the characteristic life of individual machine components, while exponential distribution (that can be shown to be a special case of Weibull distribution) is better suited to explain lives of assemblies or systems. The application of Weibull distribution in transit maintenance and repair data are found in literature [3,4,5].

A sample of the lift repair data collected specifically for this study, plotted on Weibull probability paper suggested a linear relationship typically expected of this distribution. A decision was made to apply the Weibull distribution to mathematically explain the repair needs of wheelchair lifts. A more complete discussion on the rationale for choosing Weibull distribution has been presented in the Phase I report [6].

A brief synopsis of the mathematical basis for the Weibull model (described in more complete detail in the earlier paper) is presented below.

4.1(a) Weibull Model with Minimum Life Parameter:

The Weibull Density Function is of the form [2]:

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

Where the parameters, x_0, b and θ are determined empirically or experimentally.

x_0	is the expected minimum value of x, often referred to as the location parameter.
b	is the Weibull slope, referred to as the shape parameter.
θ	is the Characteristic life, or scale parameter.

The Cumulative Distribution function, derived by integrating equation (1) is:

$$F(x) = \int_{-\alpha}^{x} f(x)dx = \int_{x_0}^{x} f(x)dx \qquad (2)$$

It can be shown that on integration,

$$F(x) = 1 - \exp\left[-\left(\frac{x-x_0}{\theta-x_0}\right)^b\right] \tag{3}$$

It can be further shown by taking natural logarithms both sides that:

$$\ln\ln\left(\frac{1}{1-F(x)}\right) = b[\ln(x-x_0)] - b[\ln(\theta-x_0)] \tag{4}$$

equation (4) has a form

$$Y = bX + C$$

Where

$$Y = \ln\ln\left(\frac{1}{1-F(x)}\right)$$

$$X = \ln(x-x_0)$$

$$C = -b\ln(\theta-x_0)$$

<u>*4.1(b) Weibull Model Without Minimum Life Parameter:*</u>

In the event that the minimum life is assumed to be zero, equations (3) and (4) can be rewritten as:

$$\left(\frac{1}{1-F(x)}\right) = \exp\left(\frac{x}{\theta}\right)^b \tag{5}$$

$$\ln\ln\left[\frac{1}{1-F(x)}\right] = b(\ln x) - b(\ln\theta) \tag{6}$$

Further, equations (6) has a form:

$$Y = bx + C$$

Where

$$Y = \ln\ln\left(\frac{1}{1-F(x)}\right)$$

$$X = \ln x$$

$$C = -b \ln\theta$$

It should be noted that the initial results reported in the Phase I report did not contain the location parameter x_0. In other words, the model presented last year was calibrated on the basis of equations 5 and 6, with the assumption that the minimum value of random variable x (whether TBR or MBR) at which a lift fails is zero. Model revalidation efforts conducted in Phase II incorporates the addition of the location parameter x_0.

In this analysis two variables 1) Miles elapsed Between successive Repairs (MBR) 2) Time elapsed in months Between successive Repairs (TBR) were used as an indicator of longevity of lift components. "Weibull Distribution" techniques is used as a tool for reliability analysis of the lift. The results of the Weibull distribution when plotted on Weibull probability paper, appeared to suggest a linear relationship typically expected of Weibull distribution.

4.2 Synopsis of Phase I Report:

Table 3 shows the MBR and TBR data for two types of lift analyzed in Phase I and is essentially reproduced from the earlier report for continuity. This data is for all types of repairs considered together (i.e. mechanical, electrical, hydraulic, etc.), other than the regular preventative maintenance. Tables 4 and 5 are also reproduced from the Phase I report to show the Weibull parameters for the MBR and TBR distribution [7]. A brief explanation of these Tables is given below.

Table 3 shows the mean and standard deviation of the TBR and MBR distributions of the five lifts for type A and type B category, for all repairs codes considered together. The means of the two distributions are referred to as Mean Time Between Repair (MTBR) and Mean Miles Between Repair (MMBR) in the report. Also included in Table 3 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 presented in Table 3.

Table 3 indicates some interesting trends that deserve attention. First, the consistency in the values of the MTBR and MMBR and their corresponding variances in clearly noteworthy, inspite of

Table 3. Summary of Repair Data for Type A and Type B Lifts. (All repairs together)

Lift Type & Number	Beginning		TBR (months)		MBR(miles)		N	N(Repairs/	End	
	Date	Milage	Mean	Std. Dev.	Mean	Std. Dev.	# Repairs	Month)	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		

Table 4. Weibull Parameters for MBR Distribution For Platform Lifts Without Location Parameters.

Lift Type & Number	R^2 Correlation Coefficient	"Θ" Characteristic Life in Months	b Slope	N # of Repairs	Equation y=bX+c*
A-1	0.9839	10075.0	0.65	19	y=0.651X - 5.9961
A-2	0.9281	10811.0	1.09	23	y=1.094X - 10.1562
A-3	0.9838	7063.0	0.76	30	y=0.768X - 6.8052
A-4	0.9772	10904.0	1.41	25	y=1.412X - 13.1255
A-5	0.9609	16317.0	1.62	17	y=1.629X - 15.8052
Average		11034.0	1.106		
B-1	0.9518	5485.0	0.96	49	y=0.962X - 8.2749
B-2	0.9558	8801.0	1.00	33	y=1.003X - 9.1082
B-3	0.9776	6942.0	0.98	42	y=0.981X - 8.6752
B-4	0.9789	7066.0	1.08	40	y=1.086X - 9.6243
B-5	0.9679	7979.0	0.98	41	y=0.989X - 8.8947
Average		7254.0	1.00		

* y=ln ln (1./1-F(x))
X= ln(x)
c=-b ln Θ

Table 5. Weibull Parameters for TBR Distribution For Platform Lifts Without Location Parameters.

Lift Type & Number	R^2 Correlation Coefficient	Θ Characteristic Life in Months	b Slope	N # of Repairs
A-1	0.956042	2.08926	0.700	19
A-2	0.848980	2.45072	1.060	23
A-3	0.963278	1.67867	0.820	30
A-4	0.973360	2.40805	1.110	25
A-5	0.958320	3.44458	1.180	17
Average	0.939996	2.41430	0.974	22.8
B-1	0.9773260	1.55440	0.758	49
B-2	0.9377720	1.86181	1.050	33
B-3	0.9837175	1.35523	0.960	42
B-4	0.9498300	1.39313	1.170	40
B-5	0.9826970	1.57874	1.160	41
Average	0.9662685	1.548662	1.019	41.0

* $y=\ln \ln (1./1-F(x))$.
$x=\ln(x)$.
$c=-b \ln \Theta$.

the difference in the number of times that repair was needed, (N-value). Secondly, lift type A appears to have higher longevity than type B. A review of the grand mean values shows, that for type A lifts, on the average a repair was warranted every 2.47 months or every 11,086 miles. The corresponding Figure for type B lift is 1.46 months or 7268 miles. Thirdly, the number of repairs needed for the same 5 year period for type A is less than that for type B. Type A Lift needed a repair at the rate of 0.42 times per month; the corresponding Figure for type B is 0.71. The above data indicates that the reliability of type A is higher with less frequent repairs and higher MTBR and MMBR values than type B. Next, there is significant difference in the number of miles driven per month for buses equipped with type A lift compared to those with type B. Although not included in Table 3, calculations indicated that for buses equipped with lift type A, the average number of miles driven per month is 4310, the corresponding Figure for type B is 3410. Lastly, there is a strong correlation between MBR and TBR (correlation coefficient exceeding 0.90, not shown in the Table). The ratio of MBR and TBR is an indicator of the number of miles driven per month for each lift type.

4.2 (a) Analysis of MBR Data :

Summarized versions of the Weibull test results of repair data of MBR distribution for the 10 lifts (5 for type A and 5 for type B) are presented in Table 4. Figures 1 and 2 are adapted from the graphics output of 'Qualitek 2' representing the density function (DF) as given by equation (1), as well as the cumulative distribution function (CDF),as given F(x) in equation (2), for lift A-1 and A-2. The following specific observation from this Table and charts are in order:

(1) Table 4 shows that in all the ten cases there is a reasonable correlation between the dependant variable Y and the independent variable X in equation (3) as indicated by high R^2 values (coefficient of correlations). The lowest R^2 value obtained is 0.928 for lift A2, and the highest is 0.983 for lift A1.

(2) Table 4 also shows that the characteristics life, (63.2 percentile value) for type A lifts varies from a low of 7063 miles to a high of 16,317 miles. The corresponding values for type B lifts range from 5485 miles to 8801 miles. The composite average values of the Characteristic value

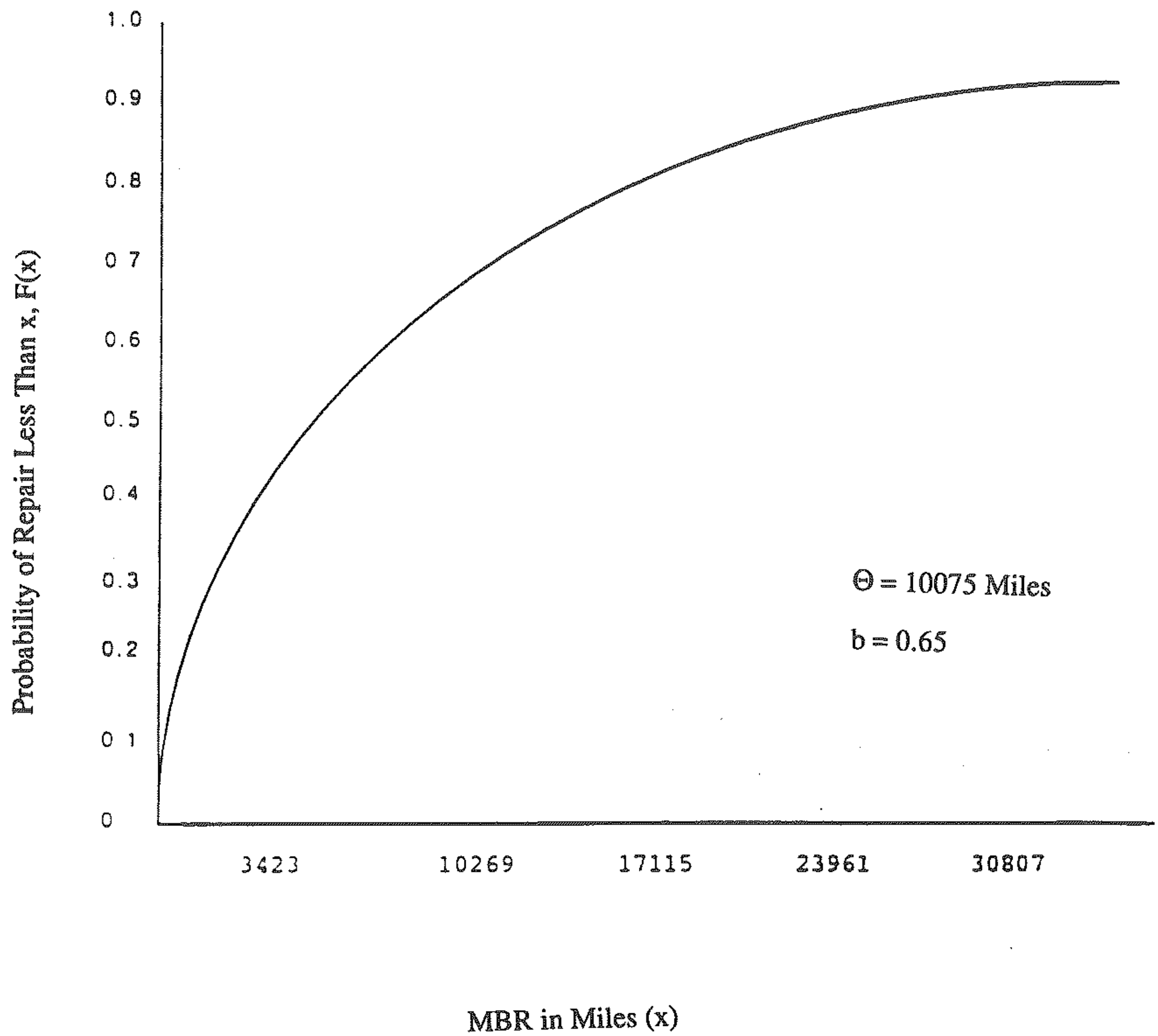


Figure 1 Cumulative MBR Probability Distribution Function For Lift A 1.

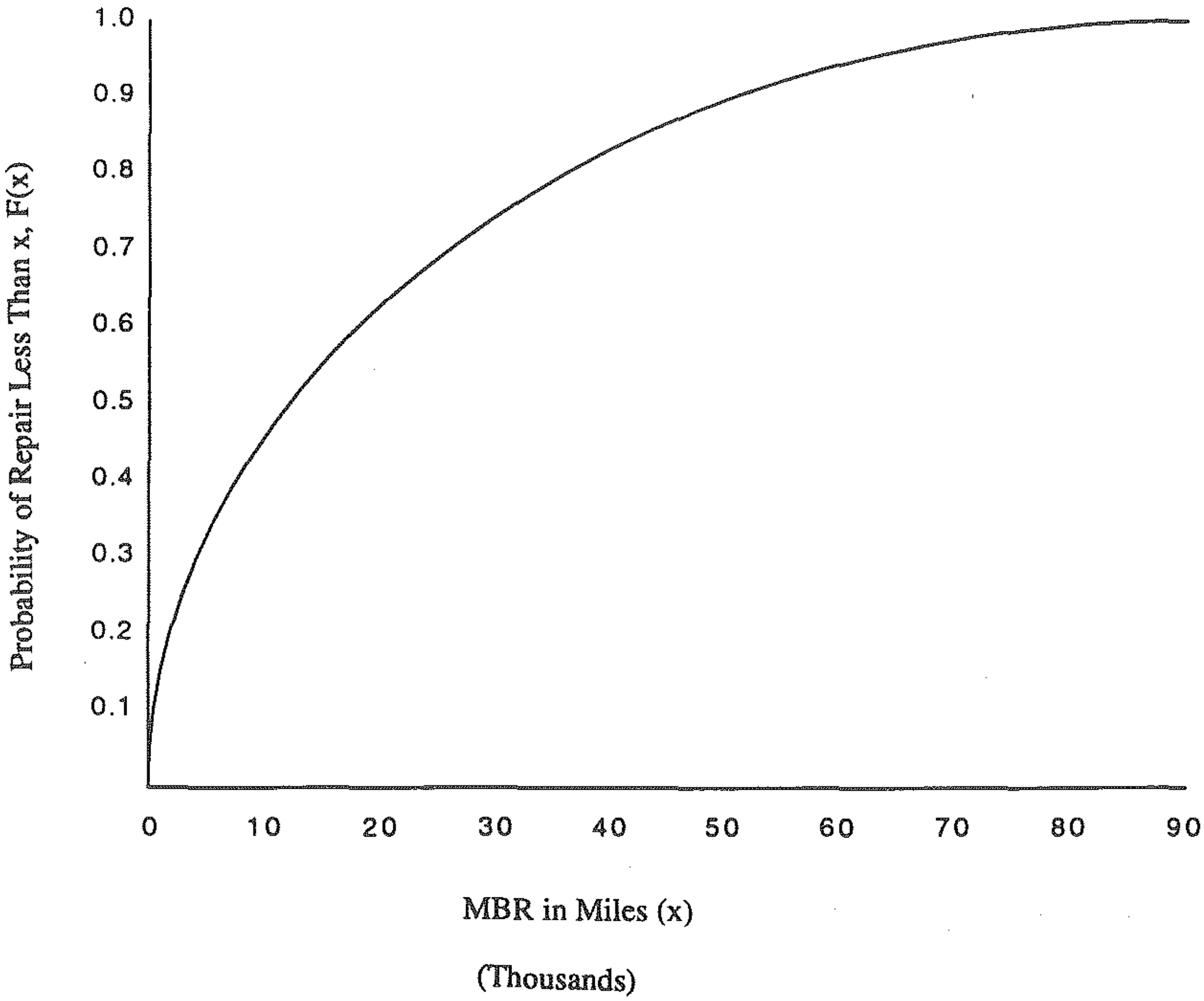


Figure 2 Cumulative MBR Probability Distribution Function For Lift A 2.

for the two types each consisting of five observations are 11,034 miles and 7254 miles. Furthermore a closer examination of the Characteristic life value shows that for both type A and type B, there are two 'outliers' each in the distribution, being A3 ,A5 and B1, B2. The Characteristic life values in the other 3 cases for both type A and B are around the respective composite average of 11,034 miles and 7254 miles respectively.

(3) The slope parameter 'b' is within the proximity of unity, with 6 of the 10 values being less than one, and 4 exceeding one.

(4) Figure 1 and Figure 2 represent the probability density function f(x) and the cumulative distribution function F(x) for lifts A-1 and A-2. It should be noted that for A-1 where b is less than unity, the density curve f(x) is monotonic with decreasing f(x) values with increase in x. For lift A-2 with b exceeding unity, the density curve attains a peak at an x-value exceeding zero, after which the curve becomes monotonic. The above feature is compatible with theoretical distribution of Weibull curves as reflected by varying value of b.

4.2 (b) Analysis of TBR Data :

Table 5 shows the Weibull parameters for TBR distribution for the same 10 lifts (5 for type A and 5 for type B). These Tables can be interpreted the same way as already explained for the MBR distribution in preceding section. As is the case of the MBR distribution, the characteristic life for the TBR distribution (63% percentile value of the time elapsed in months between successive repairs) is higher for type A lifts than type B. This would seem to further support the idea that the longevity of type A lifts is higher than that of type B. The following specific observation 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 lift type A and B. For lift type A, the composite average Characteristic life is 2.4143, indicating that 63% of times, for type A lift, a repair is likely to be warranted within 2.414 months. The corresponding Figure for type B lift is 1.548298.

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

(3) In Table 5, the equation developed for the Weibull function is also presented in last column. The relationship between these equations and the parameters b and Characteristic life are exactly similar to that already explained for the MBR distribution explained earlier.

4.2 (C) Model Validation :

The R^2-values presented in Table 4 and Table 5 exceeding 0.90 in all the cases analyzed and are indicative of an excellent correspondence between the model output and the observed data. An additional 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 3-step process was followed:

1) First, the mean values of the parameters slope and characteristic life value were computed for lifts A-1, A-3 and A-5, and B-1, B-3 and B-5 (i.e., every alternate lift).

2) These parameters were applied to compute the Cumulative Distribution F(x) for the remaining four lifts A-2, A-4 and B-2, B-4 as:

$$F(x) = 1 - e^{-\left(\frac{x}{\theta}\right)^b}, \textit{where } b, \theta \textit{ are the mean parameters}$$

x is MBR or TBR as the case may be.

3) The computed CDF (using the above parameters) were compared with the actual observations for lifts A-2, A-4 and B-2, B-4.

In Table 6 and Table 7, the results of this comparison are presented for A-2 and B-2 for MBR and TBR distributions respectively. A visual comparison of these two distributions is also presented in Figure 3 and Figure 4. These two Tables and Figures are self explanatory and indicative of the very close correspondence between the observed data and the model output. For example, Table 6 indicates that according to the model, there is a 55.3% probability that a type A lift will require a repair within 9000 miles. For lift A-2, 52.3% of the time a repair was needed within 9000 miles. Similarly, for type B lift, the model predicts that there is a 43.2% chance that it will

Table 6. Comparison of Weibull Model Output F(x) With Actual MBR Values for Lift A-2 (N=23).

MBR	Frequency	Percent	Percentile	Model[1]
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	100

1 Parameters for computing F(x): Θ=11,152; b=1.01

Table 7. Comparison of Weibull Model Output F(X) With Actual TBR Values for Lift B-2. (N=33).

TBR (months)	Frequency	Percent	Percentile	Model[1]
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	100

1 Parameters for F(x): Θ=1.5348 b=0.83

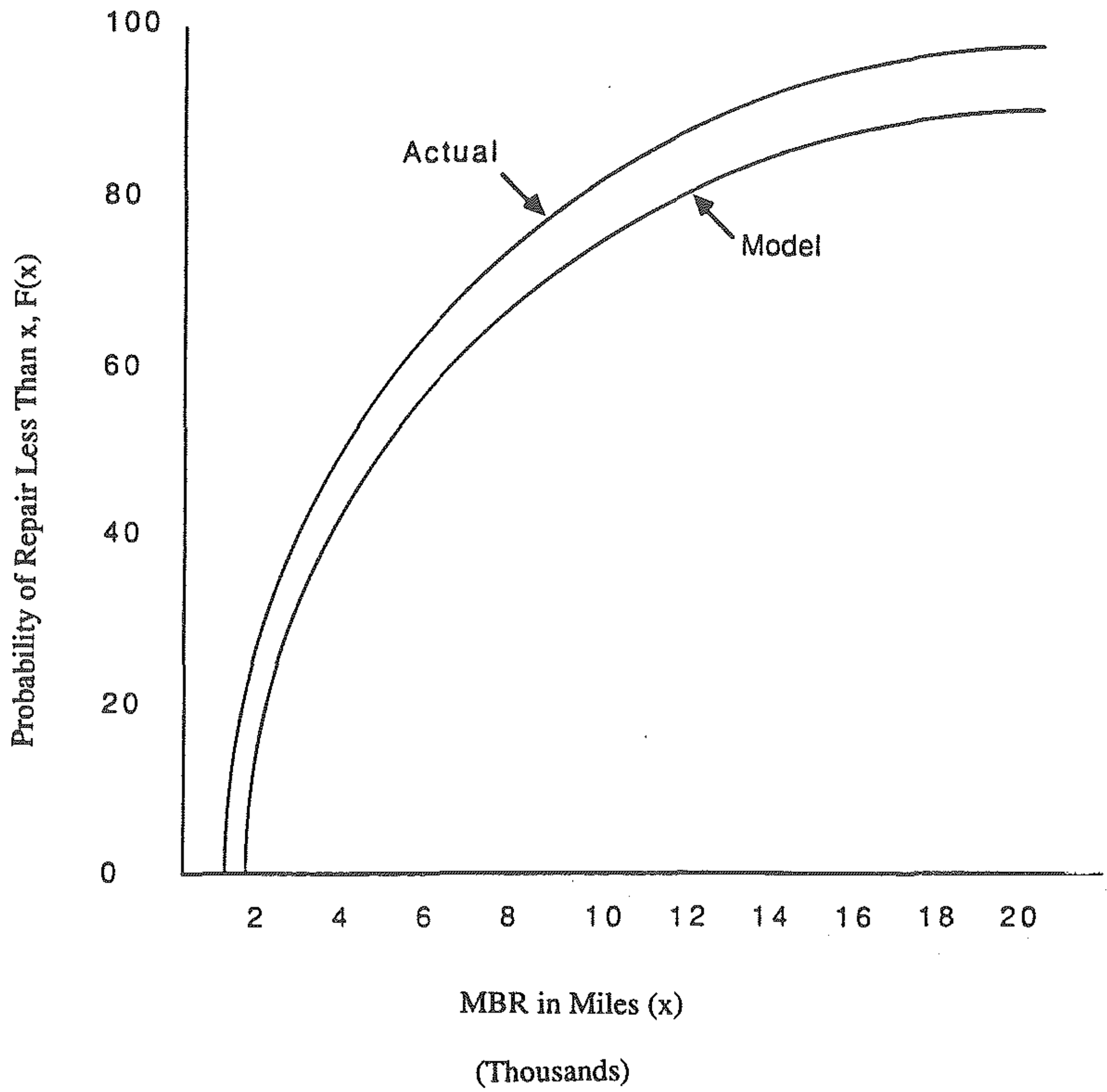


Figure 3 Comparison of Actual MBR Data With Model Output Lift A 2.

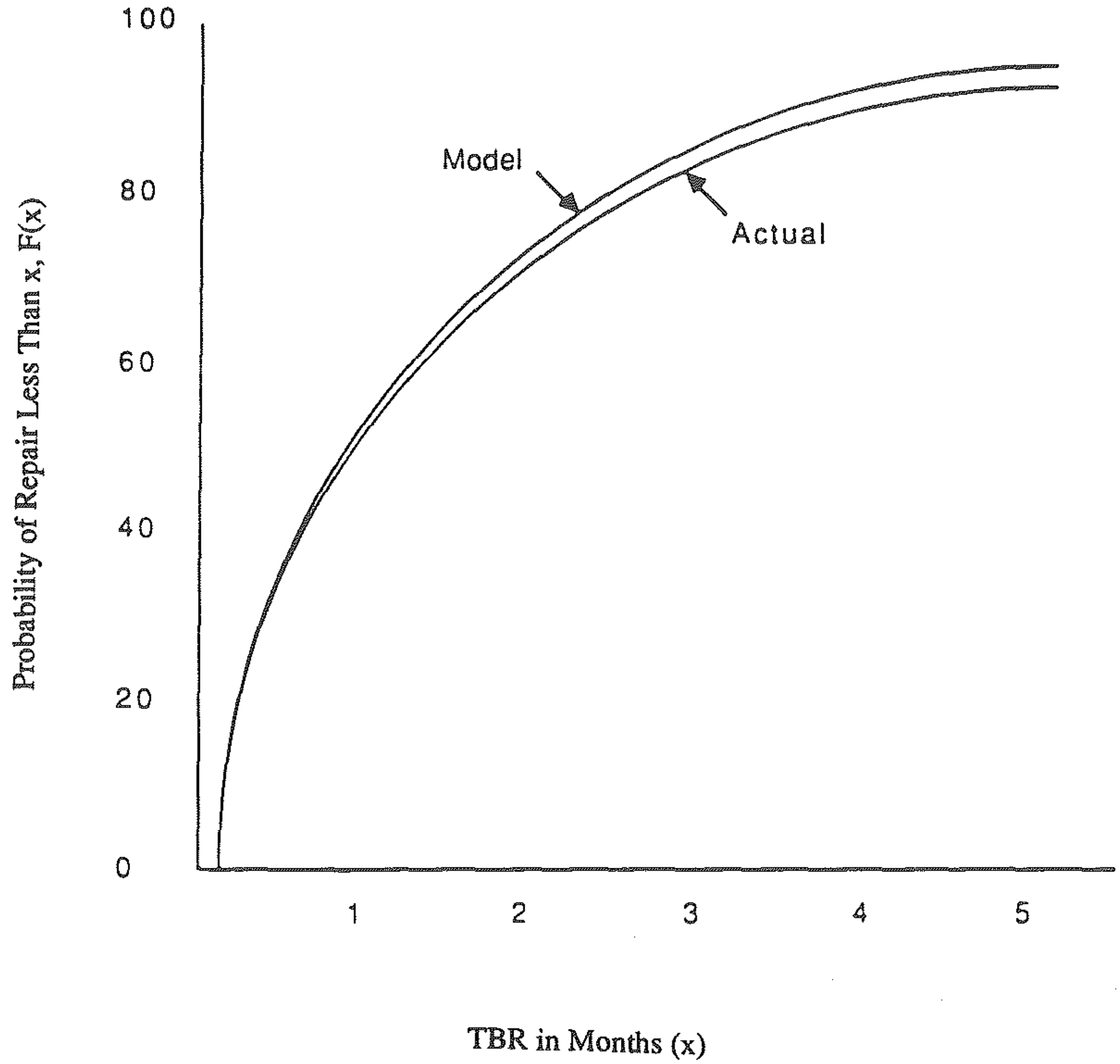


Figure 4 Comparison of Actual TBR Data With Model Output Lift A 2.

need a repair within 0.77 months. For lift B-2, 45.6% of the repairs were warranted within 0.77 months. Similar validation conducted for lifts A-4 and B-4 (not shown in this paper) showed excellent correspondence between the model output and the observed data.

Model validation efforts reported here were conducted using Phase I data base, but this work was completed in Phase II. As such this portion represents additional work.

4.2 (d) Conclusion.

The object of this analysis completed primarily in Phase I was 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 a five year period from the regional transit agency in Southeast Michigan, SMART. These data were used to develop, test and validate Weibull models for analyzing the reliability of the lifts. The conclusions of this study were:

1) There is strong correlation between miles driven between repairs (in thousands of miles) and time elapsed between repairs (in months) for wheelchair lifts.

2) The statistical analysis of a five-year repair data base of two types of lift for a total of 10 lifts (5 lifts for each type selected at random) indicates that the distribution of repair data, measured either in Miles Between Repair (MBR) or Time Between Repair (TBR) follows Weibull distribution patterns.

3) Based upon 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 TBR or MBR.

4) Based upon 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.

A summarized results of the Weibull distribution test for the 10 lifts (5 for type A and 5 for type B) were presented for both MBR and TBR distributions (Table 4 and Table 5). This study indicated that the distribution of repair data, measured whether in Miles Between Repair (MBR) or Time Between Repair (TBR) follow Weibull distribution patterns. Further, the consistency in the parameters (for similar lifts) suggest that it is possible to predict repair needs of lifts as a function of TBR and MBR. There was a strong correlation between miles driven between repairs (MBR) and time elapsed between repairs (TBR).

5. STATISTICAL ANALYSIS (PHASE II ACTIVITIES).

A statistical procedure for analyzing the reliability of wheel chair lift along with a case study application was presented in the previous chapter. Repair data for two types of step lifts for a random sample of five from each category was collected for a five year period from the regional transit agency in southeast Michigan, SMART. Note that the repair data does not include information on regular maintenance conducted at fixed intervals, usually every 3000 miles. The data collected was used to develop, test and validate Weibull models for analyzing the reliability of the lifts. It was found that the distribution of repair data, measured either in Miles Between Repairs (MBR) or Time Between Repairs (TBR) follows Weibull distribution pattern. Further, the consistency in model parameters (for similar lifts) suggests that it is possible to predict repair needs of lifts as a function of TBR or MBR.

Similar data from a smaller transit agency in Michigan was collected for a total of four platform lifts of a given type from a population of 50 lifts during Phase II. This data was used to develop reliability models for platform lifts. As in the previous use, the repair data does not include information on regular maintenance. In this chapter, the results of additional validation efforts toward the development of reliability models are presented.

5.1 Mathematical Basis.

The mathematical basis of Weibull distribution was presented in the previous chapter, and as such does not need repetition, The only major mathematical change in the models is the incorporation of the location parameters X_0, to the work on step lifts presented in the previous chapter as well as on the new work with platform lifts.

A review of the current literature indicates that for engineering analysis of repair data, two primary variables, i.e. "miles between repairs" (MBR) and "time between repairs" (TBR) are used as indicators of longevity of machine components. The repair cost data included in the data base was not used in the statistical analysis presented below, primarily because of a wide variance in the distribution. Further, miles traveled and time elapsed, rather than cost incurred are viewed as key indicators in the literature on reliability analysis. An effort was made to segregate the MBR and TBR data by cost; however, this effort was discontinued as the resulting sample size became too small for statistical validity.

5.2 Revalidation of Step Lift Model.

Table 5 and 6 in the previous chapter showed the Weibull parameters for the TBR and MBR distribution (without the x_0 parameter). Table 8 and 9 show the revalidated Weibull parameters based upon more recent work for TBR and MBR respectively. A software developed by MAZE at the University of Oklahoma was used for this purpose [8].

While the major difference between the information presented in Table 5 and Table 8 is the inclusion of the location parameter x_0 in the later work, a closer examination of these two Tables indicate the following:

(a) With the exception of lifts A-1 and B-5 there is no significant difference between the R^2 values, indicating that the goodness of fit provided by these two models are similar.

(b) The same observation can be made relative to the two parameters θ, (characteristic life) and b (slope). That is, with the exception of lifts A-1 and B-5, the inclusion of the location parameter (x_0) has not caused any significant difference in the values of these two parameters.

(c) The location parameter x_0 estimated during the revalidation forces has a range of values between 0.0001 month to 0.03 months. It stands to reason then that, because of the low values of x_0, there has not been any significant difference in the estimates of θ and b.

Table 9 shows similar data for MBR distribution. No effort was made to compare between the parameters θ and b for the MBR distributions with and without the location parameter. This is because of a strong correlation between TBR and MBR distribution, it is more meaningful to use TBR as a measure of the extent of usage of lifts rather than MBR. It should be noted that the collection of TBR data is a less involved process than that for MBR.

Table 8. Weibull Parameters for TBR Distribution of Step Lifts With Location Parameters.

Lift Type & Number	R^2 Correlation Coefficient	ΘCharacteristic Life in Months	b Slope	N # of Repairs	Xo (Minimum Life)
A-1	0.9022	2.3539	0.7681	19	0.013
A-2	0.8489	2.4507	1.0671	23	0.03
A-3	0.9633	1.6787	0.8268	30	0.003
A-4	0.9736	2.4122	1.1119	25	0.02
A-5	0.9583	3.4446	1.1853	18	0.02
Average	0.92926	2.4680	0.9918	23	
B-1	0.9542	1.5544	0.7582	49	0.001
B-2	0.9378	1.8618	1.0557	33	0.014
B-3	0.9888	1.4481	1.0186	42	0.003
B-4	0.9499	1.2542	1.1762	40	0.005
B-5	0.8876	1.6949	0.7667	41	0.0001
Average	0.94366	1.5627	0.9551	41	

Table 9. Weibull Parameters for MBR Distribution of Step Lifts With Location Parameters.

Lift Type & Number	R^2 Correlation Coefficient	ΘCharacteristic Life in Months	b Slope	N # of Repairs	Xo (Minimum Life)
A-1	0.983967	8060.28	0.6505	19	10
A-2	0.928086	10811.8	1.0935	23	0
A-3	0.983792	7063.0	0.7678	30	0
A-4	0.797426	12035.0	0.6938	23	0.5
A-5	0.701490	20401.1	0.5425	17	0
Average	0.878952	11674.3	0.7496	22.4	
B-1	0.983550	5489.0	0.7668	49	2
B-2	0.955880	6601.0	1.0027	33	100
B-3	0.957145	6966.0	0.7852	42	0
B-4	0.934650	6886.0	0.8129	40	0.5
B-5	0.924920	6856.0	0.7597	41	1.5
Average	0.951223	6560.0	0.8255	41	

5.3 Weibull Model Development For Platform Lifts.

In Table 10, summarized repair data for 4 platform lifts (type C) selected from a sample of 50 lifts from a local transit agency in Michigan is presented. Compared to similar information presented for step lifts in Table 3, it is to be noted, that for platform lifts there is a larger variation in the distribution of the repair needs. This is evident from the fact that in a majority of cases (3 out of 4), both for MBR and TBR distribution, the standard deviation exceeds those of the mean. This observation is further substantiated by a wider range of the value of n, (repairs per month) from a low of 0.609 to a high of 1.296. For step lifts, the corresponding range was form 0.327 to 0.535 for type A lift and from 0.695 to 0.881 for type B lifts (Table 3).

The Weibull parameters (including the location parameter x_0) for TBR and MBR distribution for the 4 step lifts are presented in Table 11 and Table 12. With the exception of the lift C-1, the consistency in the values of the parameters b and θ for the other three lifts is worth noting. It does appear that the lift C-1 is somewhat of an "outlier" in the distribution, in that it needed a much larger number of repairs (35) compared to the others for the same time period. It is not a surprise that the characteristics value θ, which measures the 63rd percentile value of the distribution is much lower, compared to the others (0.674 months and 994 miles for the TBR and MBR respectively). Further, in Table 10, it is to be noted, that the lift C-1 needed a much larger number of repairs per month, being equal to 1.296, whereas for the other three lifts, it is less than 1. Discounting the information on lift C-1, the consistency in the values of θ and b for the remaining lifts clearly suggests that repair needs of platform lifts can be predicted with some degree of statistical significance. It may be noted that a similar conclusion was reached relative to step lifts in the previous chapter.

The probability density function f(x) and the cumulative distribution function F(X) of the Weibull TBR distribution for the lifts C-1 through C-4 are shown in Figure 5 through 8. The corresponding MBR distribution for the same lifts are shown in Figures 9 through 12. The interpretation of these Figures are to be made in the same manner for type A and type B lifts, as

Table 10. Summary of Repair Data for Type C Lifts. (All repairs together)

Lift Type & Number	Beginning		TBR (months)		MBR (miles)		N	N(Repars/	End	
	Date	Milage	Mean	Std. Dev.	Mean	Std. Dev.	# Repairs	Month)	Date	Mileage
C-1	12-27-88	99,031	1.9589	2.46931	3,623	5,298	35	1.296	03-22-91	142,713
C-2	12-09-88	106,178	3.5235	3.9217	8,687	10,950	14	0.609	10-29-90	156,292
C-3	12-07-88	17,457	3.1408	2.8589	10,155	11,302	16	0.667	01-18-91	91,843
C-4	02-01-89	25,593	2.241	2.241	7,720	8,593	24	0.923	04-22-91	109,135
Grand Average			2.71605	2.8727	7546	9,036	22.25	0.8738		

Table 11. Weibull Parameters for TBR Distribution of Platform Lifts With Location Parameters.

Lift Type & Number	R^2 Correlation Coefficient	ΘCharacteristic Life in Months	b Slope	N # of Repairs	Xo Minimum Life
C-1	0.887	0.674043	0.7196	35	0.0034
C-2	0.954	1.522202	0.8017	14	0.0067
C-3	0.971	1.723309	0.8593	16	0.0034
C-4	0.979	1.117742	0.9002	24	0.0034
Average	0.948	1.259324	0.8202	22.25	

Table 12. REB Weibull Parameters for MBR Distribution of Platform Lifts With Location Parameters.

Lift Type & Number	R^2 Correlation Coefficient	ΘCharacteristic Life in Miles	b Slope	N # of Repairs	Xo Minimum Life
C-1	0.905	994.76	0.5384	35	0
C-2	0.950	3557.79	0.5934	14	0
C-3	0.964	4191.71	0.7151	16	11.6
C-4	0.978	3341.13	0.6994	24	0
Average	0.949	3021.35	0.6366	22.25	

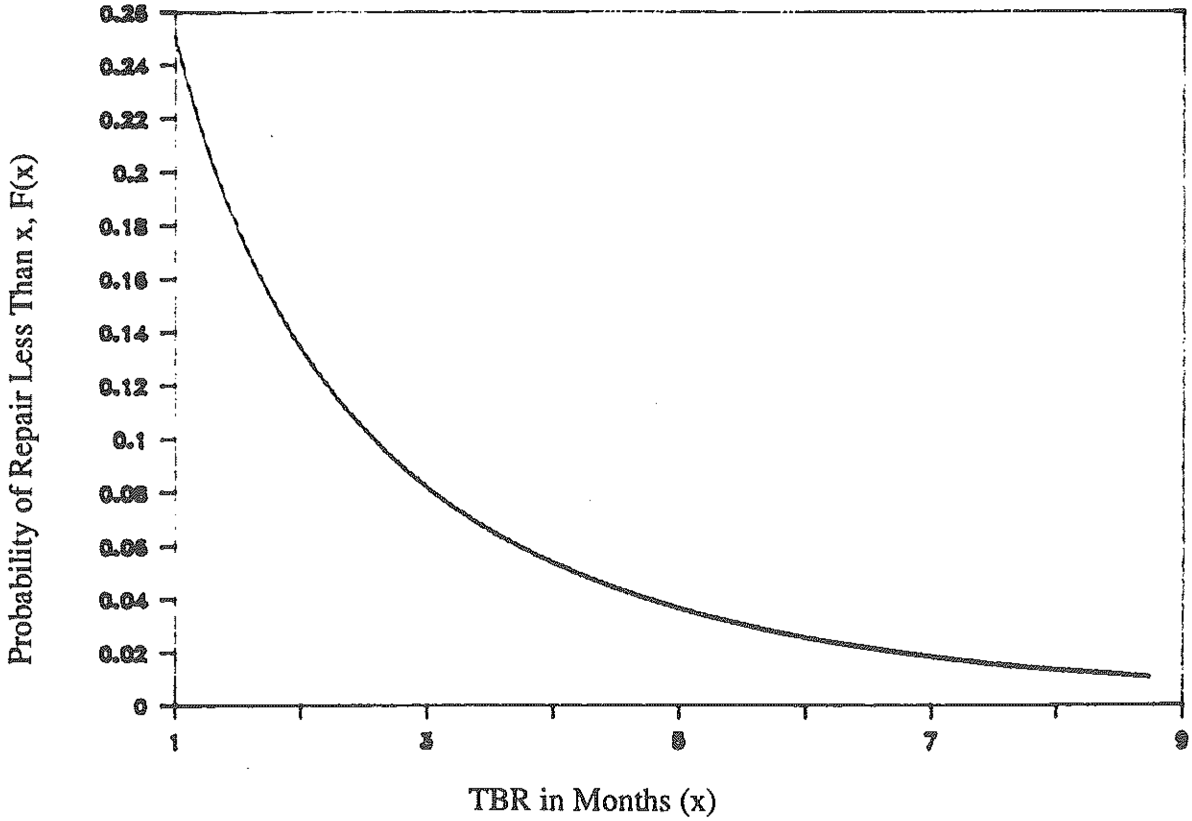


Figure 5 (a) TBR Probability Distribution Function For Lift C 1.

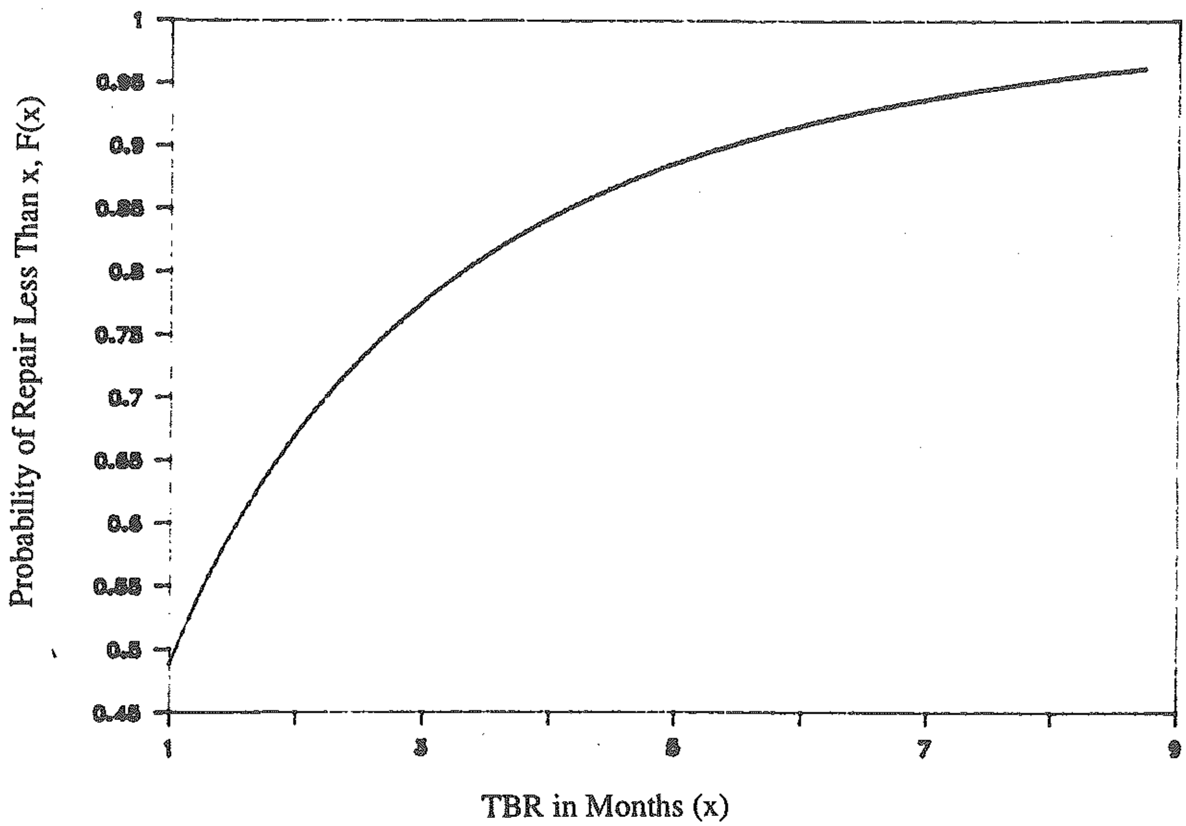


Figure 5 (b) Cumulative TBR Probability Distribution Function For Lift C 1.

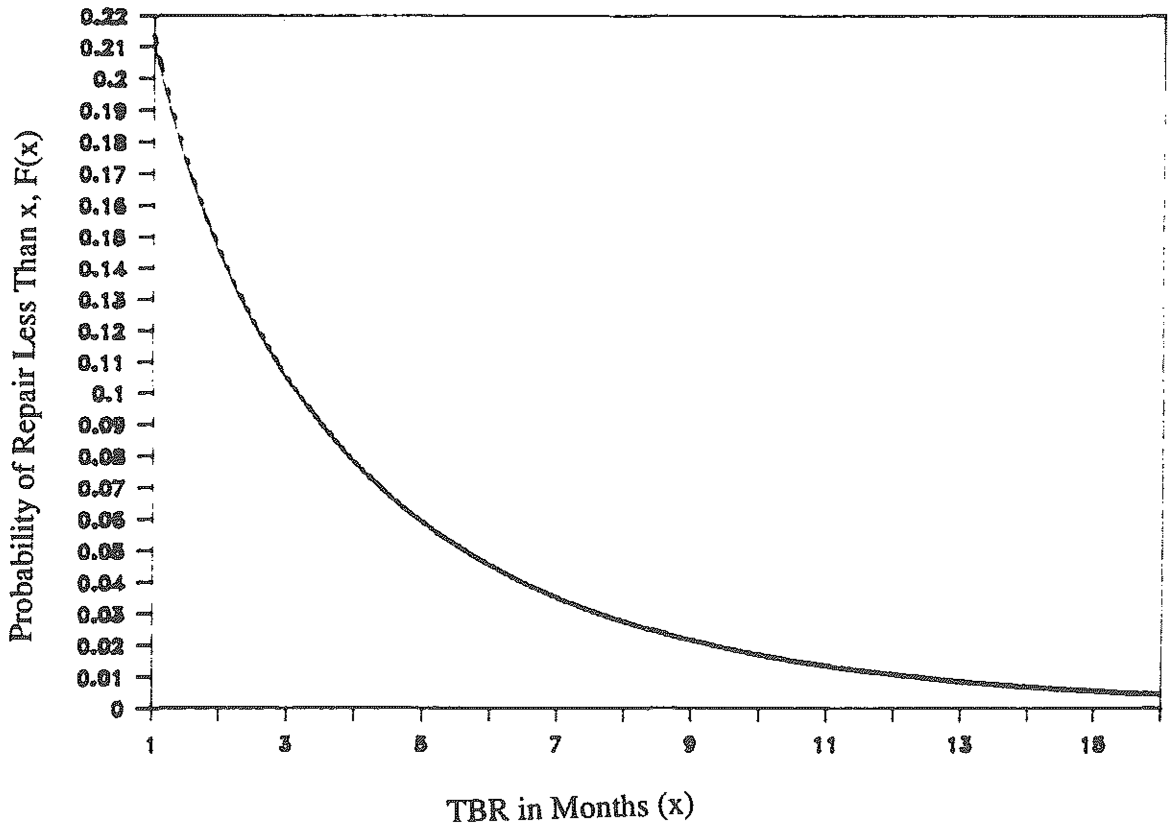


Figure 6 (a) TBR Probability Distribution Function For Lift C 2.

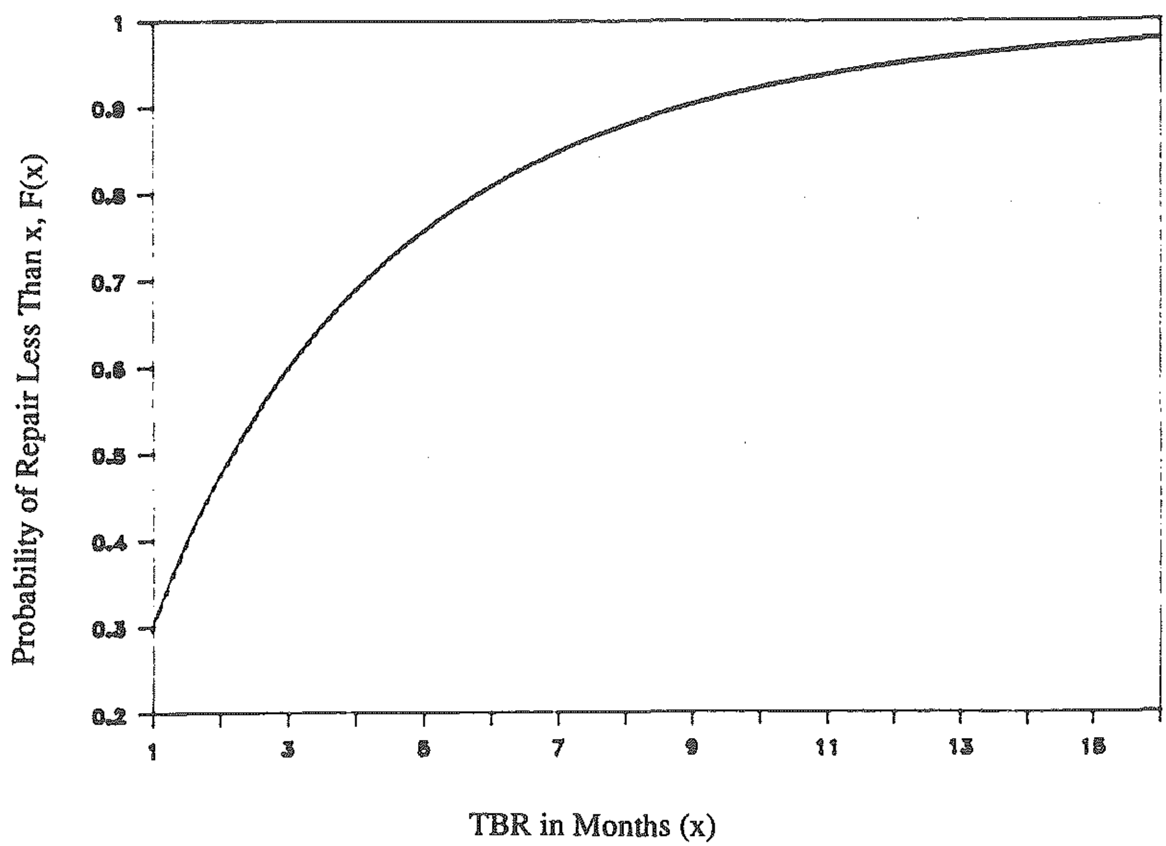


Figure 6 (b) Cumulative TBR Probability Distribution Function For Lift C 2.

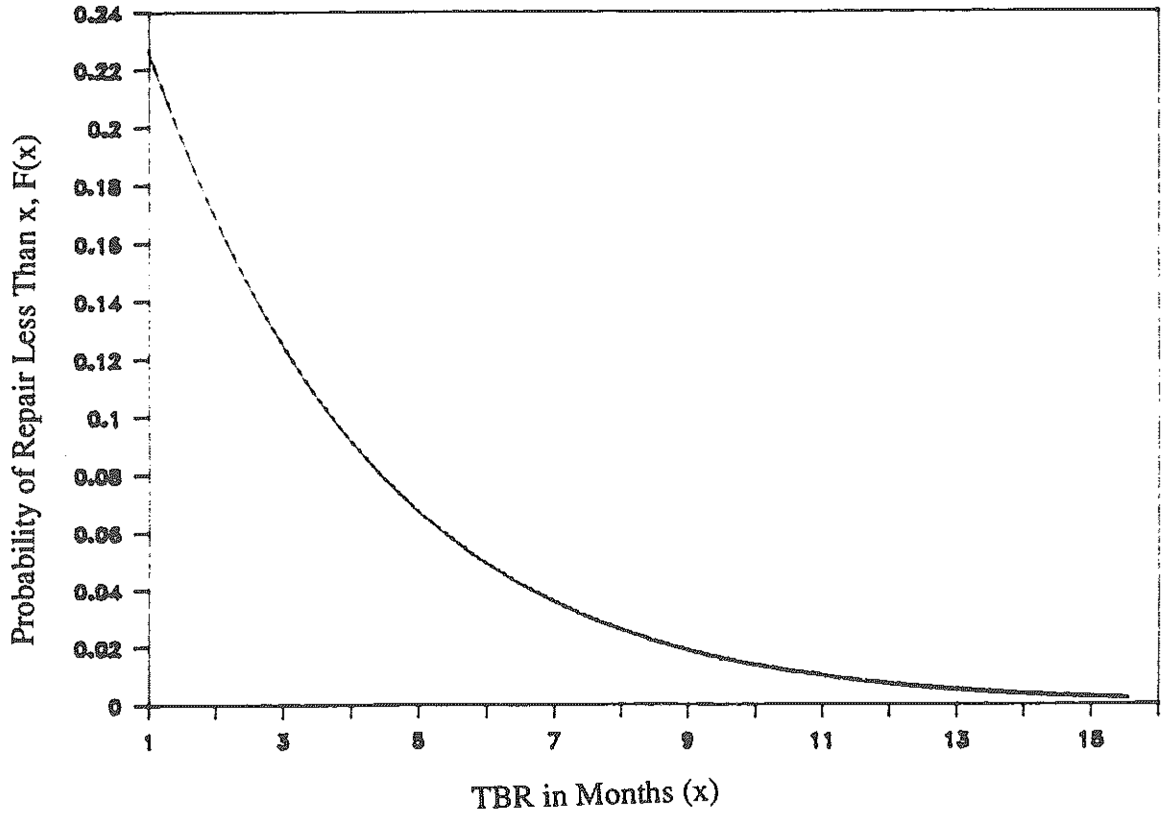


Figure 7 (a) TBR Probability Distribution Function For Lift C 3.

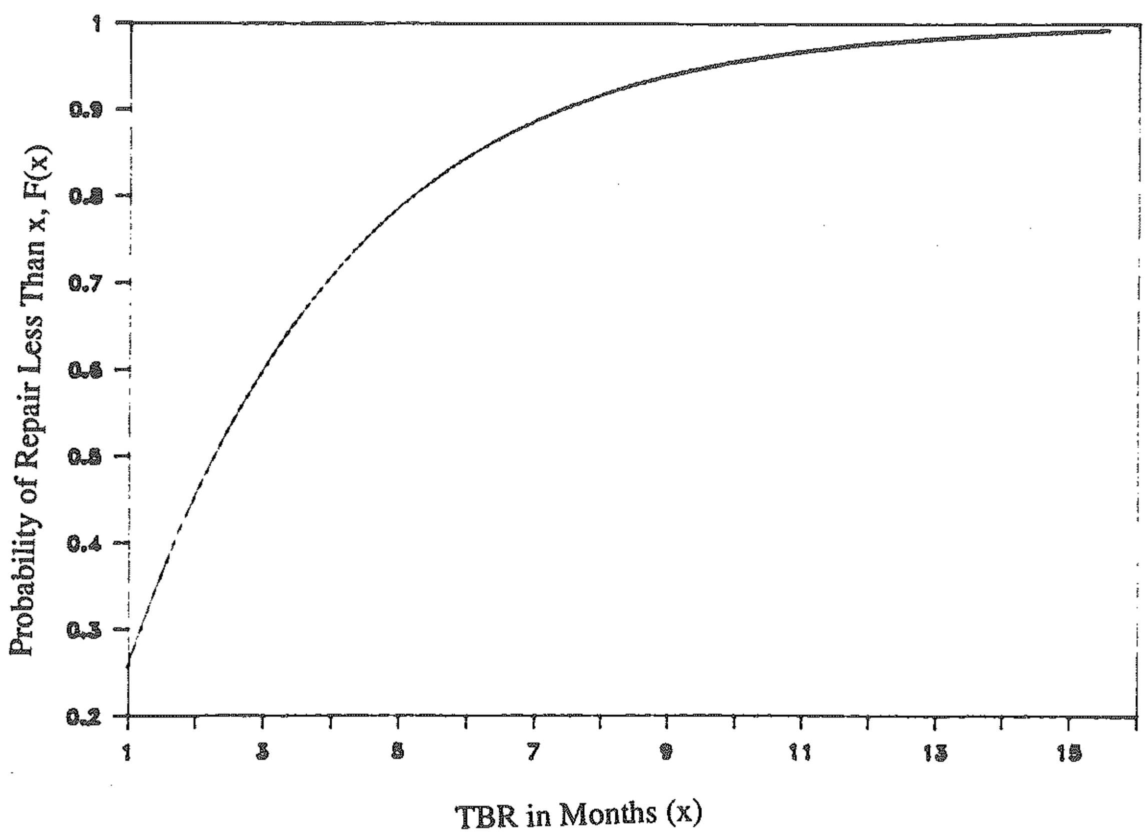


Figure 7 (b) Cumulative TBR Probability Distribution Function For Lift C 3.

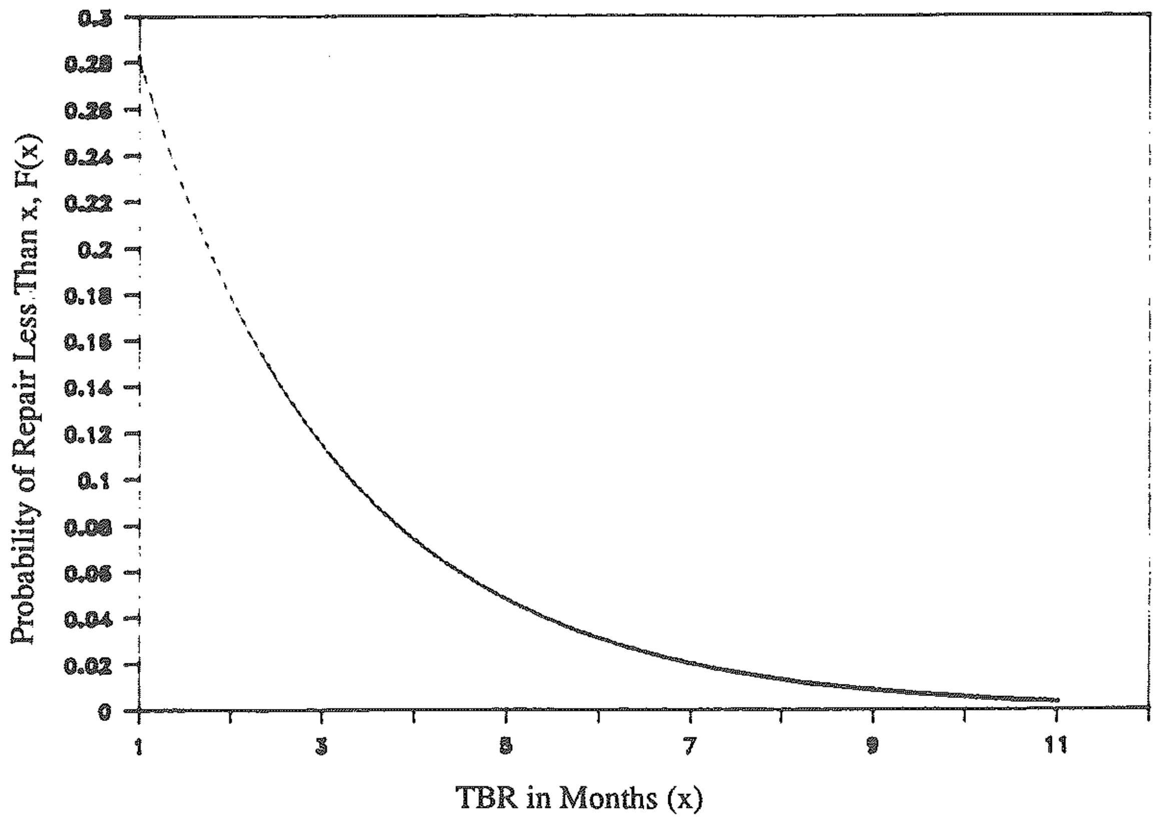


Figure 8 (a) TBR Probability Distribution Function For Lift C 4.

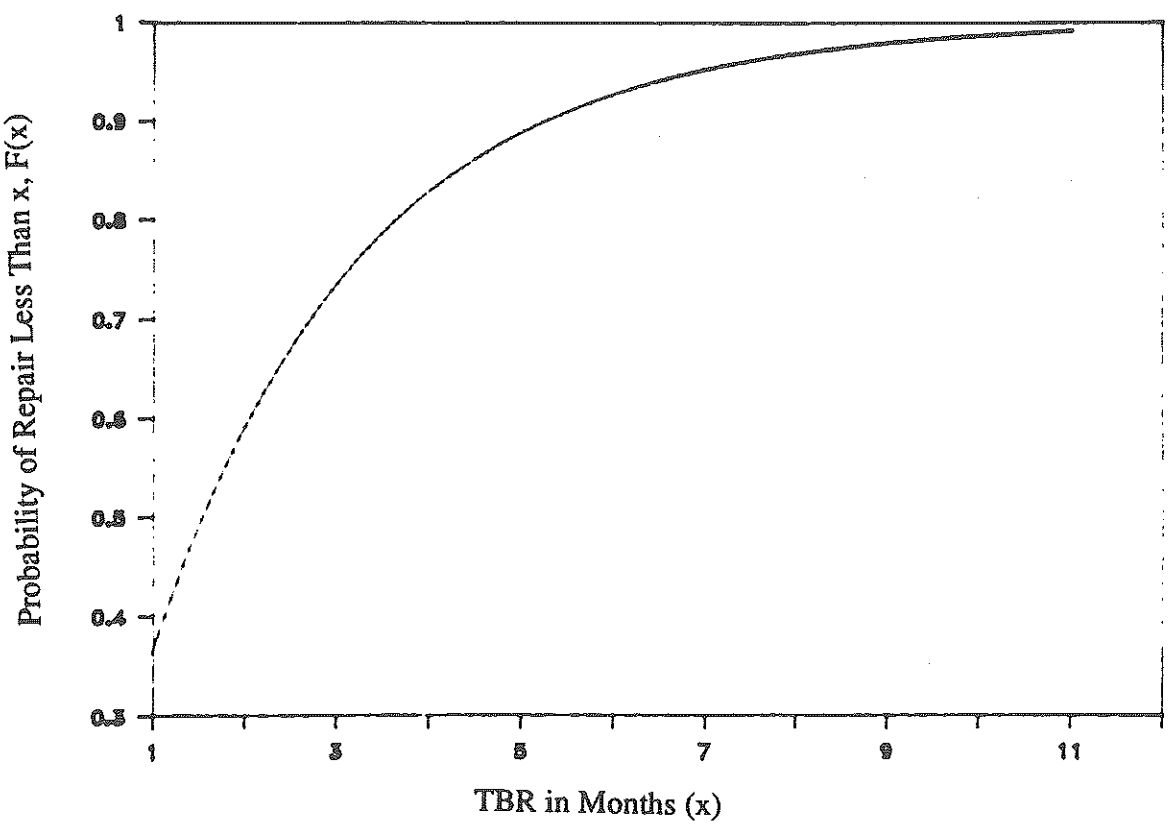


Figure 8 (b) Cumulative TBR Probability Distribution Function For Lift C 4.

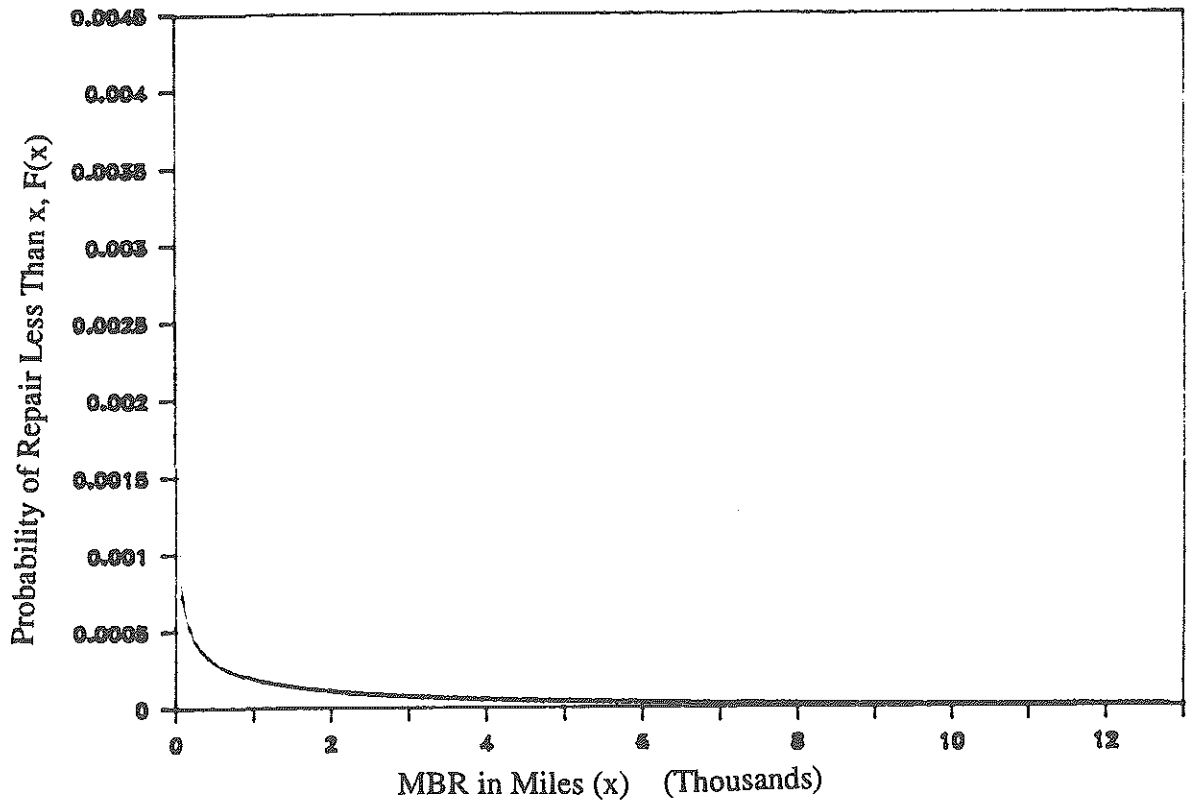


Figure 9 (a) MBR Probability Distribution Function For Lift C 1.

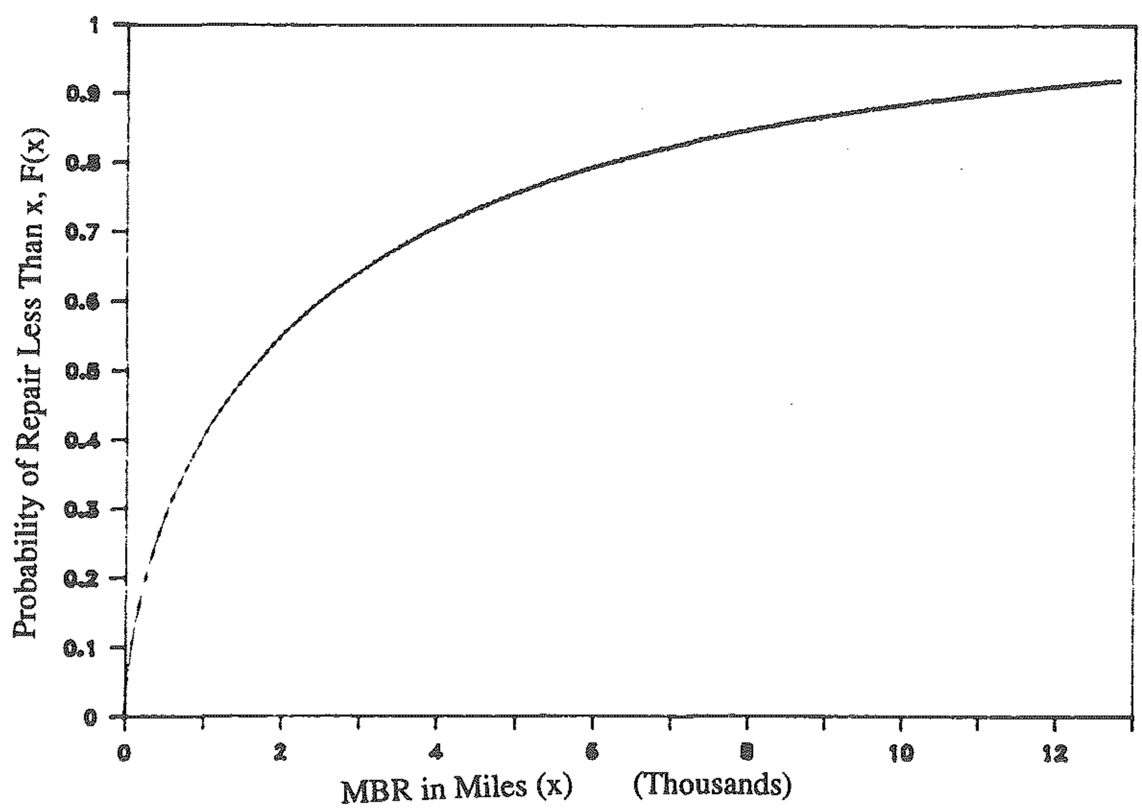


Figure 9 (b) Cumulative MBR Probability Distribution Function For Lift C 1.

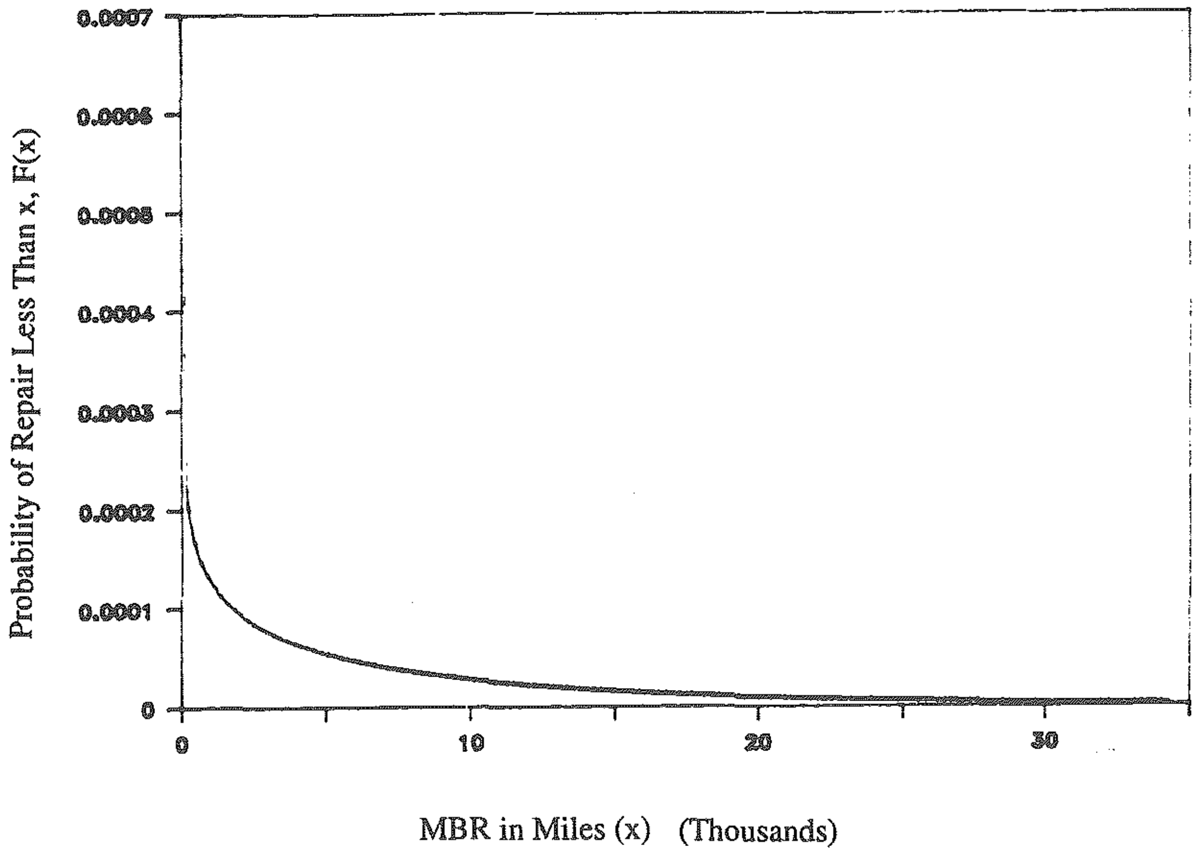


Figure 10 (a) MBR Probability Distribution Function For Lift C 2.

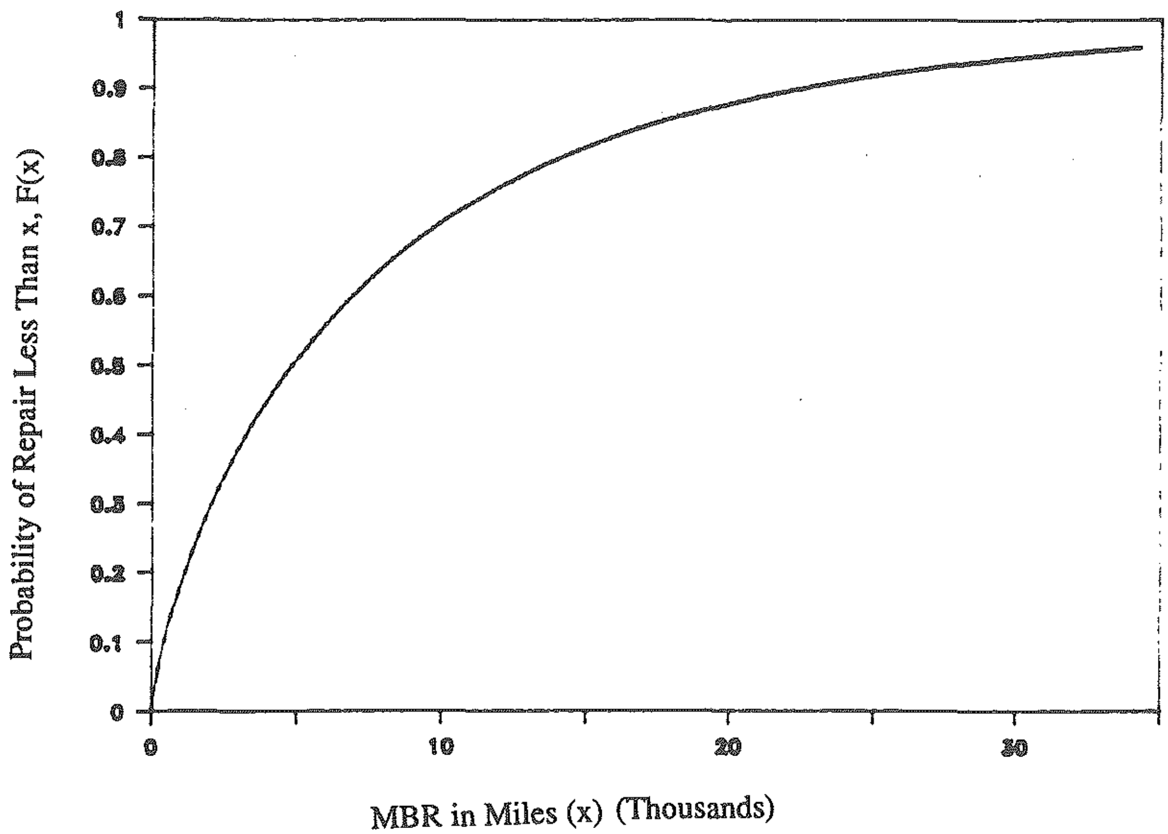


Figure 10 (b) Cumulative MBR Probability Distribution Function For Lift C 2.

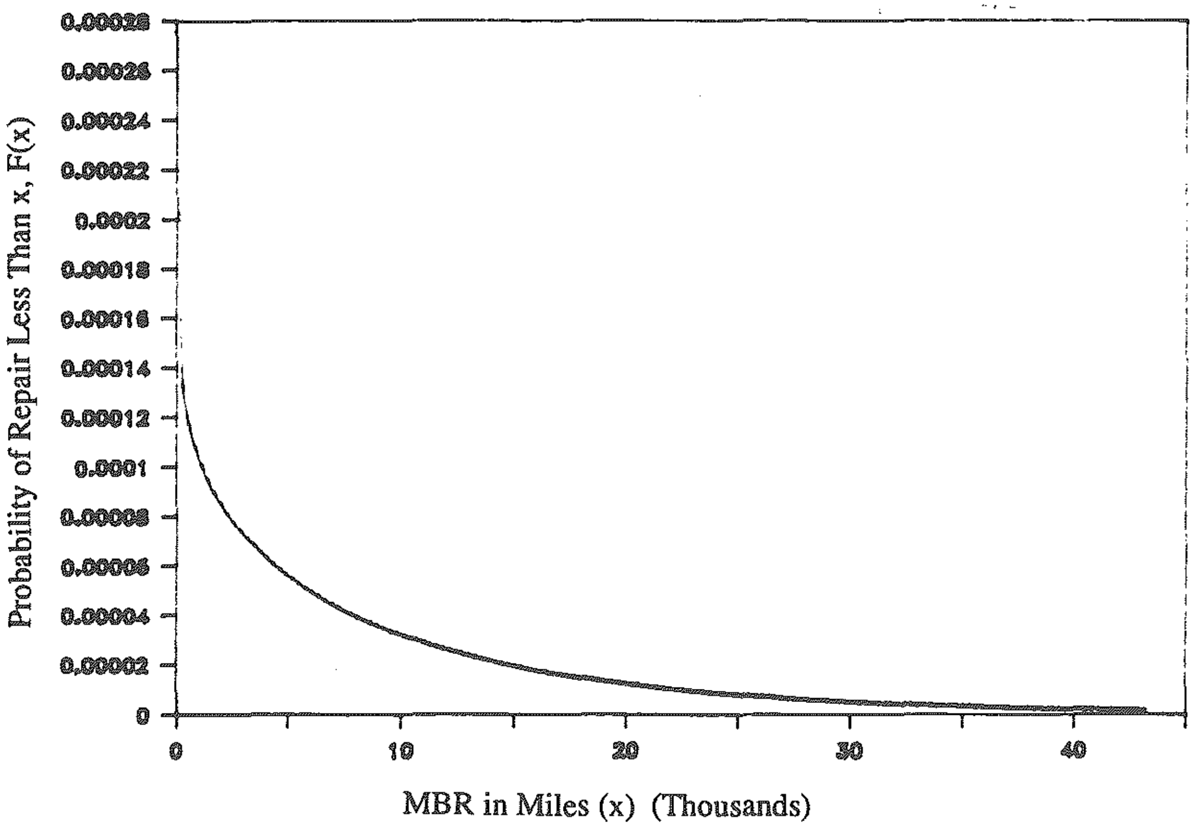


Figure 11 (a) MBR Probability Distribution Function For Lift C 3.

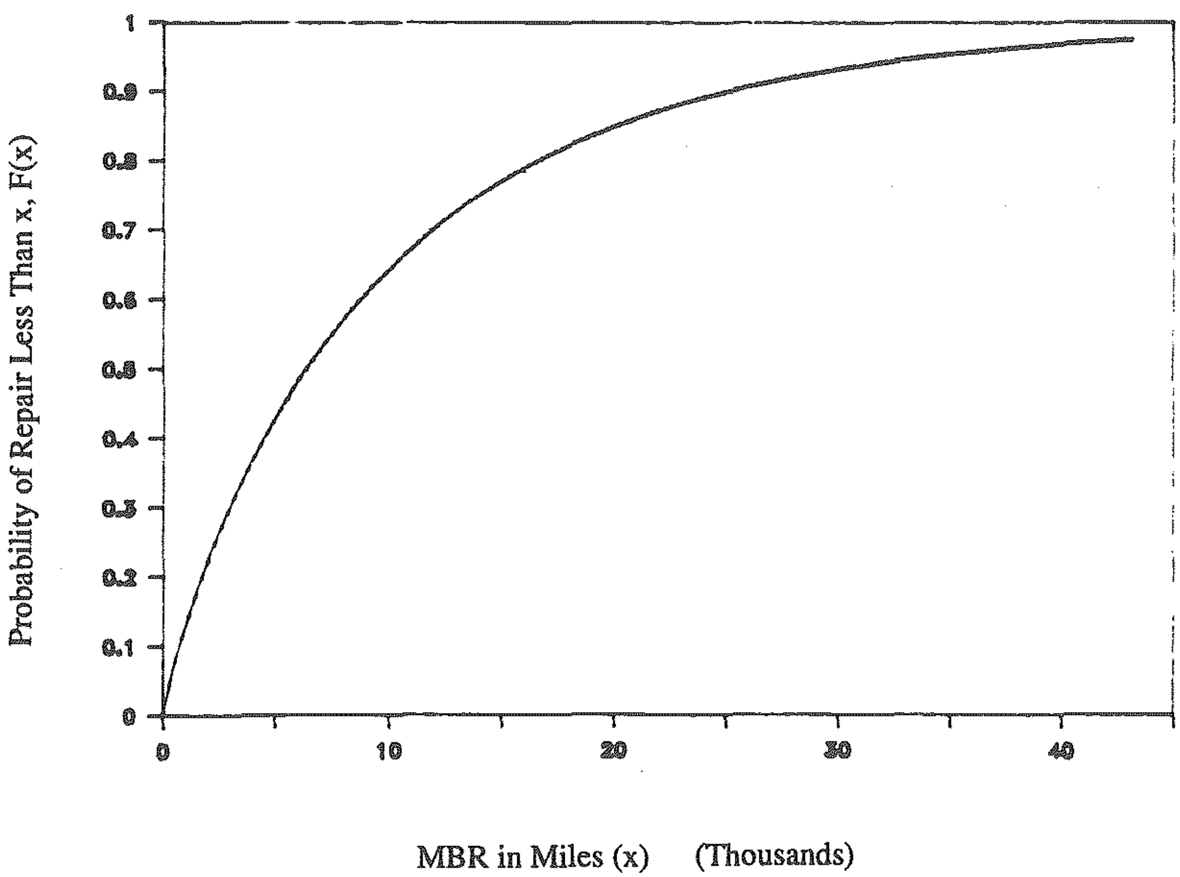


Figure 11 (b) Cumulative MBR Probability Distribution Function For Lift C 3.

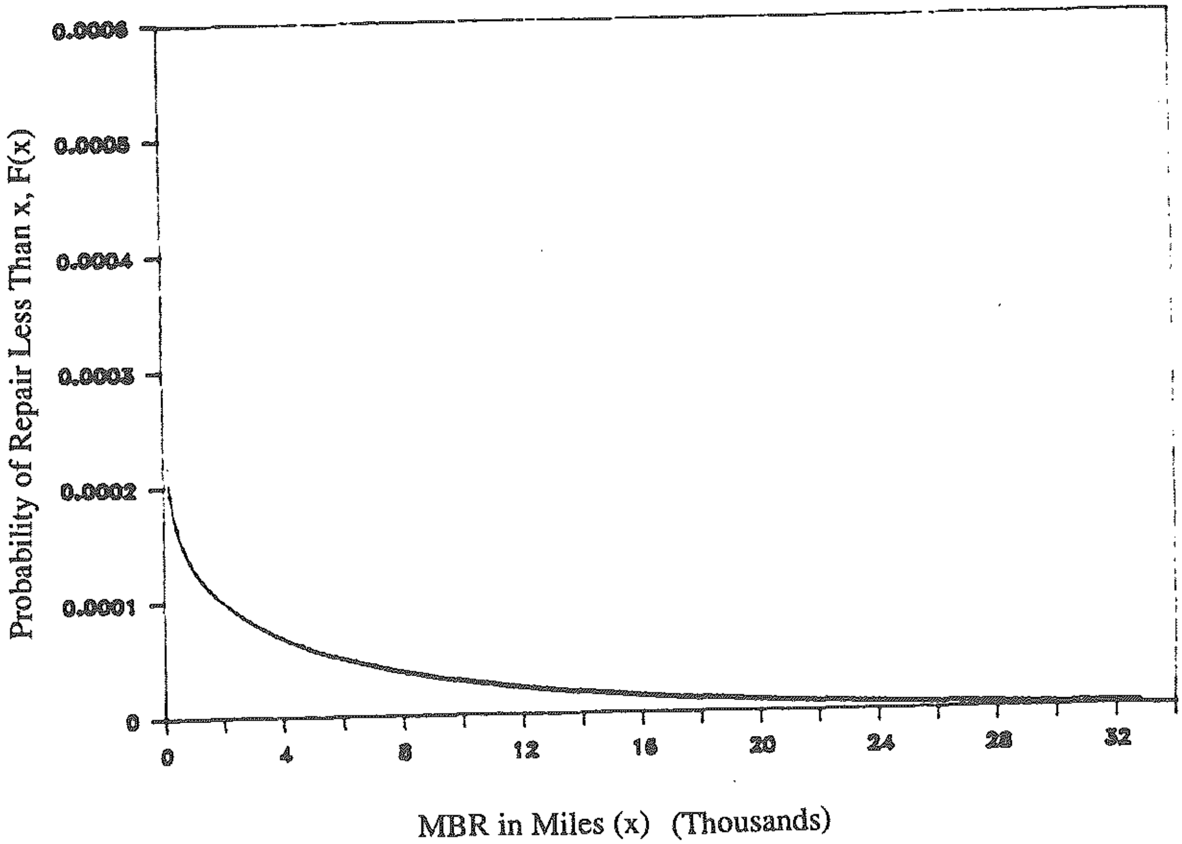


Figure 12 (a) MBR Probability Distribution Function For Lift C 4.

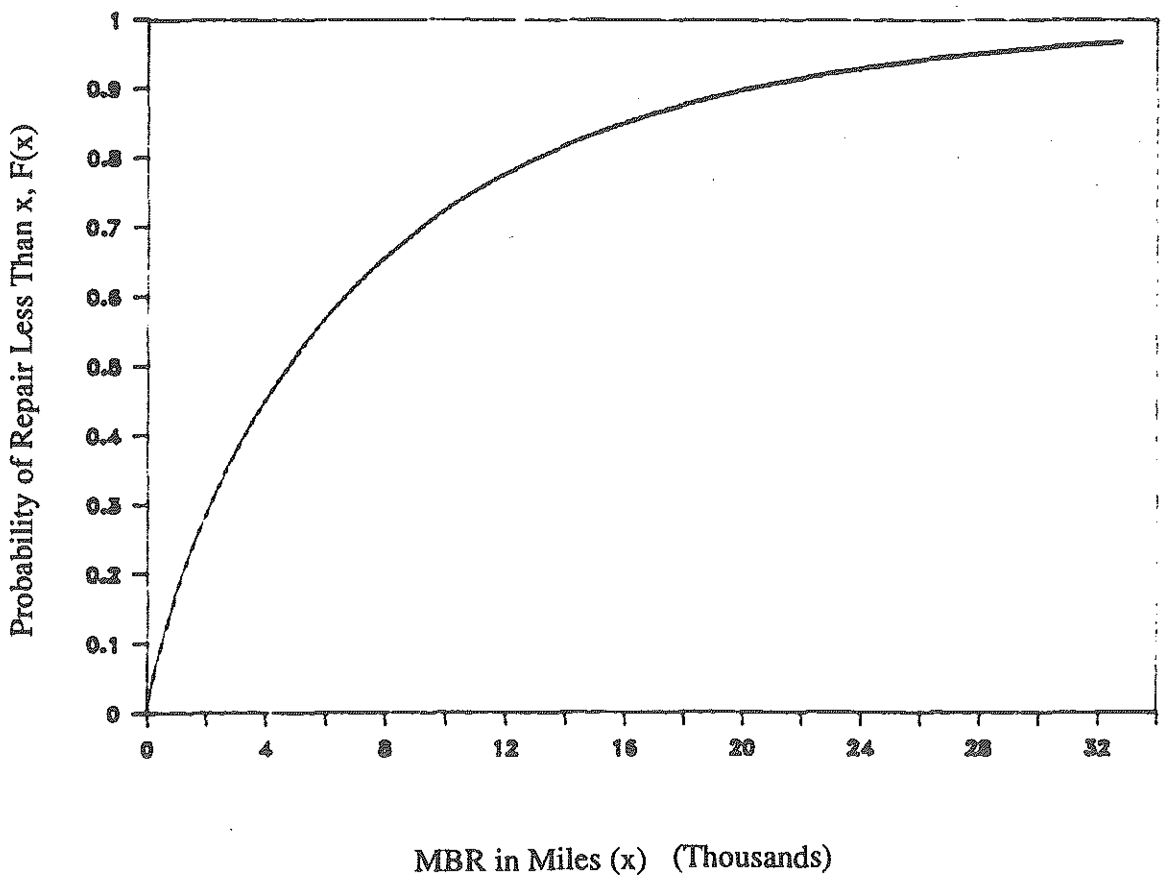


Figure 12 (b) Cumulative MBR Probability Distribution Function For Lift C 4.

explained in the previous chapter. These graphs and the data (model parameters) presented in this chapter were developed through the use of the software developed at the University of Oklahoma under the direction of Prof. T.H. Maze.

5.4 Model Validation (for step lifts).

The high R^2-values presented in Table 11 and Table 12 (exceeding 0.90 in most cases) are indicative of an excellent correspondence between the model output and the observed data. An additional validation effort was made by developing the parameters from a group of 2 lifts, applying these parameters on another lift, and comparing the predicted failure rates with the actuals. The following 3-step process was followed:

1) First, the mean values of the b, θ, and x_0 parameters, were computed for lifts C-3 and C-4.

2) These parameters were applied to compute the Cumulative Distribution F(x) for the lift C-2 as: (note: C-1 being considered on "outlier" was not included in the validation.

$$F(x) = 1 - e^{-\left(\frac{x - x_0}{\theta - x_0}\right)^b}$$

where b, θ, and x_0 are the mean parameters and x is MBR or TBR as the case may be.

3) The computed CDF (using the above parameters) were compared with the actual observations for lifts C-2.

In Table 13 and Table 14, the results of this comparison are presented for C-2 for TBR and MBR distribution, respectively. A visual comparison of these two distributions is also presented in Figures 13 and 14. These Tables and Figures are self explanatory and are indicative of the very close correspondence between the observed data and the model output. For example, Table 9 indicates that according to the model, there is a 50% probability that a type C lift will require a repair within 0.75 months. For lift C-2, 46% of the time a repair was actually needed within 0.75 months. Figures 13 and 14 also shows the remarkable correspondence between the model prediction and actual performance.

Table 13. Comparison of Weibull Model Output (CDF) With Actual TBR Values for Lift C-3(N=14).

TBR (Months)	Frequency	Percent	Percentile	Model*
0-0.2	2	14.3	14.3	18.1
0.2-0.5	3	21.4	35.7	35.45
0.5-0.75	2	14.3	50.0	46.10
0.75-1.2	3	21.4	71.4	60.24
1.21 Onwards	4	28.6	100.0	100.0

* Parameters for computing CDF Θ=1.3199 b=0.85095

Table 14. Comparison of CDF With Actual MBR Values.

MBR	Frequency	Percent	Percentile	Model*
1-600	3	21.4	21.4	25.2
600-1100	3	21.4	42.8	39.7
1100-3100	2	14.4	57.1	60.7
3100-6800	3	21.4	78.5	78.8
6800 Onwards	3	21.4	100.0	100.0

* Parameters for CDF Θ=3449.46 b=0.6464

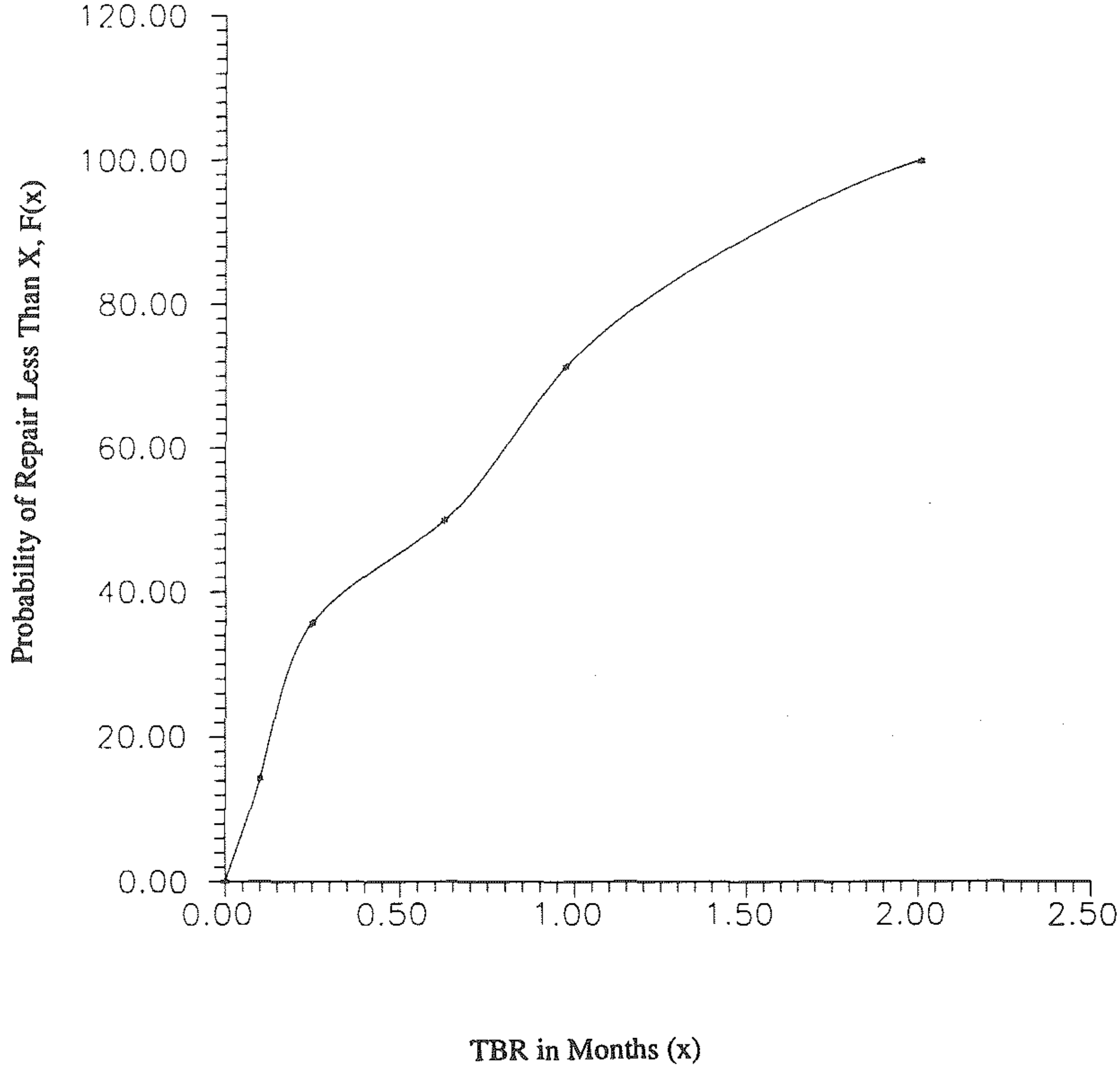


Figure 13(a) Comparison of Weibull Model Output (CDF) With Actual TBR Values for Lift C-3. (Actual)

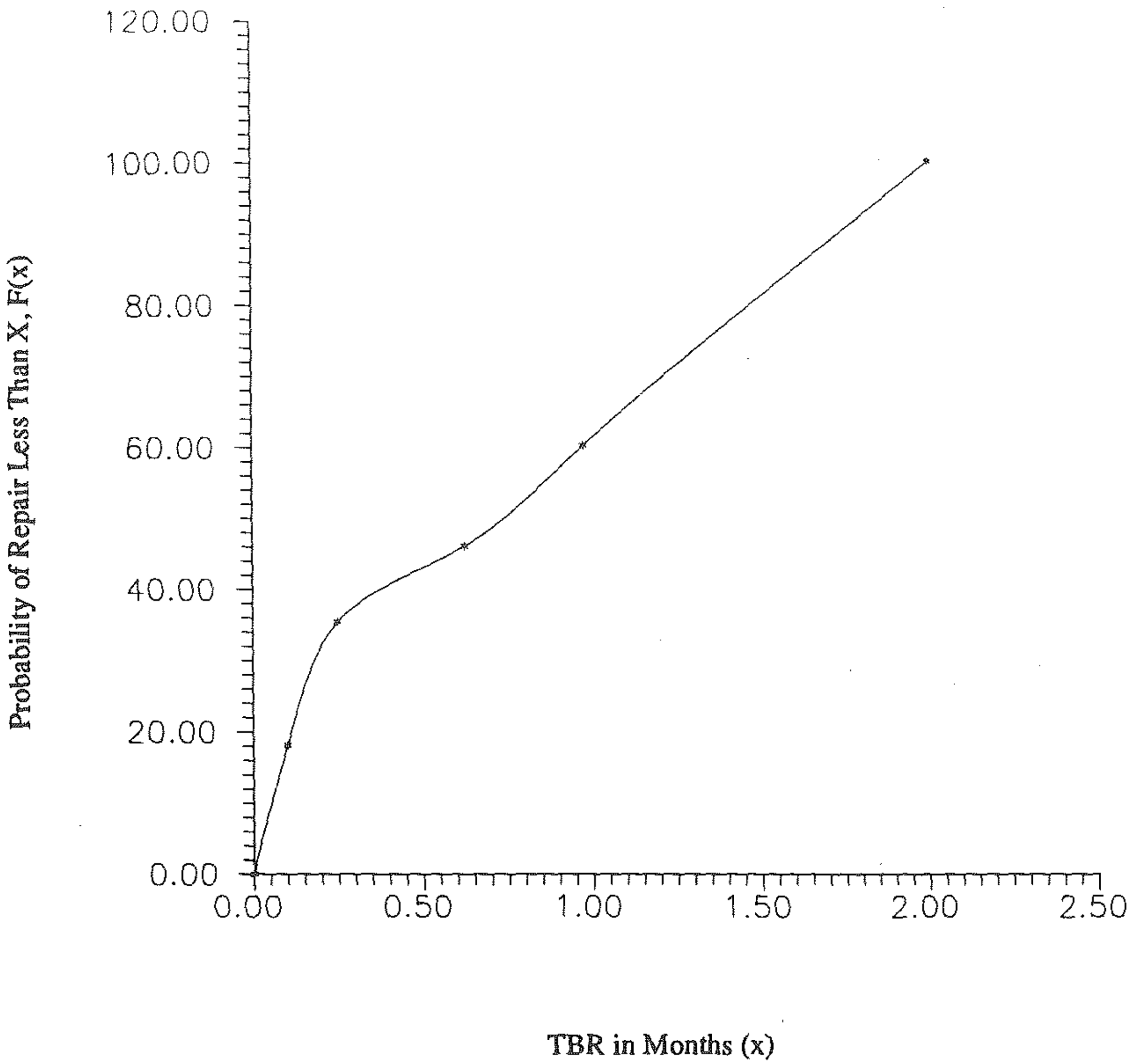


Figure 13(b) Comparison of Weibull Model Output (CDF) With Actual TBR Values for Lift C-3. (Model)

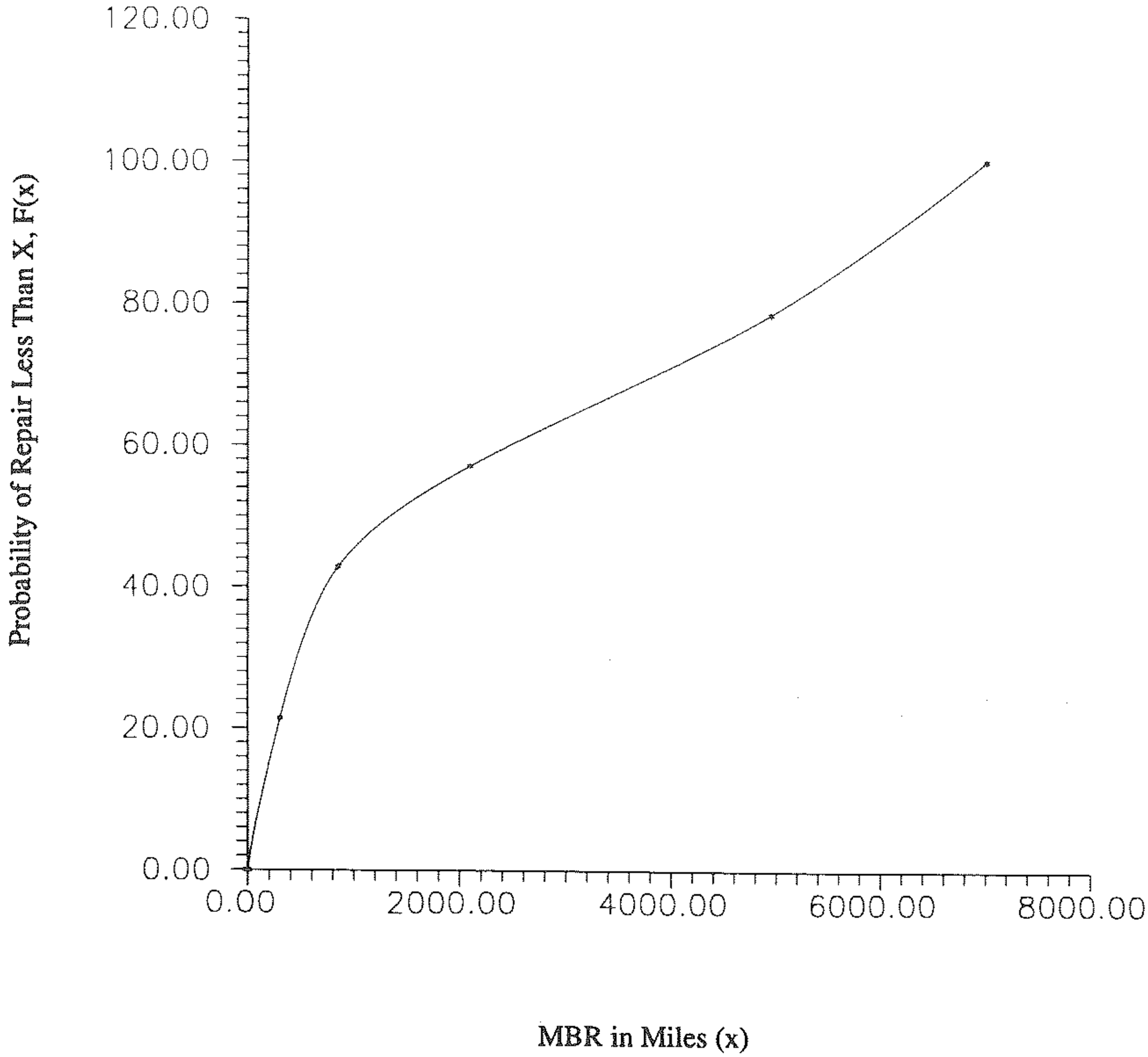


Figure 14(a) Comparison of CDF With Actual MBR Values. (Actual)

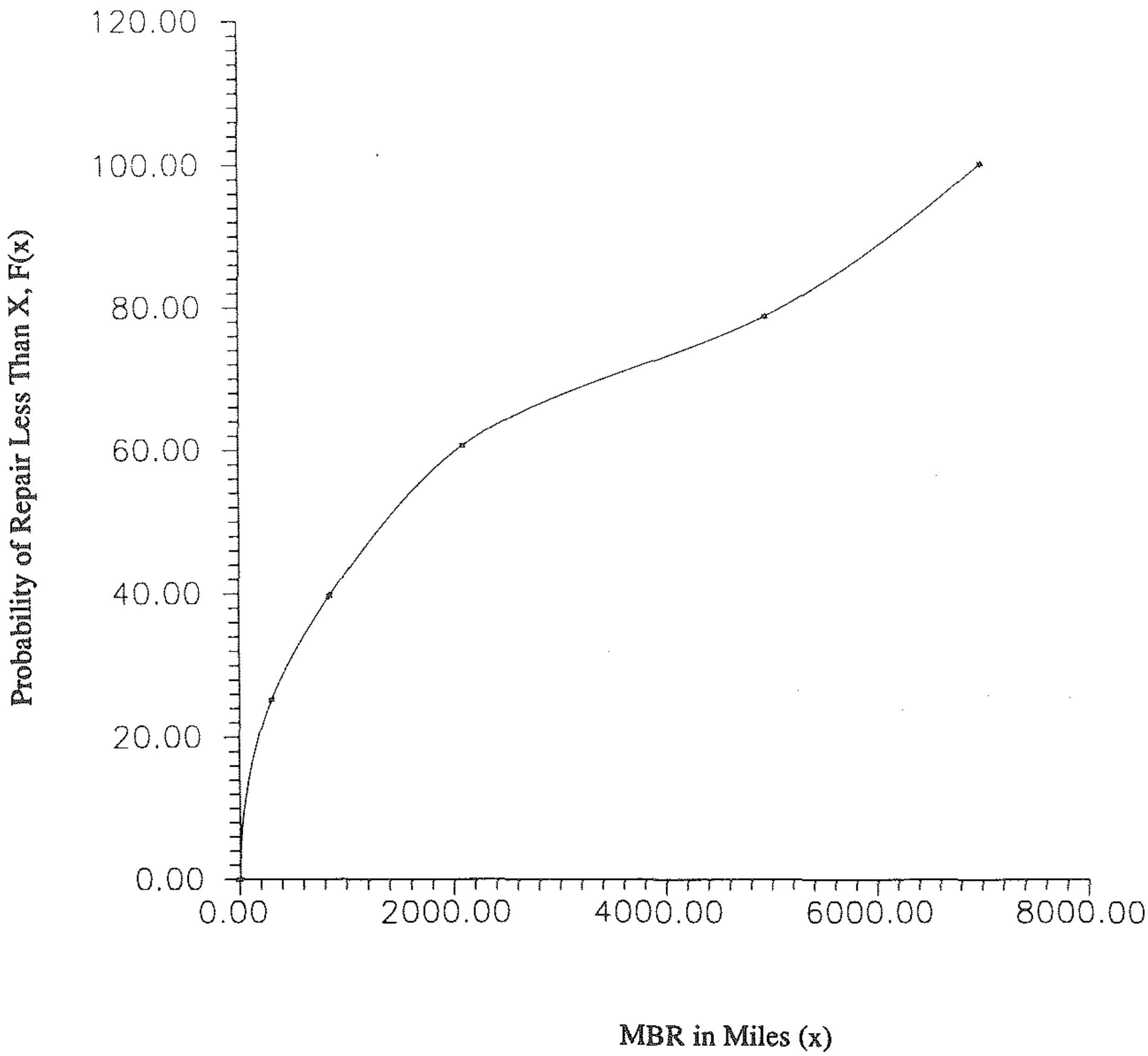


Figure 14(b) Comparison of CDF With Actual MBR Values. (Model)

5.5 Analysis of Cost Data.

An effort was made to analyze the cost repair data of the ten step lifts available from SMART. In Table 15 the cost data of the ten lifts is tabulated as a function of Time Between Repair (TBR) along with N, the number of repairs that occurred in that category and the mean cost of the repair for the given number of data points. Table 15 shows the mean cost of the repair for each lift for 3 TBR ranges: zero to 2.64 months, from 2.64 to 5.2 months and from 5.28 to 7.9 months. For example, it costs 126.81 dollars per repair for lift A 1 for the TBR range of zero to 2.64 months (based upon 12 repairs). Also the Table shows that this lift is likely to need a repair for every 2.64 months or less and generally, repair needs go down after 2.64 months. However no patterns seems to emerge from the cost data as a function of TBR. For example for lift A 1, the average cost goes down from the first TBR range to the second and to the third. The trend is exactly opposite for lift A 4 and A 5. Lastly there is no trend for lifts A 2 and A 3. Similar lack of trend is true for lift B as depicted in Table 15.

Table 16 shows the mean TBR as a function of cost of the wheelchair lifts along with N the number of the repair data points in each category for type A and type B lifts. Table 16 shows that for the A-1 lift, for the first cost category (0 to 162 dollars) a repair is needed for every 2.05 months. The remainder of the Table 16 is to be interpreted in a manner similar to Table 15. As in the previous case, no pattern seemed to emerge out of the cost data expressed as a function of TBR or TBR data expressed as a function of cost.

The repair data retrieved from the SMART data base and plotted on Weibull probability paper as described in the previous section, appeared to suggest a linear relationship typically expected of Weibull distribution. This seemed to suggest that there is a statistical pattern in the frequency and distribution of repair cost of wheelchair lifts. As such Weibull analysis of repair cost data was conducted following the procedure presented earlier.

The Weibull test results for the 10 lifts (5 for type A and 5 for type B) presented in Table 17 include the cost, the slope (b) and characteristic value (θ). A review of the cost data shows that for type A lifts, the average characteristics value of cost is \$74.64 and \$74.82 for type B lifts.

Table 15. Repair Cost as a Function of Time Between Repair for Step Lifts.

Time (Months)		Lift Type - A.					Lift Type - B.				
		A-1	A-2	A-3	A-4	A-5	B-1	B-2	B-3	B-4	B-5
0-2.64	N	12	13	21	15	6	36	19	34	34	31
	Mean Cost	126.81	66.62	58.36	69.46	34.02	66.36	34.06	74.10	45.60	77.23
2.64-5.2	N	3	7	6	8	9	7	10	5	4	8
	Mean Cost	46.73	54.4	106.1	82.82	113.75	117.34	66.2	132.8	54.86	80.0
5.28-7.9	N	1	3	1	1	1	2	3	2	1	1
	Mean Cost	24.36	56.47	20.34	104.38	26.0	114.35	52.47	35.13	51.43	25.61

Table 16. Repair Data Expressed As a Function of Cost for Step Lifts.

Cost (Dollars)		Lift Type - A.					Lift Type - B.				
		A-1	A-2	A-3	A-4	A-5	B-1	B-2	B-3	B-4	B-5
0-162	N	12	23	24	21	13	39	31	36	38	34
	Mean Time	2.05	2.074	1.3475	1.982	2.815	1.41	1.759	1.475	1.85	1.474
162-324	N	2	1	3	2	3	5	1	3	1	5
	Mean Time	0.53	0.66	2.31	1.6	2.74	1.804	3.84	2.26	0.8	1.066
324-490	N	2	1	1	1	0	1	1	2	0	1
	Mean Time	1.065	0.43	0.43	4.0		3.43	3.484	0.24		1.64

Table 17. Weibull Parameters for COST Distribution.

Lift Type & Number	R^2 Correlation Coefficient	ΘCharacteristic Life in Dollars	b Slope	N # of Repairs	Equation y=bX+c*
A-1	0.8973	108.83	0.77	19	y=0.7795X - 3.656
A-2	0.8679	57.76	0.99	23	y=0.9976X - 4.047
A-3	0.8868	64.82	0.80	30	y=0.8072X - 3.367
A-4	0.8289	72.22	0.76	25	y=0.7667X - 3.282
A-5	0.9011	69.55	0.92	17	y=0.9207X - 3.9056
Average		74.64	0.85		
B-1	0.9747	102.65	0.85	49	y=0.8539X - 3.9548
B-2	0.8733	54.75	1.00	33	y=1.0072X - 4.0313
B-3	0.9212	80.53	0.98	42	y=0.9847X - 4.3213
B-4	0.9521	55.21	1.00	40	y=1.0076X - 4.0414
B-5	0.9275	80.93	1.01	41	y=1.0193X - 4.4779
Average		74.82	0.97		

* y=ln ln (1./1-F(x))
X= ln(x)
c=-b ln Θ

Thus there is no significant difference in the cost per repair data for type A lifts and type B lifts. It is important to note that the repair data analyzed is for all repairs conducted for general category (All repairs together).

The following are the observations from the cost distribution Table:

1). Table 17 shows that in all the ten cases there is a reasonable correlation between the dependent variable Y and the independent variable X in the equation. The coefficient of correlation (R^2) values are higher for type B lifts than type A lifts.

2). Table 17 also shows that the characteristic life value (63.2 percentile value) for type A lifts varies from a low of 57.76 dollars to a high of 108.83 dollars. The corresponding values for type B lifts is range from 54.75 dollars to 102.65 dollars.

3). The slope parameter 'b' is within the proximity of unity for type B lifts and lesser than unity for type A lifts.

5.6 CONCLUSIONS.

In this section a statistical approach for analyzing the reliability of wheelchair lifts is presented. The approach presented is the continuation of the development effort of Weibull models for two types of step lifts reported in the Phase I report. This part of the research includes the incorporation of the location parameter in the model. Additionally, a separate Weibull model was developed for platform lifts of a specific type using repair data on a total of four lifts for a three year period. The conclusions are:

1) The addition of the location parameter does not make any significant difference in the estimates of the two major parameter of the Weibull distributions, θ (characteristic life) and b (slope), particularly when the numerical value of the location parameter x_0 is very small. The data base used in the study was not broad enough to test whether the estimates of the parameters θ and b would be significantly different, had the numerical value of the location parameter been larger.

2) The statistical analysis of a three year repair data base for a particular type of platform lift confirms the earlier finding that the distribution of repair data measured either in Miles Between Repairs (MBR) or Time Between Repairs (TBR) follows Weibull distribution.

3) Since TBR and MBR are highly correlated, and since it is easier to collect TBR data, (compared to MBR), it is recommended that TBR distribution of repair data be used in analyzing reliability of wheelchair lifts.

4) Based upon 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 TBR and MBR. The implication of this finding is quite significant in the context of the recent enactment of the American With Disabilities Act By the US congress. The approach presented by the authors will enable transit operators anticipate in advance when (either in terms of mileage or months) a repair will be needed for a given wheelchair lift.

5) Based upon 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.

6. STRUCTURAL ANALYSIS.

6.1 Introduction.

6.1 (a) Review of Previous Work.

In Phase I the finite element model of the lift structural system, shown in Figure 16, was developed from the simplified fully deployed wheelchair lift geometry shown in the Figure 15. In this Figure the node numbers designate the element boundaries and the connectivity between each element. The geometrical coordinates of the nodes are shown in Table 18. The structural model was described by seven element groups for two element types. The element types are three dimensional beam element and three dimensional truss element. A total of 17 nodes and 20 elements describes the model. The interaction of the lift structure with the bus structure is ignored and the connection between the lift frame and the bus frame was assumed as fixed.

The finite element model (FEM) was utilized to analyze the structural component strengths of the lift mechanism. The analysis was performed for two specific load cases, i.e., service load condition and ultimate load condition. These load conditions are given in the UMTA recommendations [1]. The analysis results for these two load conditions were presented as nodal deformations and component stresses. The critical components under these two load cases were identified.

The component stresses are calculated as the uniaxial stress for truss members and bending stress for beams. The internal force distribution within the lift structure is described in Figure 17(a) and Figure 17(b) under the ultimate load of 11100 newtons (2500 pounds). Under the ultimate load, the main frame (element 5) pushes down on the cam bracket (element 3) and produces maximum bending moment on the deployment frame at the location of the cam bracket. The majority of components are designed with strength supply sufficient for the ultimate load. Only the cam bracket (element 3 and 4) and platform side beams (element 13 and 14) reach yield stress at ultimate load. Additional yielding was computed in the pins which provide rotational degree of freedom between two components. There are five different pins diameters. These are located at

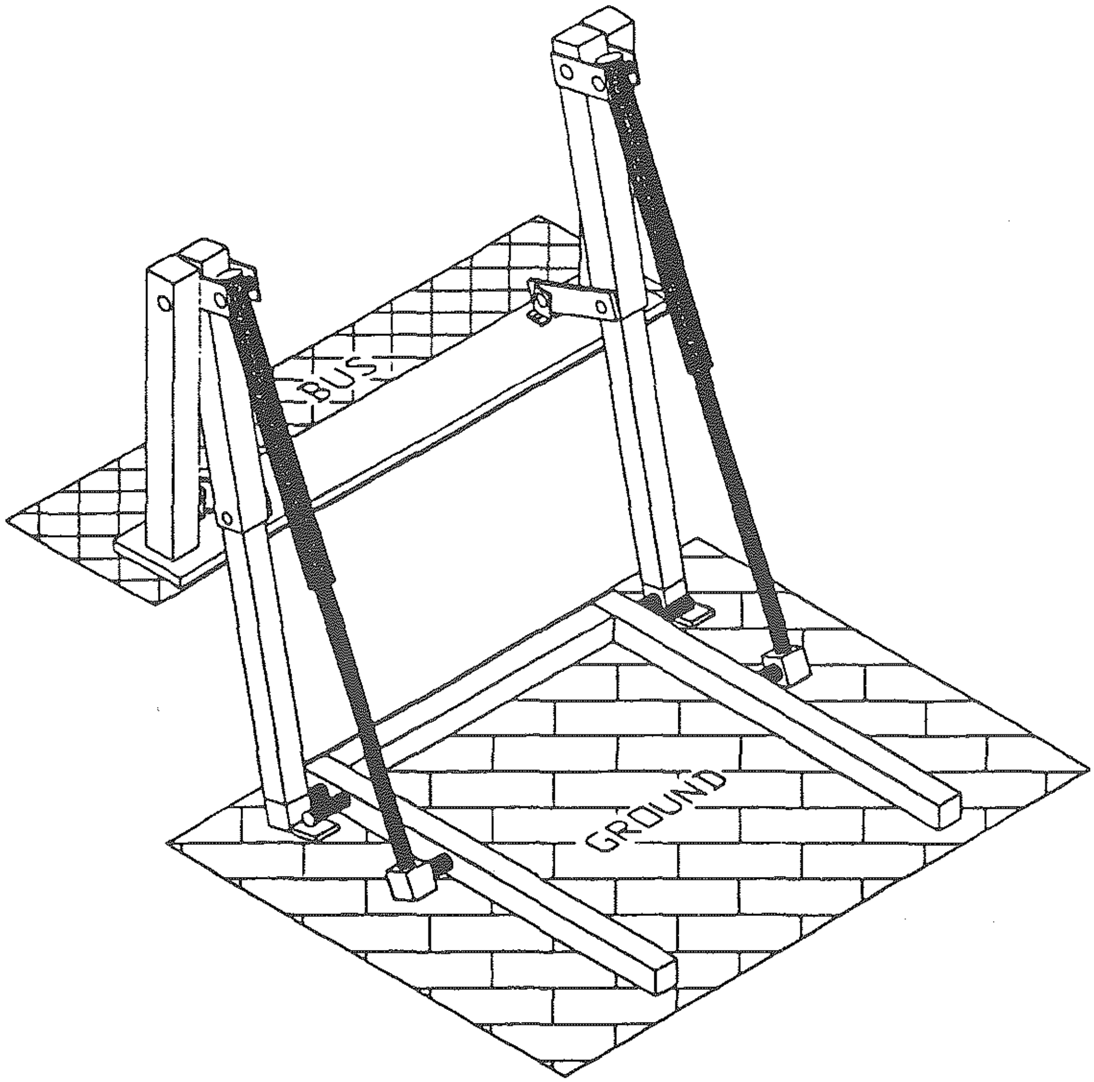


Figure 15 A Rigid Platform Lift in Deployed Position.

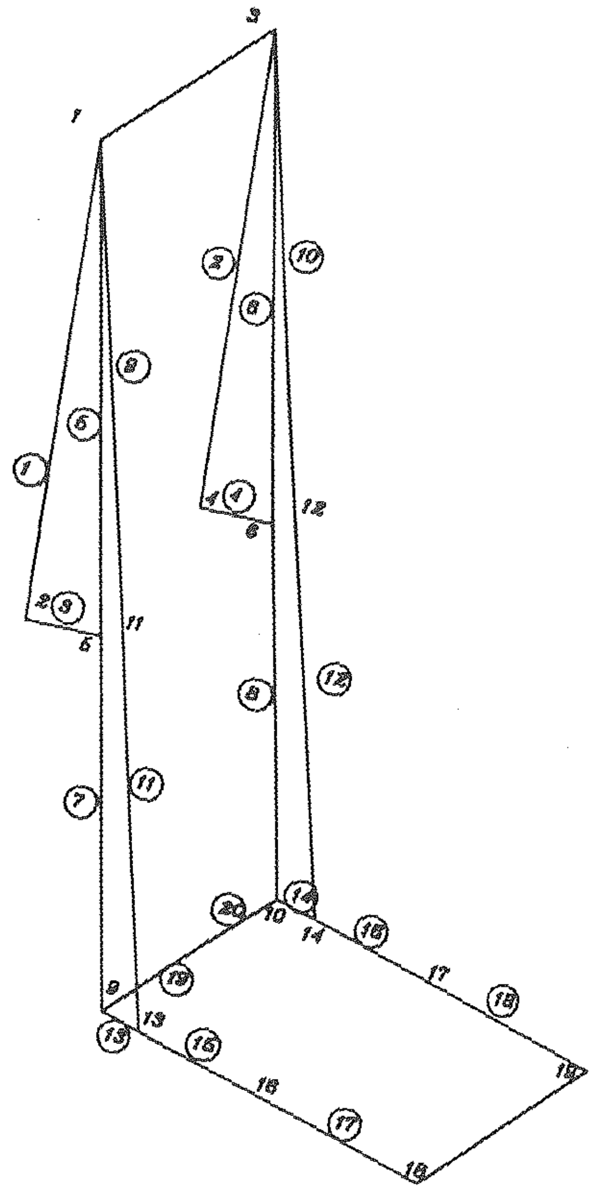


Figure 16 Discrete Model of Fully Deployed Lift.

Table 18. Nodal Coordinates.

Node Number.	X millimeter.	Y millimeter.	Z millimeter.
1	0	1625.6	762
2	0	0	762
3	0	1625.6	0
4	0	0	0
5	241.3	76.2	762
6	241.3	76.2	0
9	431.8	-1092.2	762
10	431.8	-1092.2	0
11	302.3	152.4	762
12	302.3	152.4	0
13	558.8	-1092.2	762
14	558.8	-1092.2	0
15	431.8	-1092.2	381
16	965.2	-1092.2	762
17	965.2	-1092.2	0
18	1498.6	-1092.2	762
19	1498.6	-1092.2	0

Note : Node number 7 and 8 coincides with node number 5 and 6.
1 Inch = 25.4 millimeter.

Units.

Moment Kilo Newton - millimeter.

Force Kilo Newton

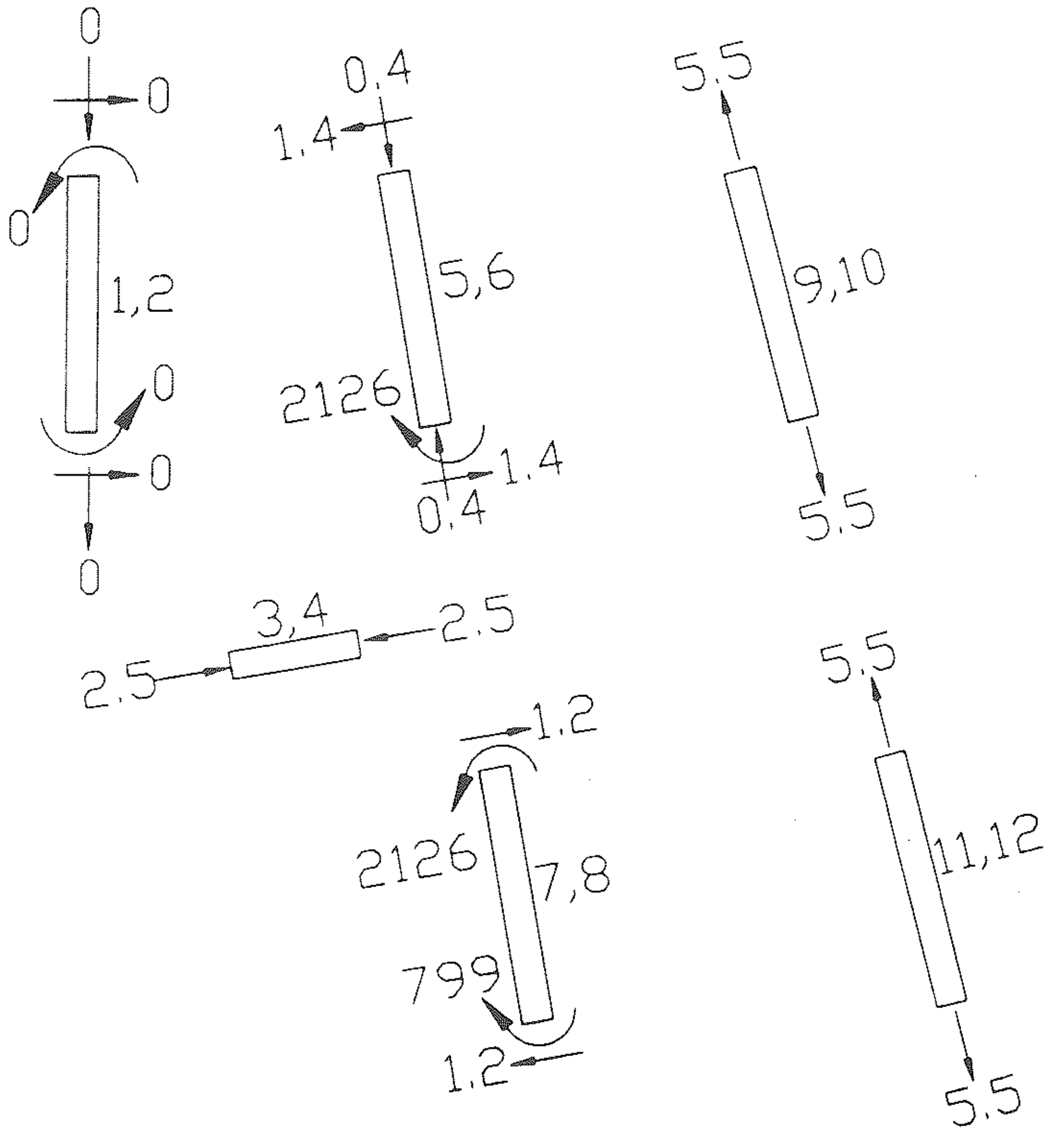


Figure 17 (a) Element Forces of Platform Lift Under Ultimate Level Gravity Load.

Units.

Moment Kilo Newton - millimeter.

Force Kilo Newton

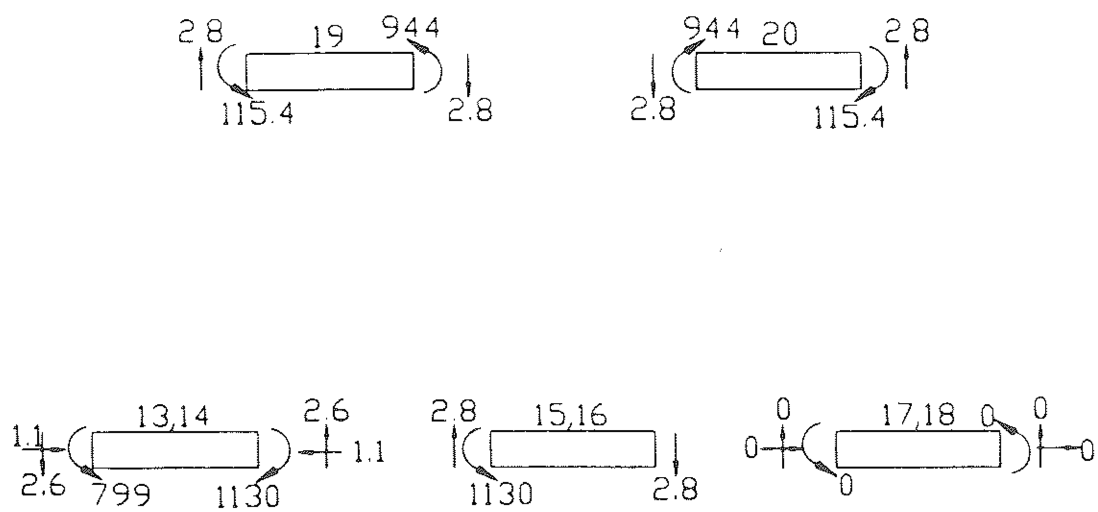


Figure 17 (b) Element Forces of Platform Lift Under Ultimate Level Gravity Load.

nodes numbered 1 - 6 ,9,10,13 and 14 (Figure 17 and 18). The shear force that needs to be transferred by the pins, shown in Figure 18, are evaluated from free body diagrams. The pin shearing stress computed were in excess of allowable stress at nodes 1,3,2,4,13 and 14.

6.1 (b) Objective.

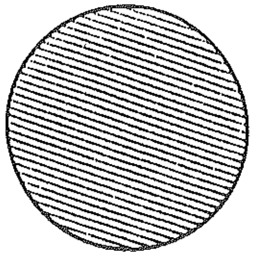
During deployment and stow away operations the lift structure is subjected to static and dynamic loads in addition to those described in first Phase. The primary objective of the structural analysis in this Phase is to describe these load demands, conduct structural analysis under these load demands and evaluate component stresses and structural deformations. Some examples of these load demands are: the upward force from the ground due to lift overextension while in deployment (some active lifts include a ground sensor, however, the sensor may be inoperable or ground may be uneven), impact factor at the instance the platform comes in contact with ground under passenger load, inertia force on the lift in the stowed position while the bus is in motion, etc. These loading conditions and the combinations will be explained in this report. However the detailed dynamic analysis of the stowed lift during bus motion and experimental investigation is the scope of Phase III report.

In this Phase modeling and analysis of fully deployed passive (step) lift is also described. The model is developed for the verification of structural capacities under service and ultimate load conditions and the experimental analysis of passive lift will not be performed. The primary objective of passive lift model is to evaluate if weak links exists in the structure.

6.2 Platform Lift Analysis.

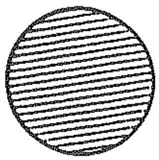
6.2 (a) Demand Analysis.

The demands (load cases) on the platform lift are described below. These load cases are developed based on extensive field investigation and interviews with the maintenance - shop personal that was conducted during the Phase I of the study. These are divided into two groups based on the model requirements, i.e. static or dynamic analysis models.



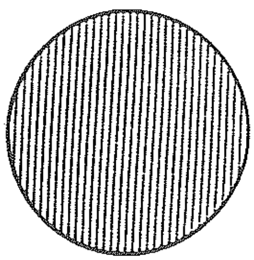
Diameter = 19 millimeter (0.75 inch) At nodes 1 & 3.

Shear stress S = 18.4 MPa (2670 Psi).



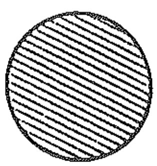
Diameter = 12.7 millimeter (0.5 inch) At nodes 2 & 4.

Shear stress S = 49 MPa (7100 Psi).



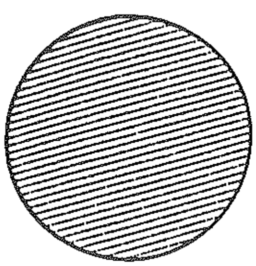
Diameter = 19 millimeter (0.75 inch) At nodes 5 & 6.

Shear stress S = 21.7 MPa (3150 Psi).



Diameter = 12.7 millimeter (0.5 inch) At nodes 9 & 10.

Shear stress S = 68 MPa (9880 Psi).



Diameter = 19 millimeter (0.75 inch) At nodes 13 & 14.

Shear stress S = 31 MPa (4480 Psi).

Figure 18 Shear Forces in The Pins.

i) *Static Load Demand :* The lift structural static gravity load demand requirements are determined as 3790 newtons (850 pounds) for service and 11100 newtons (2500 pounds) for ultimate load. These demand requirements are greater than those required by UMTA specifications but, in the opinion of the investigators these reflect more realistic loads observed during the operation of lifts [6].

During deployment and stow away operation the lift structure is subjected to additional static and dynamic loads that are not included in the specifications. One example of these load demands is the upward force from the ground due to lift overextension while in deployment (some active lifts include a ground sensor, however, the sensor may be inoperable or ground may be uneven). The analysis is performed for twenty load conditions in addition to the service and ultimate loads. The loading condition that are described in Table 19 consists of limit gravity load i.e. minimum gravity load to cause first yield of the lift structure, and conditions observed when the lift is overextend to the uneven ground.

The service level load is increased to 4450 newtons (1000 pounds) with the impact factor (It is equating dynamic forces to equivalent static forces.) of 1.175 which is a function of rise time and dynamic properties of the lift structures. The impact factor is computed using the lift platform velocity of 250 millimeters/second (10 inches/second) and a rise time of 0.5 seconds from zero to maximum velocity which generates an acceleration of 0.05 g, where g is the gravitational acceleration 9660 millimeters/sec^2 (386.4 inches/sec^2).

The ultimate limit gravity load is 11100 newtons (2500 pounds) inclusive of impact load. The value is computed from a factor of safety of 2.5 against yielding as required by specifications [1,11]. The total load due to lift overextension is established as loads which account for the hydraulic actuators pushing against the ground. Each lift is actuated by a pair of the hydraulic cylinders with capacity of 4450 newtons (1000 pounds). This load is moved around platform acting upward to simulate different points of contact over an uneven ground.

Table 19. Load Conditions.

Load Index	Load Condition	Configuration	Description
1	Gravity	2@1100 N & 1 @ 2225 N	Service Load
2	Platform two beams toe against ground.	2 @ 4450 N	Impace Load
3	Platform one beam toe against ground.	1 @ 8900 N	Impact Load
4	Platform two beams middle against ground.	2 @ 4450 N	Impact Load
5	Platform one beam middle against ground.	1 @ 8900 N	Impact Load
6	Platform two beams heel against ground.	2 @ 4450 N	Impact Load
7	Platform beam joint with cylinder against ground.	1 @ 8900 N	Impact Load
8	Platform one beam against ground.	3 @ 3100 N	Impact Load
9	Platform one beam against ground.	2 @ 4450 N	Impact Load
10	Platform side beam heel against ground.	1 @ 8900 N	Impact Load
11	Platform back beam middle against ground.	1 @ 8900 N	Impact Load
12	Gravity	2 @ 2780 N & 1 @ 5560 N	Ultimate Load

1 Pound = 4.45 Newton.

The first yield capacity of the lift structure is computed by analyzing the structural model under incrementally increasing gravity load until the maximum stress in any one component attains yield strength. All other load combination analyses are conducted in combination with service load condition.

The loads acting upward due to lift overextensions, are distributed in the following fashions for the different load cases. The first case is that two platform side beams against the ground. The contact of side beams with ground are incorporated in three load cases corresponding to limited contact point at the platform toe, middle or heal. Since the total upward load is computed to be 8900 newtons (2000 pounds), 4450 newtons (1000 pounds) load applies at each side beam.

The second case is that one platform side beam maintains contact with the ground. In this case the contact is assumed to take place at the middle point of the beam i.e. the point of joint for platform beam and cylinder against the ground or at the platform heel. Only one static load of 8900 newtons (2000 pounds) is applied at this point of contact.

The third case we consider is that the platform back beam making contact with the ground. The contact of the back beam assumed to be established at three points with the ground. These three points are two joints with side beams and one middle point. The loads applied at these points are 2970 newtons (667 pounds) at each point. Also a force of 8900 newtons (2000 pounds) is considered when only the middle point of the beam contact with the ground.

All these cases are analyzed combined with service load conditions and independently with individual ground contact load case for fully deployed lift model.

ii) Dynamic Load Demand : Ultimate dynamic load demand to the lift will occur during an extreme event such as collision of the bus with another vehicle or a stationary object. During the crash condition the lift will be in stowed away configuration and sudden decelerations will cause dynamic effects on the lift. Such kind of dynamic stresses may cause failure of the connection member between bus and lift.

The service dynamic loading on the lift occurs when the bus is in motion. The motion of the bus floor will excite the lift and its components. If there is a resonance condition with in the lift the dynamic loads may cause repeated contact of lift components with each other. Such contact may lead to damage and cause annoyance due to noise. In addition, the repeated nature of the dynamic loading sequence may lead to fatigue failure at the connection of the lift with the bus frame. In fact, the field investigation during Phase I revealed that on a number of occasions, the operator replaced the lift connection to the bus from a bolted to a welded connection because of loose bolts [6]. This resulted in repeated weld failures which is evidence of force transfer between the lift and bus frame. The fatigue effects of the service dynamic action should be considered in the design of this connection. Our objective is the development of a preliminary dynamic model such that the force transfer could be evaluated.

Thus two load conditions concerned are : the inertia force on the lift in the stowed positions while the bus is in steady state motion and the inertia force on the lift in the stowed position while the bus is in extreme deceleration.

In dynamic analysis the inertia forces applied at generalized mass element with six degree of freedom are used as input to the linear transient dynamic analysis. Note that the acceleration pulse duration is taken small. Thus, the action is considered as an impulsive inertia force applied at the platform.

The inertia force is given by the equation F=ma, where m is the mass of the lift platform calculated as 0.0454 Newton-sec^2/mm (0.259 pound-sec^2/in) and a is the acceleration or declaration of the bus.

For the service load condition the produced acceleration assumed as 1250 millimeters/second^2 (50 inch/second^2). We assumed a lower bound triangular pulse of inertia force starting from zero to 60 newtons (12.95 pounds) and again zero, with a pulse duration of 0.5 seconds. The pulse time history is shown in Figure 19(a).

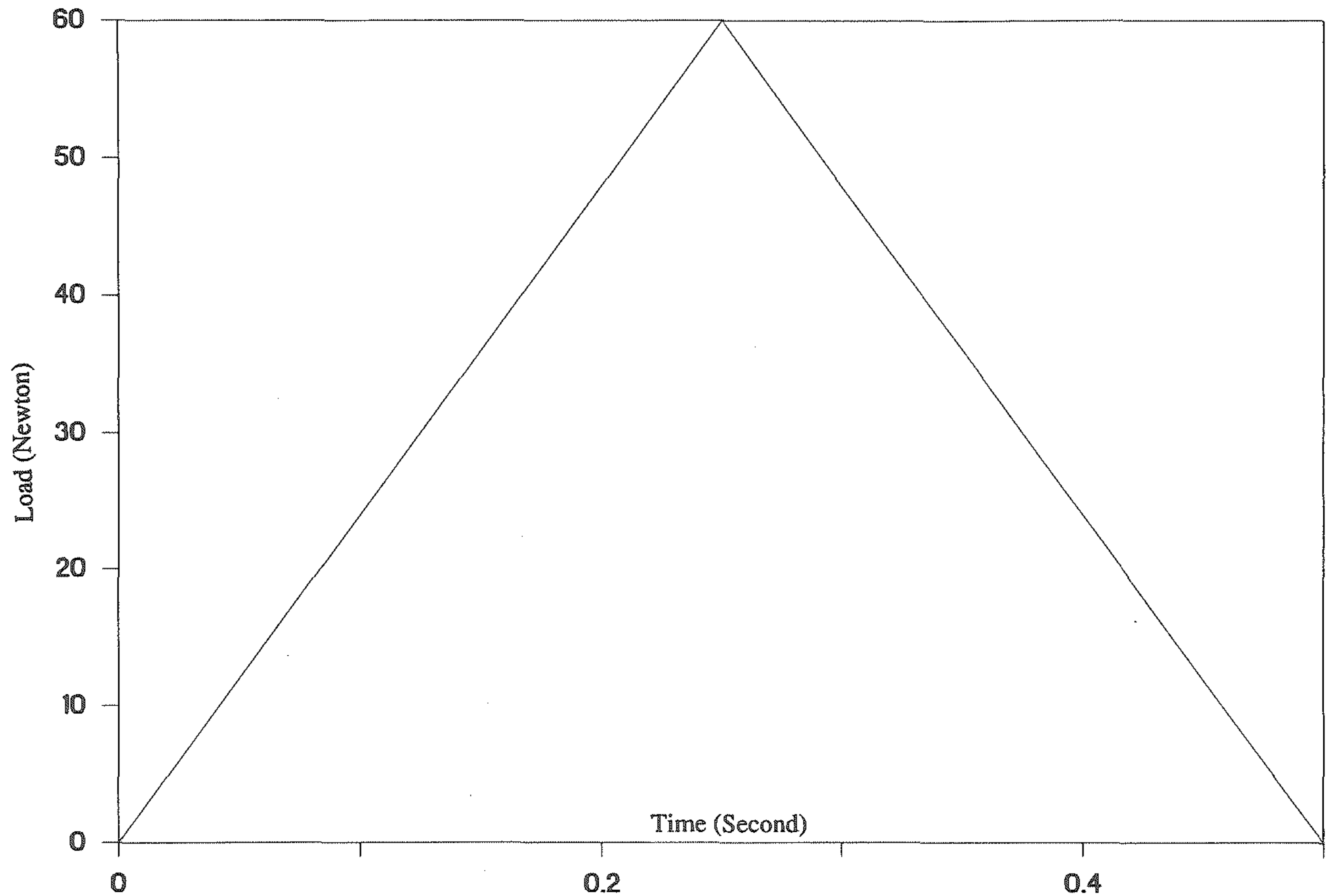


Figure 19 (a) Dynamic Load on The Lift. (Service)

For the ultimate load condition the produced acceleration assumed as 96500 millimeters/second^2 (3865 inch/second^2). We assumed a lower bound triangular pulse of inertia force starting from 4450 newtons (1000 pounds) to zero, with a pulse duration of 0.5 seconds. The pulse time history is shown in Figure 19(b).

6.2 (b) Finite Element Model.

The models are described separately for static and dynamic analysis.

i) Static Analysis Model : The finite element model of the fully deployed lift structural system, shown in Figure 16, was developed, during Phase I of the study. In this model the geometry of the fully deployed lift is simplified and center to center dimensions were used. In this Figure the node numbers are included which designated the element boundaries and the connectivity between each element. The structural model is described by seven element groups for two element types. The element types are three dimensional beam element and three dimensional truss element. A total of 17 nodes and 20 elements describes the model.

The three dimensional truss elements are described by cross-sectional area only. The three dimensional beam elements are described by the moment of inertia with respect to two orthogonal axes in addition to cross sectional area. One aspect to note here is the description of hollow box sections, noted as element number 7 and 8 in Figure 16 that, telescopes during deployment. In these two elements bending stiffness should be present, however, there cannot be any axial stiffness since, the components are allowed to slide in and out. This characteristic is modeled by releasing the axial degree of freedom along the axis of the element.

The element groups, node numbers designating the element boundaries, element indexes, cross sectional geometry and geometric properties are given in Table 20. Element indexes 1 and 2 constitute the main framing, element indexes 3 through 12 constitute the deployment system and the remaining elements, 13 through 20, represent the platform structure.

For the purposes of the static analysis the interaction of the lift structure with the bus structure is ignored. The lift frame connection to the bus frame connections are assumed fixed.

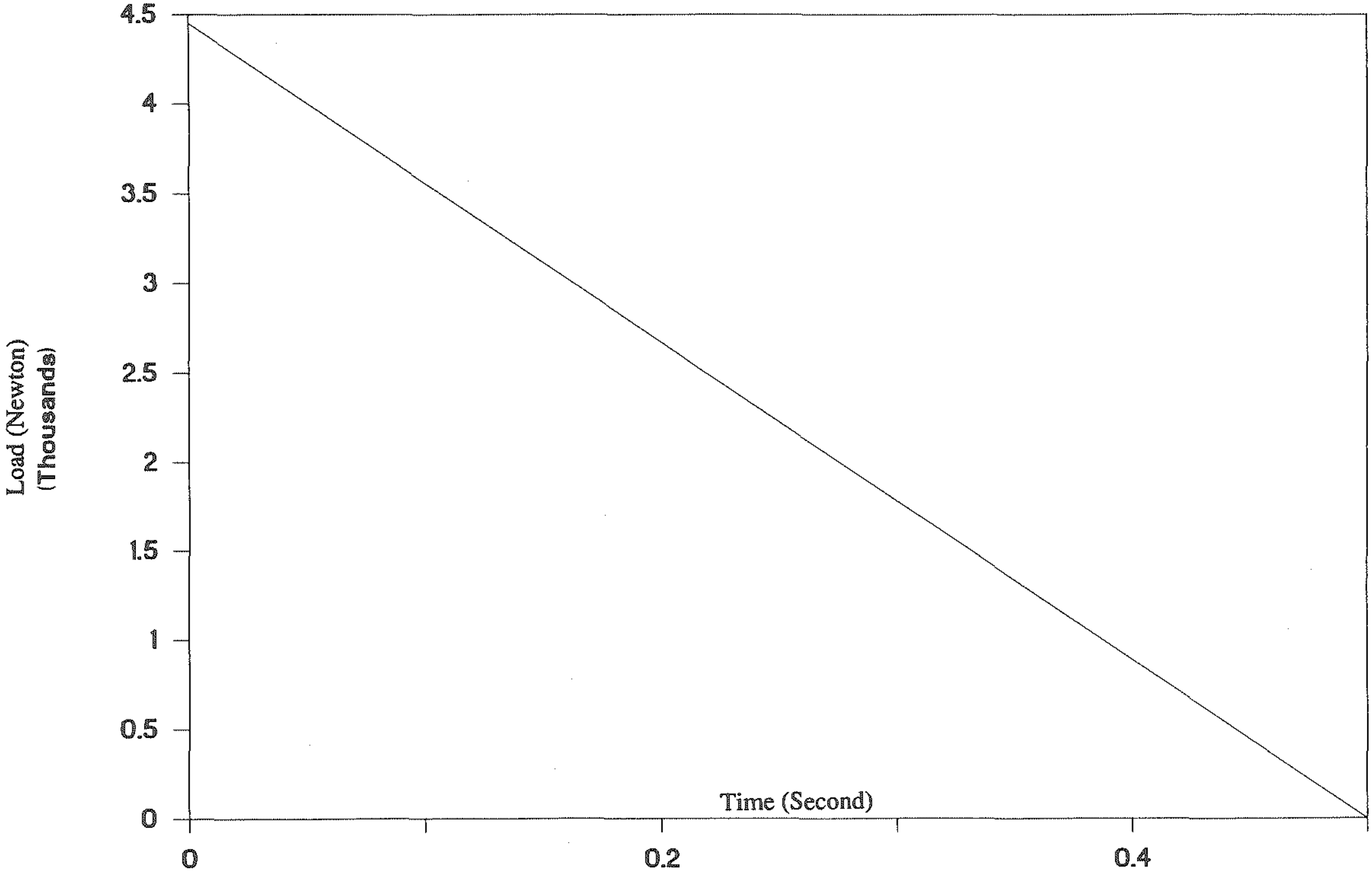
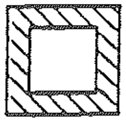
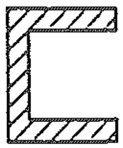
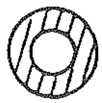
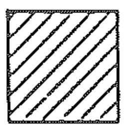
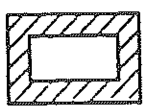


Figure 19 (b) Dynamic Load on The Lift. (Ultimate)

Table 20. Lift Structural Element Geometry and Properties.

Element	Nodes	Geometry	Type	Property
1 2 5 6	1 - 2 3 - 4 26 - 5 27 - 6		Beam Beam Beam Beam	A = 1620 mm^2. I_x = 1061390 mm^4. I_y = 541100 mm^4.
7 8	24 - 9 25 - 10		Beam Beam	A = 810 mm^2. I_x = 466180 mm^4. I_y = 124870 mm^4.
9 10	20 - 11 21 - 12		Truss	A = 1160 mm^2.
11 12	11 - 22 12 - 23		Truss	A = 1030 mm^2.
13 14 15 16 17 18	9 - 13 10 - 14 13 - 16 14 - 17 16 - 18 17 - 19		Beam Beam Beam Beam Beam Beam	A = 1290 mm^2. I_x = 141520 mm^4. I_y = 141520 mm^4.
19 20	9 - 15 15 - 10		Beam Beam	A = 1290 mm^2. I_x = 264310 mm^4. I_y = 865760 mm^4.
3 4	2 - 5 4 - 6		Truss	A = 290 mm^2.

1 $Inch^2$ = 645.1 $millimeter^2$.

1 $Inch^4$ = 416231 $millimeters^4$.

ii) Dynamic Analysis Model : As described earlier the rigid platform lift structural system consists of three main subassemblages: the main frame, the deployment systems and the platform system. When the lift is in stowed position, the main frame that consists of the two side columns connected to the bus chassis provide support to the stowed lift. The deployment system that consists of the two telescoping members and two hydraulic actuators is also responsible for holding the lift in stowed position as shown in Figure 20. These members provide stiffness to the stowed lift in x, y, z and rotation of x directions as shown in Figure 21. The two telescoping members, two hydraulic actuators are considered as spring-damper elements. The platform structure that consists of the platform beams, handle bar and the decking is considered as a rigid body with lumped inertia. When a mass is subjected to acceleration, inertia force will be generated which is acting in a direction opposite to the direction of the acceleration. This inertia force has a magnitude equal to the product of mass and acceleration. Since the platform structure is assumed as rigid, the inertia force effect of all members of the platform structure is equal to the one concentrated mass represented by the summation of all masses. This one concentrated mass is located at the center of the platform structure. The point mass element located at the center of the platform structure represents the total mass of the platform system. The remainder of the structure is assumed mass less.

The detailed stowed lift structural system analysis under dynamic loads will be the subject of Phase III. The model is described by the three dimensional beam elements, a three dimensional generalized mass, a two dimensional longitudinal spring-damper element and a three dimensional torsion spring-damper element. The preliminary model describing the mass and stiffness properties is shown in Figure 21.

The weight of lift platform and contributing components is computed as 445 newtons (100 pounds) which equals a mass of 0.0454 Newton - sec^2/mm (0.259 pound-sec^2/in). There are four springs in the model attached to the lump mass, i.e. k_x, k_y, k_z and k_θ. Among them k_x is horizontal stiffness in the plane of platform, k_y is vertical stiffness, k_z is in horizontal stiffness in z direction and k_θ is torsional spring.

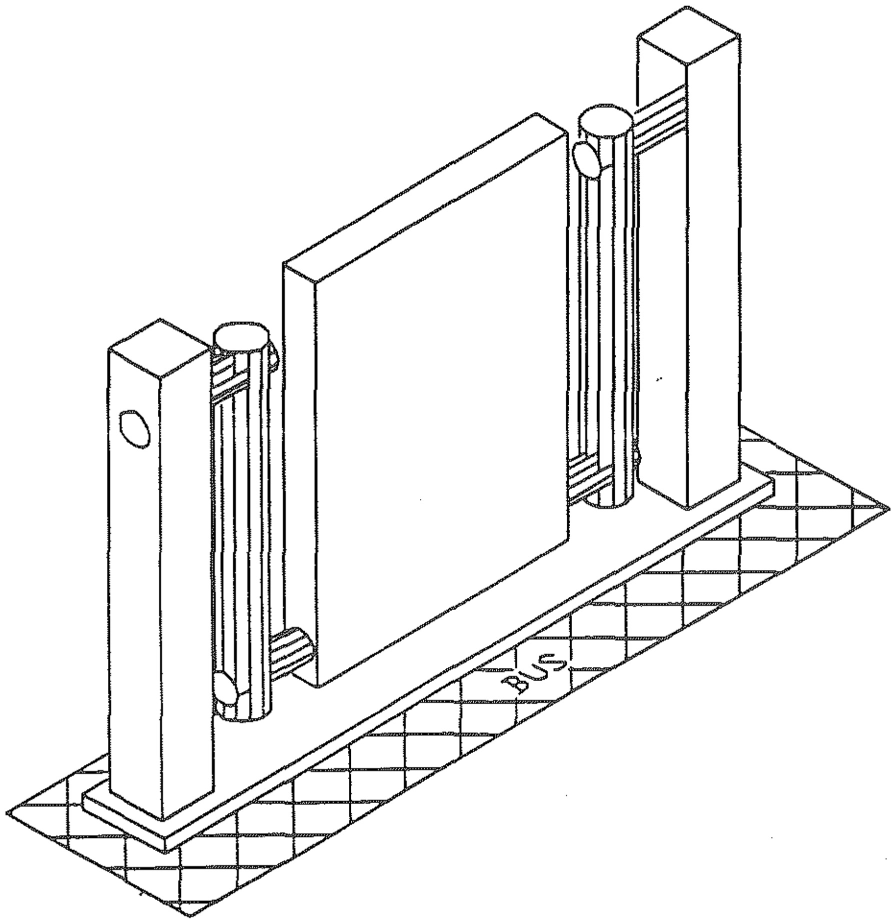


Figure 20 A Platform Lift in Stowed Position.

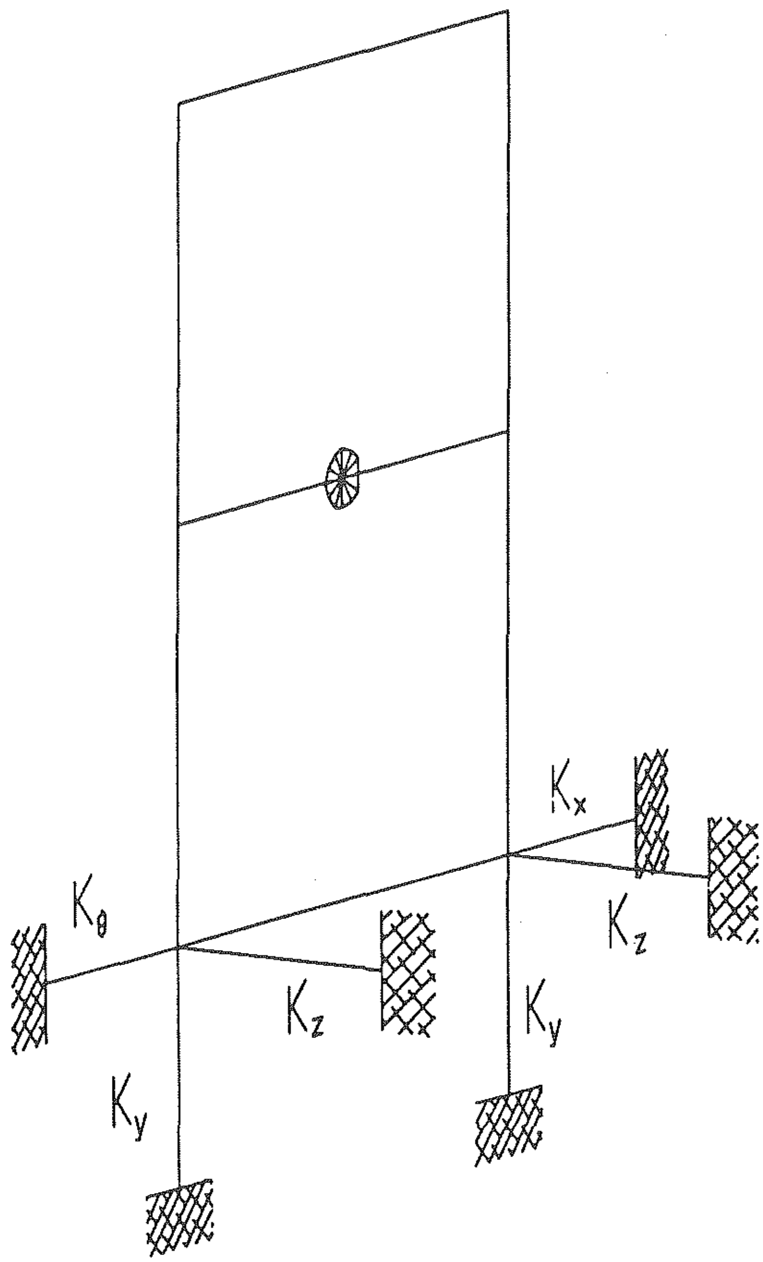


Figure 21 Dynamic Analysis of Lift in Stowed Position.

The spring stiffness coefficient k_x, k_y, k_z and k_θ will be obtained using the model shown in Figure 21. The stiffness coefficient is defined as force required to cause a unit displacement. Thus, to calculate the stiffness in x direction, we will apply a force at the node of interest in the same direction to produce unit displacement by restraining other degrees of freedom. But for computational reasons we apply a unit force at the node of interest in x direction of the model and determine the displacement in x direction, which allows to compute the analytical flexibility which is inverse of stiffness.

To calculate the flexibility in x direction, apply the unit force in the x direction at the platform center. The displacement produced by the applied unit force is flexibility and inverse of that is the stiffness. Similarly the stiffness k_y and k_z can be calculated by applying unit force at the platform center in the y and z direction respectively.

For the calculation of rotational stiffness k_θ, divide the k_x by the vertical distance between the platform center and the lift base. The detail of the analysis and results will be discussed in Phase III report.

6.2 (c) Structural Analysis.

i) Static Analysis : The finite element analysis of the lift structural system is performed using ANSYS finite element analysis (FEA) program. The analysis output contains the stresses in the members under axial load, shear, and bending actions. For the purposes of this analysis, the member properties were described by their nominal properties. The properties of certain critical members, such as the cam bracket, changes significantly along its length. In such cases, the exact member stress variation was recomputed using the exact cross-sectional properties and applying the boundary force to the component computed from FE analysis.

The finite element analysis of the lift structure is performed for various load conditions. The primary load condition is the combined passenger and wheelchair weight which is applied as a concentrated load group: 25 % of the total load is applied at the center of each platform edge beam and 50 % of the total load is applied to the center of the platform back beam all acting downward as shown in Figure 22. The lift structure is subjected to the additional load conditions that are described in Table 21.

Table 22 shows the analysis results describing the stresses of critical components while Table 23 describes the nodal deformations under service load condition. Further explanation of Table 22 and Table 23 is provided in 6.2 (d).

ii) Dynamic Analysis : Dynamic analysis is the investigation of the additional deformation and stresses produced by the impulsive inertia forces applied to the lift platform. In dynamic analysis the inertia forces applied at generalized mass element with six degree of freedom are used as input to the linear transient dynamic analysis. As discussed earlier the inertia forces are 60 newtons (12.95 pounds) and 4450 newtons (1000 pounds) for service load and ultimate load conditions respectively.

The governing equation for the dynamic analysis ignoring the damping forces is;

$$m\ddot{x} + kx = p$$

Where,

m = Mass properties of the lift platform.

k = Platform stiffness.

$\ddot{x}$ = Resultant acceleration.

x = Displacement.

p = Inertia force applied to the lift platform.

The above governing equation implies that the dynamic analysis is the investigation of mass properties and stiffness properties of the lift platform in the direction of produced acceleration. We already discussed about mass and stiffness properties in articles 6.2(a)ii and 6.2(b)ii respectively. The detail dynamic analysis results is the subject of Phase III report.

<u>*6.2 (d) Structural Analysis Results.*</u>

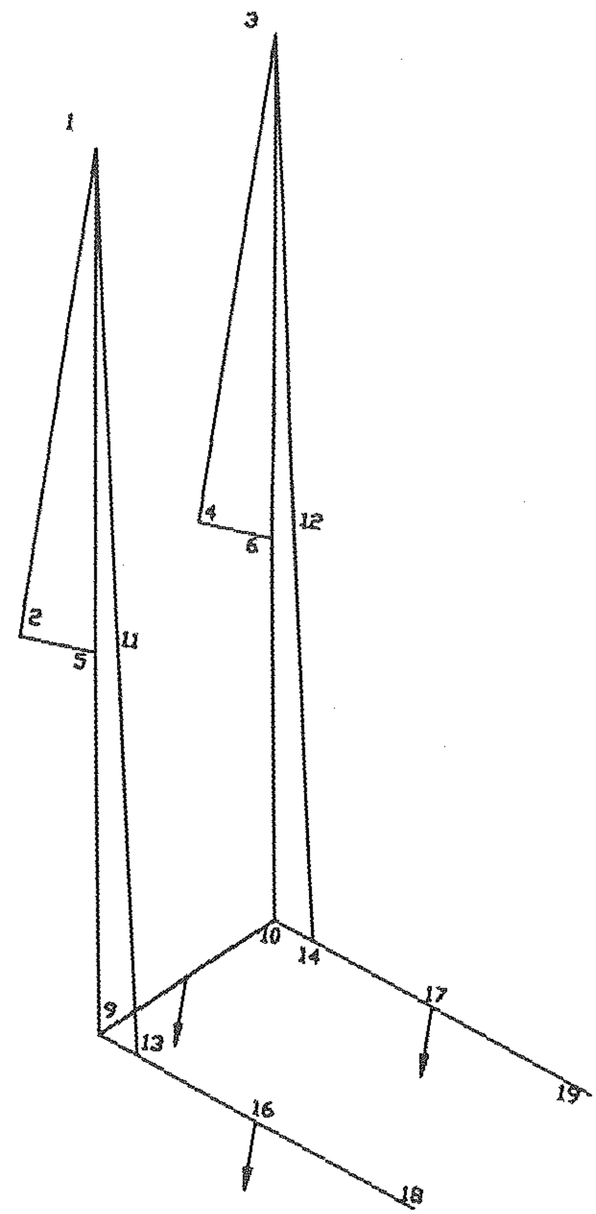


Figure 22 Service Loading and Point of Application.

Table 21. Load Combinations.

Analysis No:	Load Condition
1	1
2	2
3	1+2
4	3
5	1+3
6	4
7	1+4
8	5
9	1+5
10	6
11	1+6
12	7
13	1+7
14	8
15	1+8
16	9
17	1+9
18	10
19	1+10
20	11
21	1+11
22	12

Table 22. Stress of Critical Components.

Load Case	Critical Components	Element Stress (mpa) Yield Stress = 344.5 mpa.
1	3,4	289.4
2	3,4,13,15,17	344.5
	7	303.2
3	3,4,13,15,17	344.5
	7	275.6
4	3,4	344.5
	13,14	234.3
	15,16	227.4
5	3,4,13,15	344.5
6	3,4	344.5
7	3	344.5
8	3,4	344.5
9	3	344.5
10	3	344.5
11	3,4	344.5
12	3,4	344.5

1 Psi = 6.89 kPa.

Table 23. Nodal Deformations Under Service Load Condition.

Node	U_x millimeter	U_y millimeter	θ_z radian
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5,6	- 0.004572	- 0.000025	- 0.002097
9,10	- 7.597826	- 0.277139	- 0.009526
11,12	- 4.109491	-0.857682	- 0.002798
13,14	- 7.598054	- 1.590599	- 0.011257
15	- 7.600899	- 0.601701	- 0.009526
16,17	- 7.598054	- 7.044868	- 0.014502
18,19	- 7.598054	- 14.780641	- 0.581915

1 Inch = 25.4 millimeter.

The static load analysis results are presented in terms of component stresses for various load conditions. The various components stresses obtained under the load condition of Table 21 are described in Table 22. In the Table 22 the load condition, the critical components and a nominal values for uniaxial stress or the yield condition are described. Under these load conditions, element 3 and 4 (cam bracket) appears on the list of critical components under every load combination. These stresses are computed based on nominal cross - sectional properties of the components. The cam bracket stresses are recomputed using exact properties which are shown in Figure 23. This analysis shows significant yielding in this component during normal use.

6.3 Step Lift Analysis.

6.3 (a) Introduction.

To assess and identify the sources of step lift failures used in large transit buses, the finite element model (FEM) was developed to understand the resistance mechanism of the step lift structure.

The analysis was conducted by developing a computer based finite element model of the lift structural system. This section is focused on the modeling and structural analysis of the step platform lift. The detailed structural analysis of the step lift will not be included here.

6.3 (b) Step Lift Structural Model.

The step lift (Figure 24 in semi deployed position) structural system consists of three main subassemblages: the main frame, the deployment system and the platform system. The main frame comprises a frame with the corner posts mounted in a rectangular floor section for connection to the bus chassis, The corner posts also act as guides for up and down movement of the platform lift. The deployment system consists of two pivot shafts for raising and lowering the platform. The platform system consists of three sections foldable into a lower step, a riser, and an upper step. These three sections are pivoted on shafts along their adjacent edges.

The step lifts are commonly used in large-size transit buses that require a deployment distance of approximately 600 millimeters (24 inches). The platform dimension vary between different man-

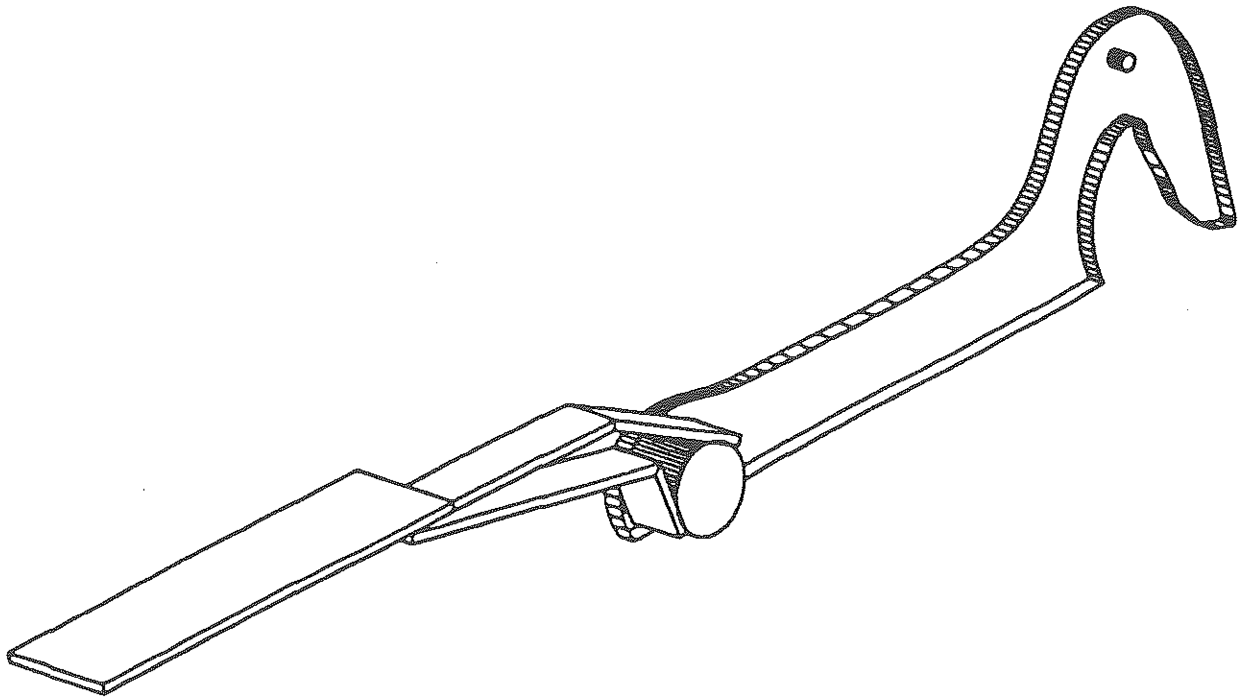


Figure 23 Cam-bracket Connecting the Middle of the Inside Frame With the Base of the Lift.

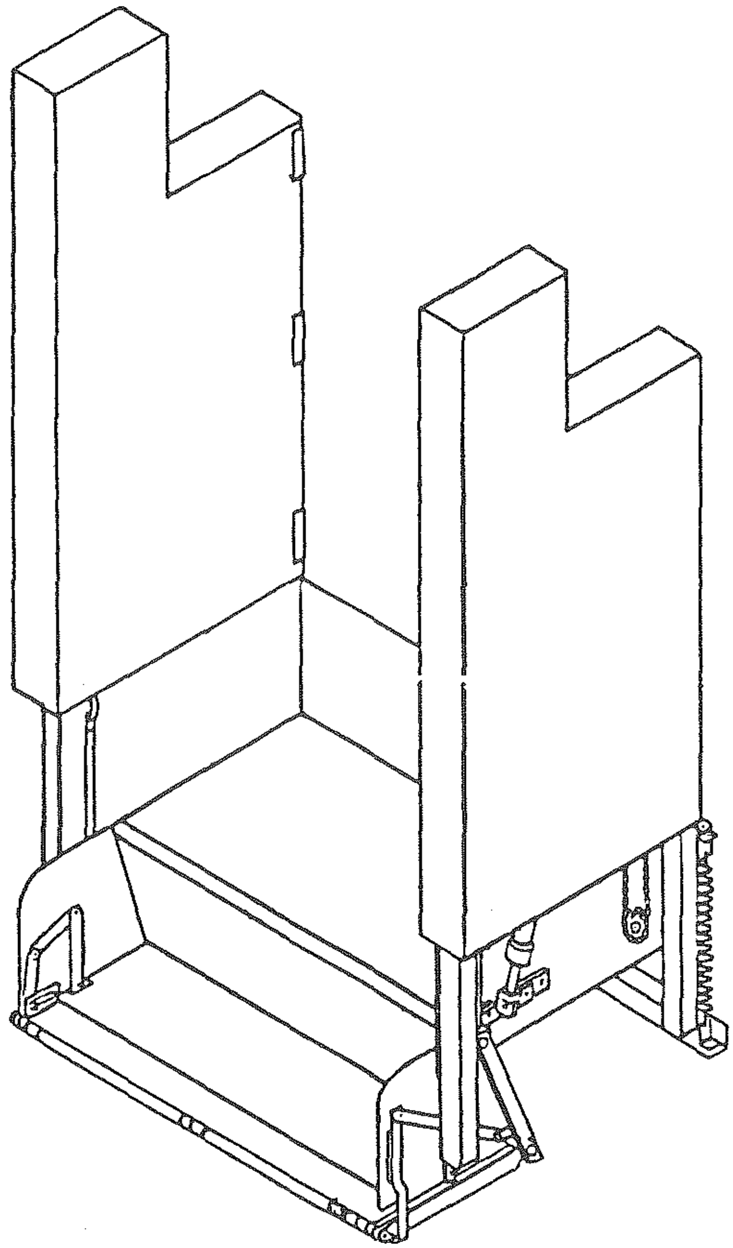


Figure 24 Passive Lift Used in Transit Busses.

ufacturers and models. In this study a typical platform dimension of 860 millimeters (34.5 inches) wide and 625 millimeters (25 inches) long is used. The structural model is based on the step platform lift shown in Figure 24. The model represents the fully deployed lift configuration. The structural model shown in Figure 25 is described by five element groups with one element type. The element type is three dimensional beam element. A total of 20 nodes and 17 elements describes the model.

No structural analysis results will be presented in this report for the step lift. We have not conducted load demand analysis for the step lift. For this reason structural analysis results are excluded in order to avoid any conclusions based on the hypothetical load conditions used for checking the finite element model of the step lift.

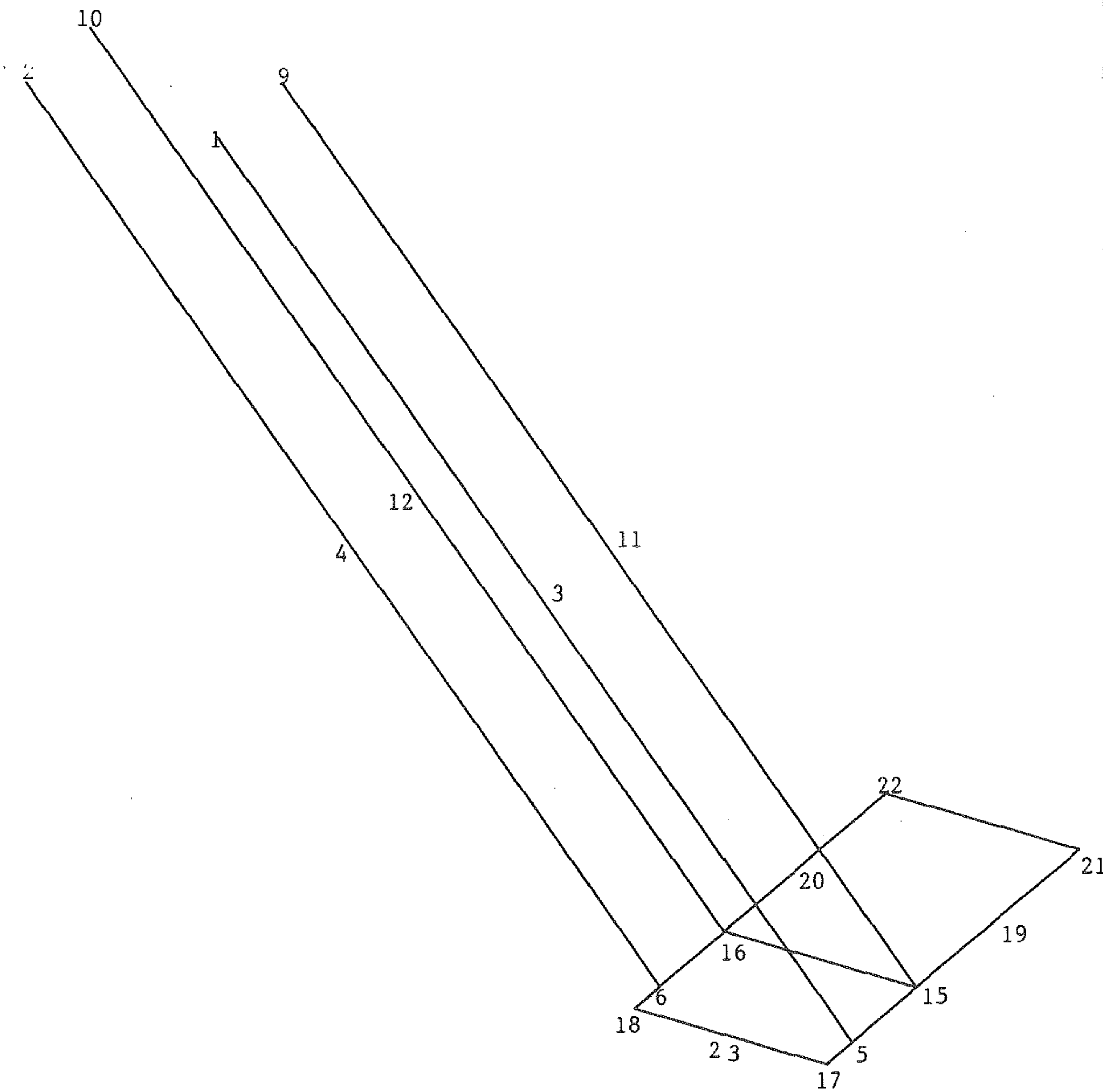


Figure 25 Finite Element Model for Folding Lift.

7. EXPERIMENTAL INVESTIGATION OF PLATFORM LIFT.

7.1. Background and Need.

An experimental investigation of the load response of wheelchair lifts structure is initiated to provide data in the development of structural specifications. The preliminary investigations and the analysis results clearly indicate that weak links exists in the lift structural system. One of the objectives of the experimental investigation is to verify these weak links. The primary objective is to develop and verify non destructive experimental indicators for lift reliability.

In structural analysis of wheelchair platform lift using finite element method, a determination of nodal displacement was made of wheelchair lift structural model under service load condition. The experiments will verify the results of our analysis. Also, we will investigate the lift performance by experimentally determining certain parameters such as flexibility, strength, deformability.

7.2. Apparatus / Instrumentations.

The experiments is conducted under a uniaxial loading frame. The loading ram of the frame is connected to a controller which provides a closed loop control of the servohydraulic system. A load cell is attached to the loading ram piston for measuring and / or controlling the load application to the platform lift. Additional components for loading system are the loading frame. A steel frame was designed and fabricated to hold the lift in position. A loading beam was attached between load cell and the lift to transfer load into point loads that duplicate the wheel print of a tri-wheelchair on the lift platform.

The acquired data includes vertical displacements at platform corners and horizontal displacement of platform heal. Direct current displacement transducer (DCDT) as displacement measurement instrument are used. Figure 26 shows the experimental apparatus.

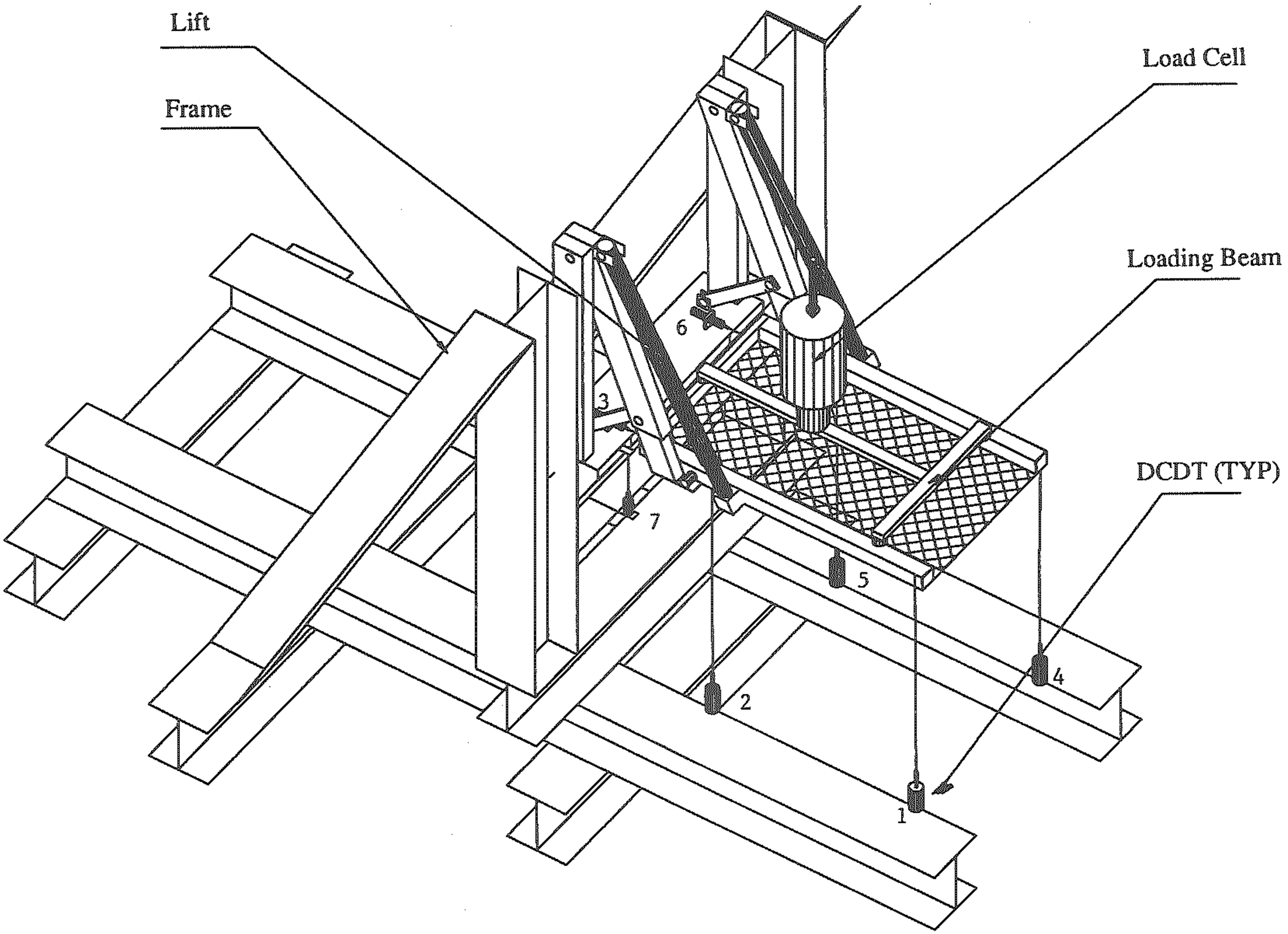


Figure 26 Apparatus and Measurement

7.3. Experimental Procedure.

Figure 27 shows the testing system flow chart. The loading ram controller is programmed to generate a specific actuator displacement as shown in Figure 28. The program commands the actuator to apply 37.5 millimeters (1.5 inches) downward in 60 seconds and to return to zero position in the next 60 seconds. During this time the displacements and actuator force are continuously acquired.

The actuator force is measured using a load cell with calibration relation provided by the manufacturer. The load cell output was amplified and conditioned prior to reading with the data acquisition system. The DCDT's measure changes in voltage where this change is linearly proportional to displacement of the point where the devices are connected to. For the purpose of measurement the relation between voltage and displacement i.e. calibration of DCDT is obtained prior to the experiments. Figures 29 to 36 indicates the calibration curves of the DCDT's. Table 24 shows detailed information about loading and measurement instruments.

Data acquisition includes ram load from the internal ΔP cell and stroke, lift displacement from DCDT and the load cell attached to the ram. Data acquired is collected in a desk top computer and is saved on a disk file. Thus test data can be manipulated, reduced in the computer and also can be displaced and plotted.

7.4. Preliminary Experimental Results.

A total load of 445 newtons (100 pounds) was applied on lift platform as shown in Figure 21. Vertical displacements at platform toe and platform heel, horizontal displacement at platform heel were measured. From Figure 37 we can see the displacement of the lift increases linearly with load increment. The measured displacement at center of platform is 22 millimeters (0.86 inch) at an applied load of 445 newtons (100 pounds).

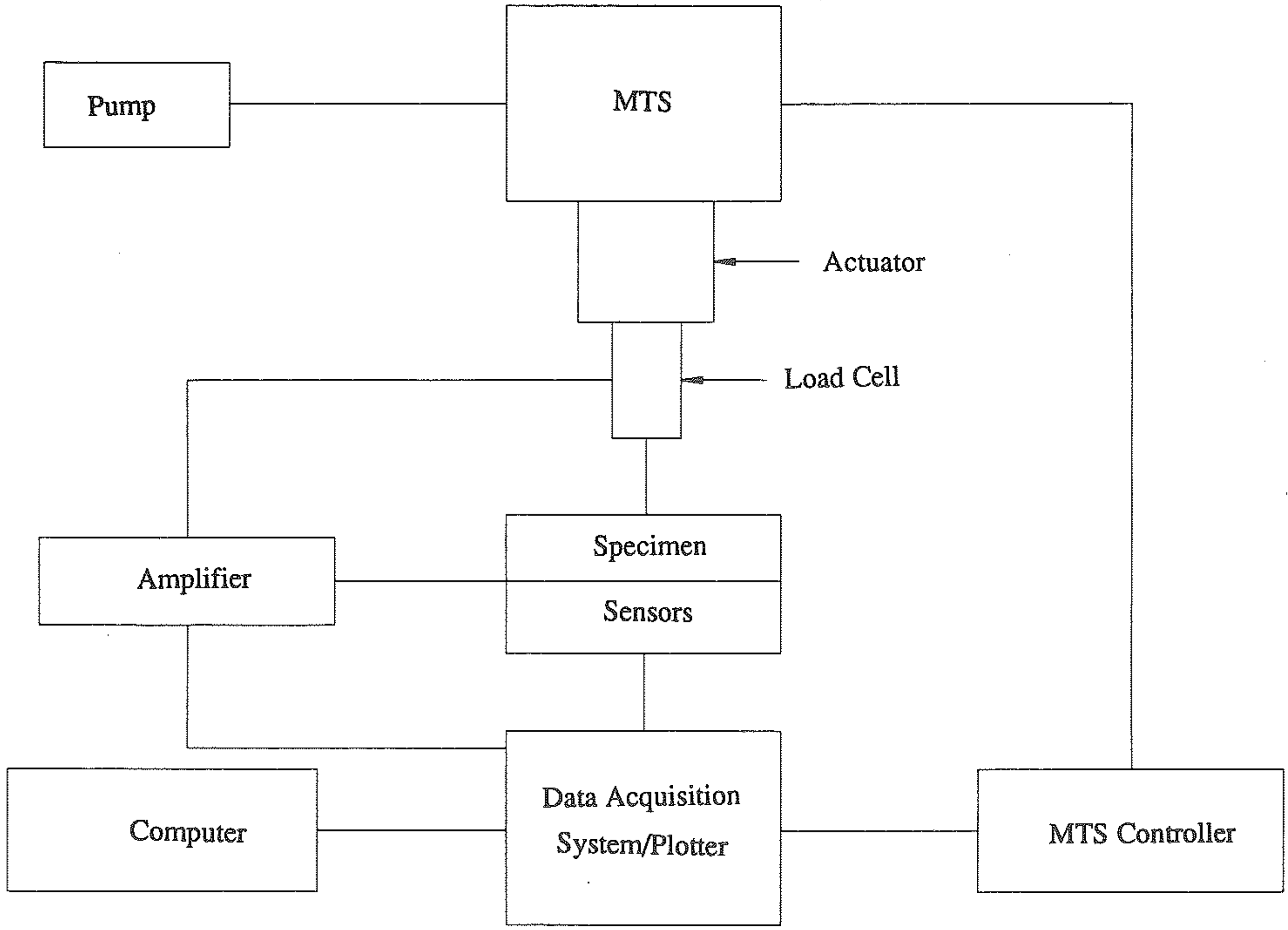


Figure 27 Testing System Architecture.

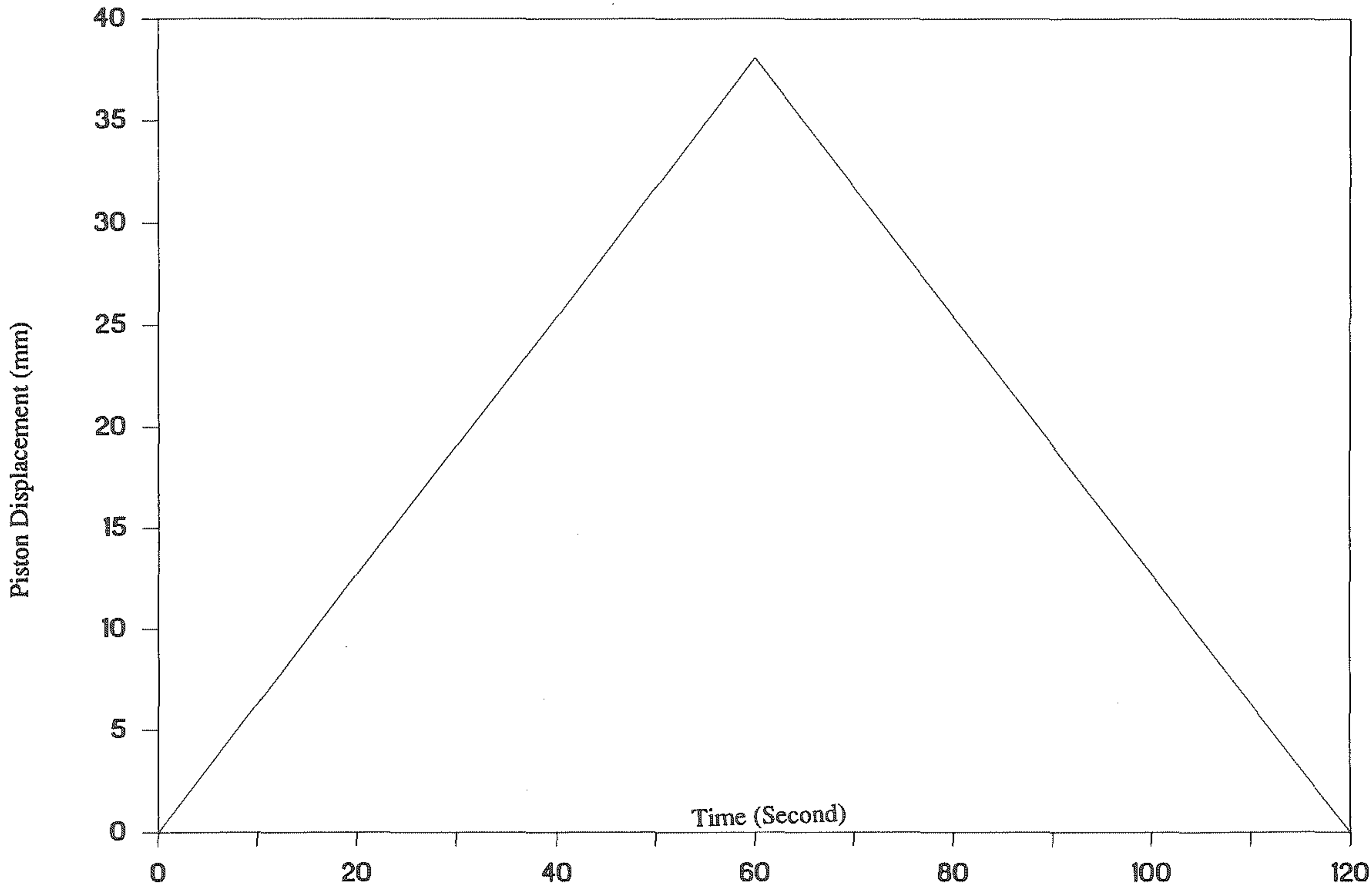


Figure 28 Piston Displacement vs. Time.

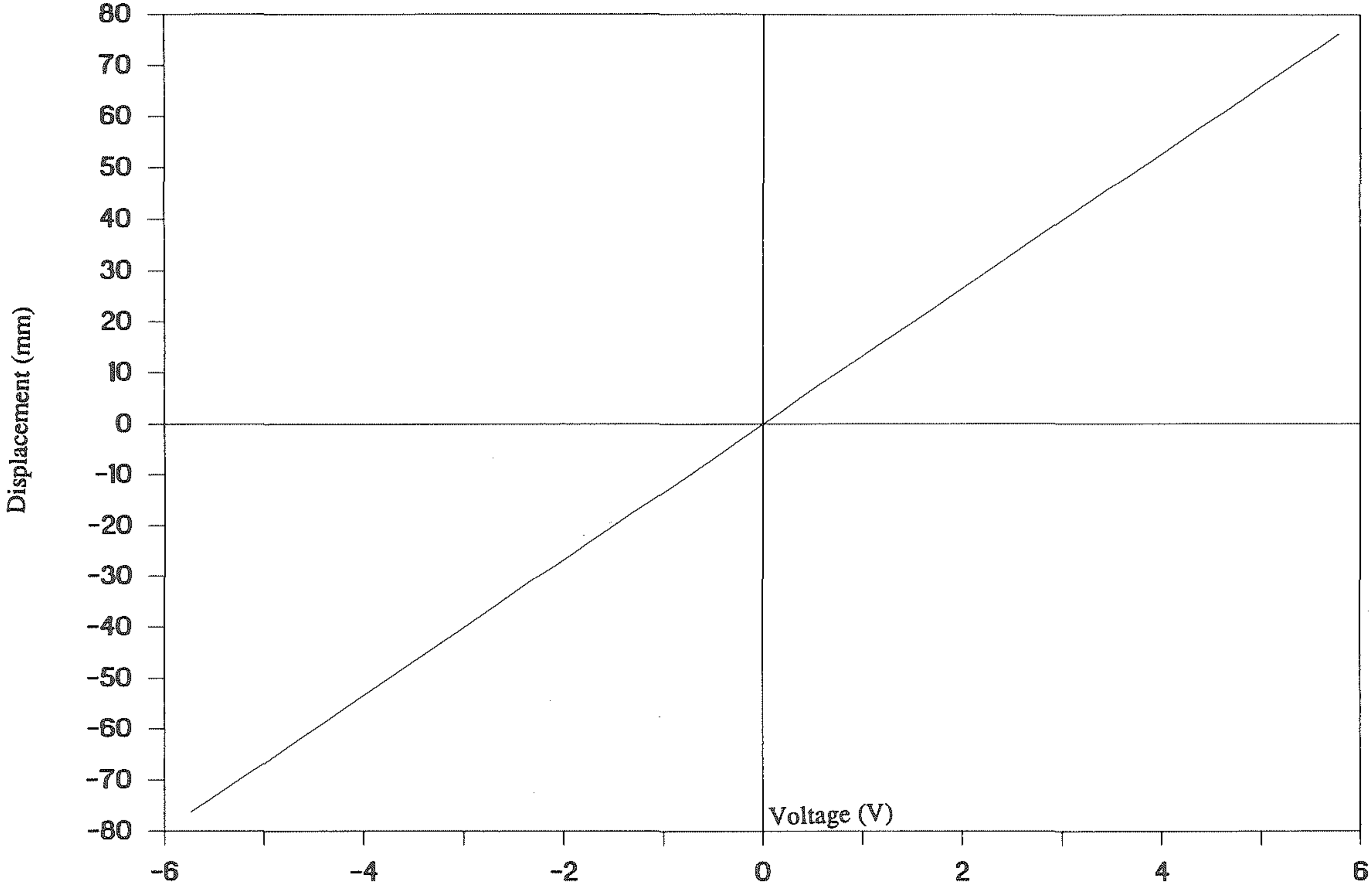


Figure 29 Calibration of DCDT 1.

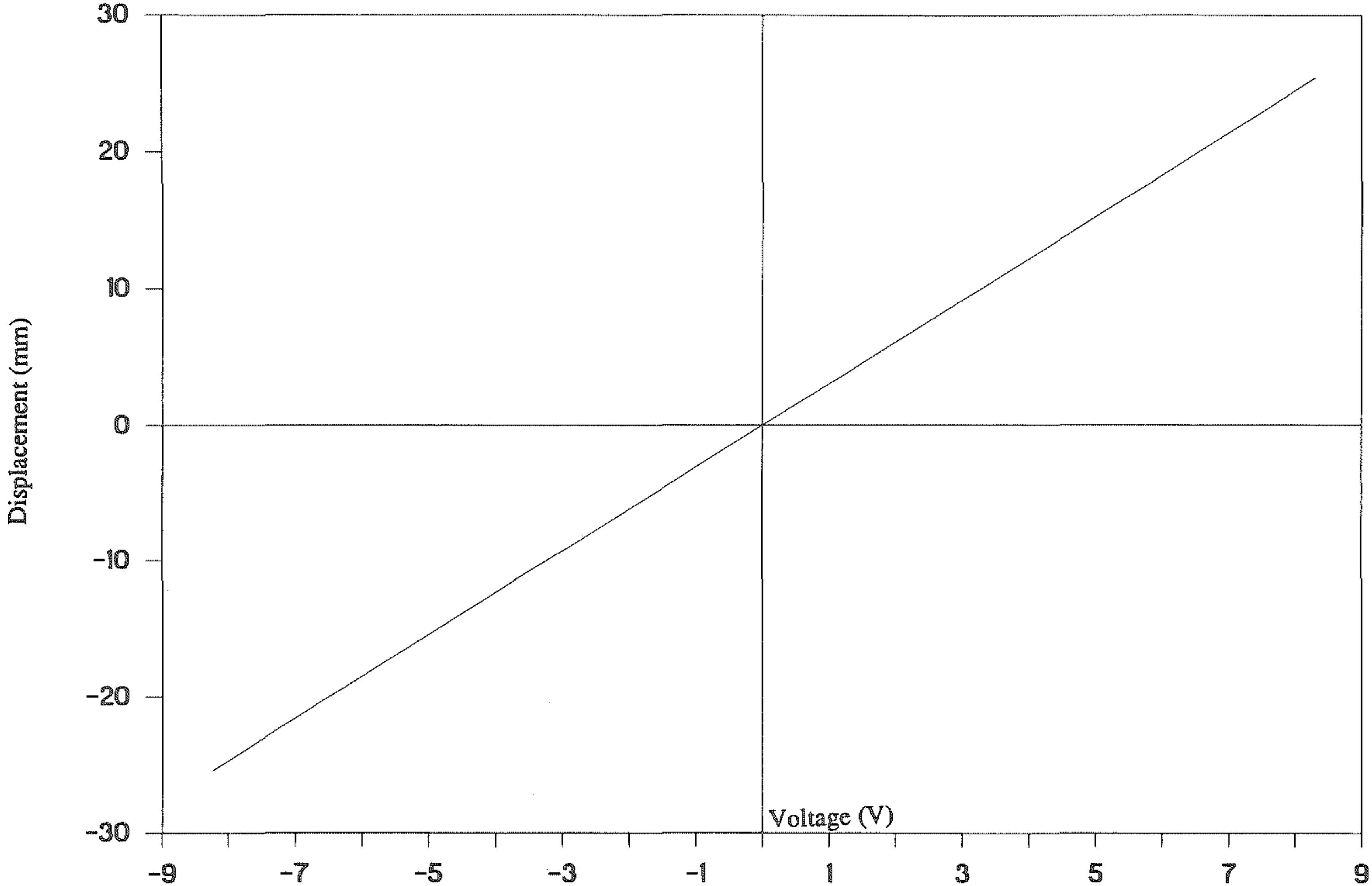


Figure 30 Calibration of DCDT 2.

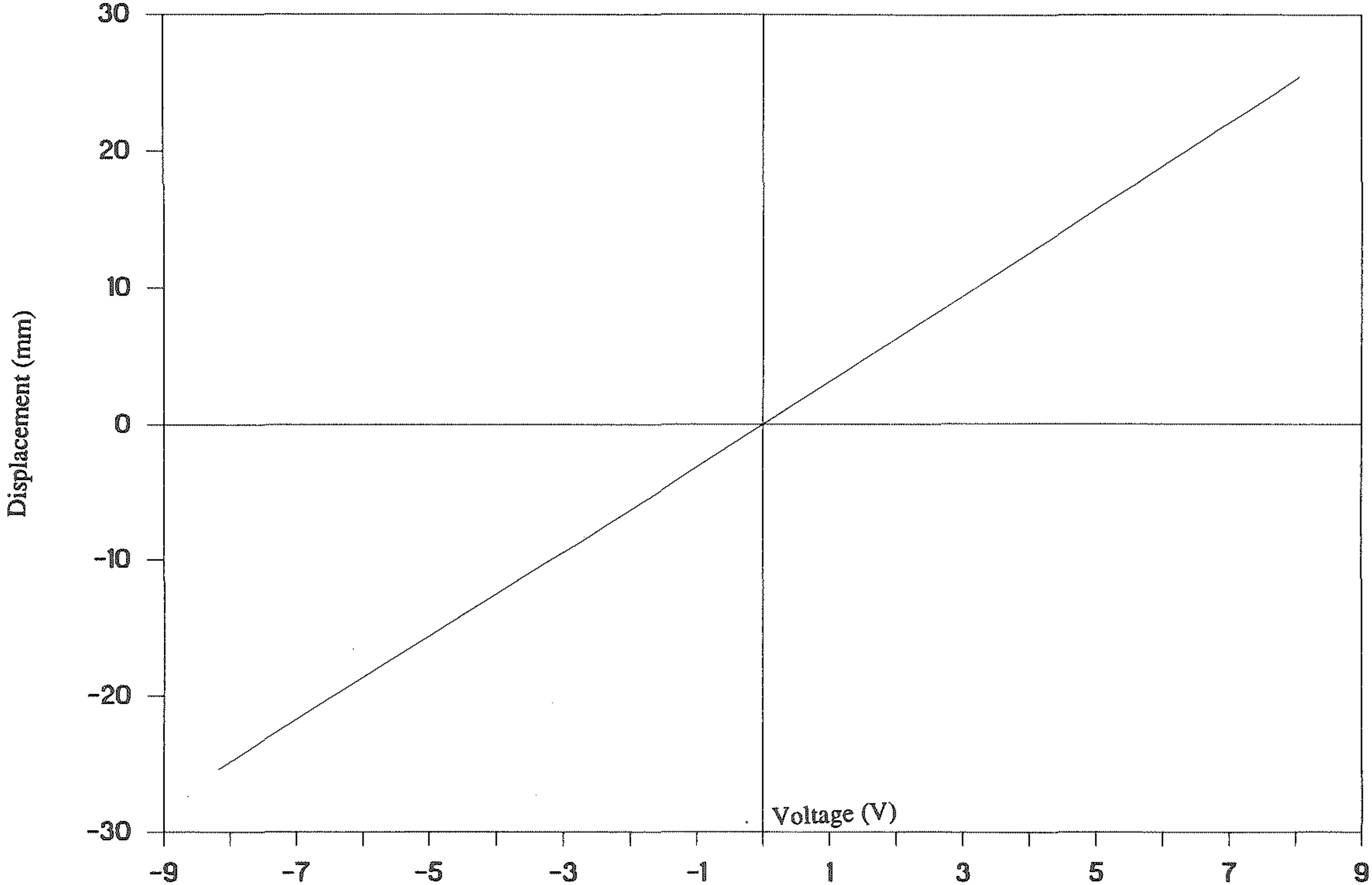


Figure 31 Calibration of DCDT 3.

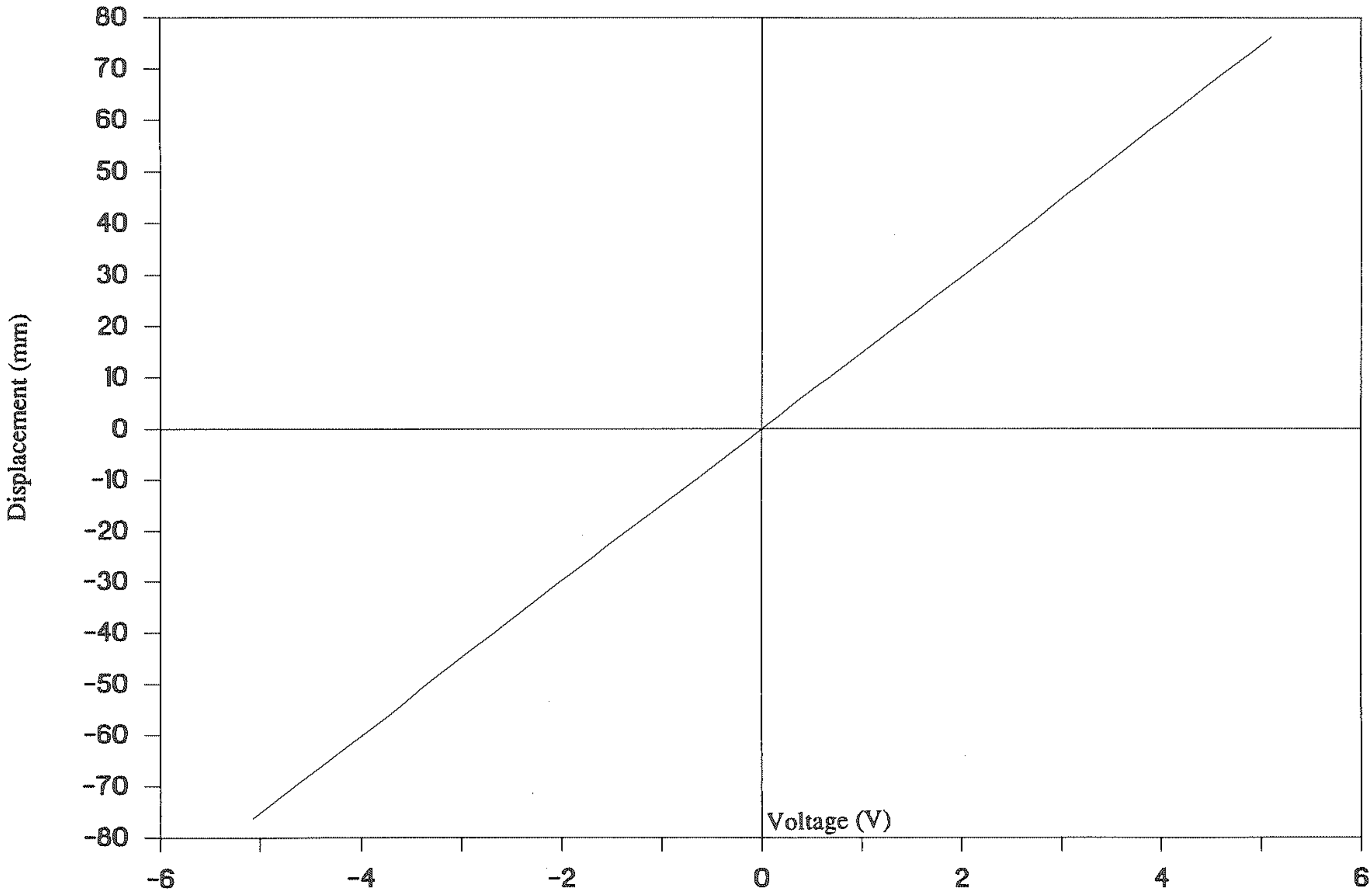


Figure 32 Calibration of DCDT 4.

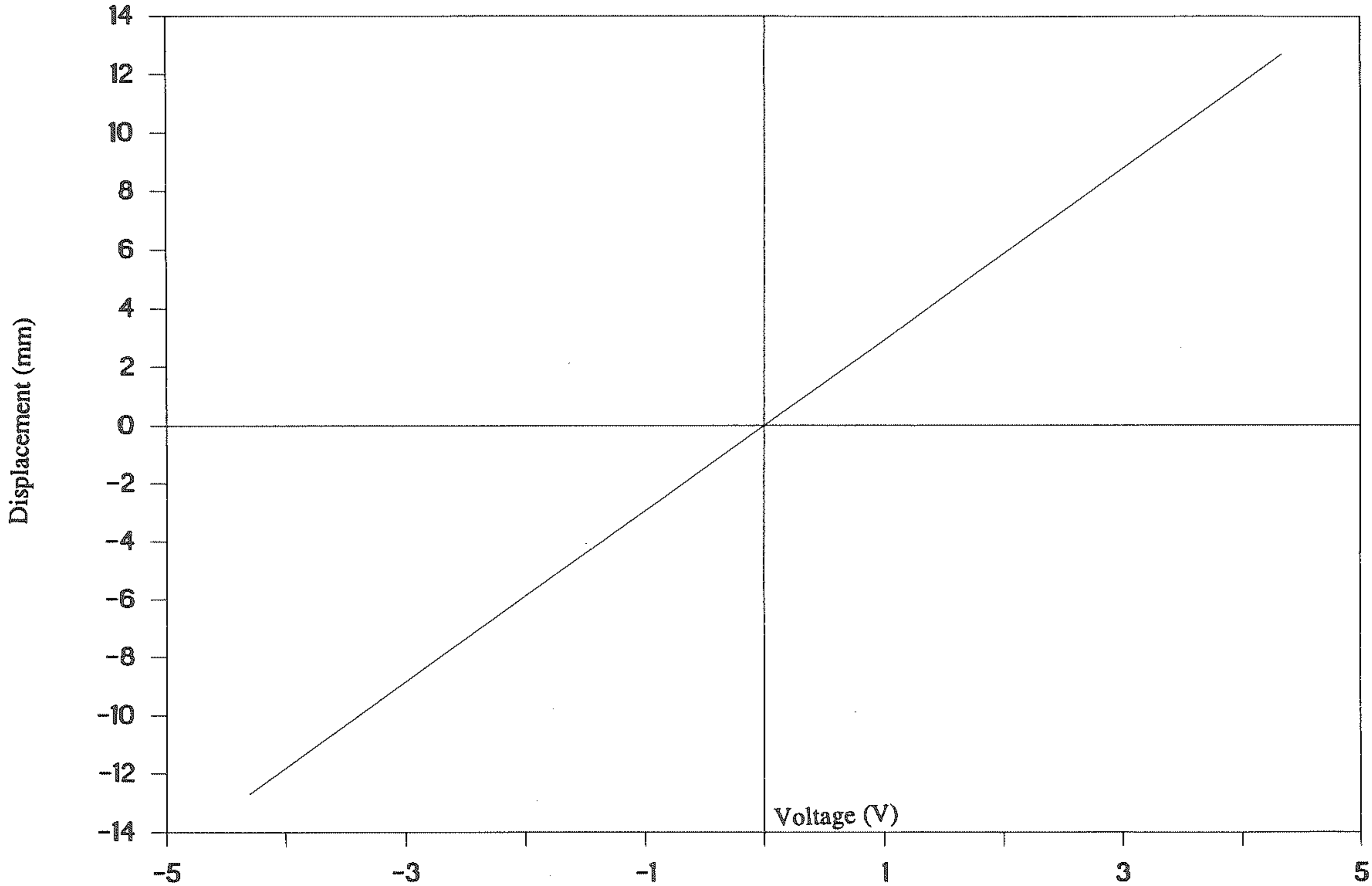


Figure 33 Calibration of DCDT 5.

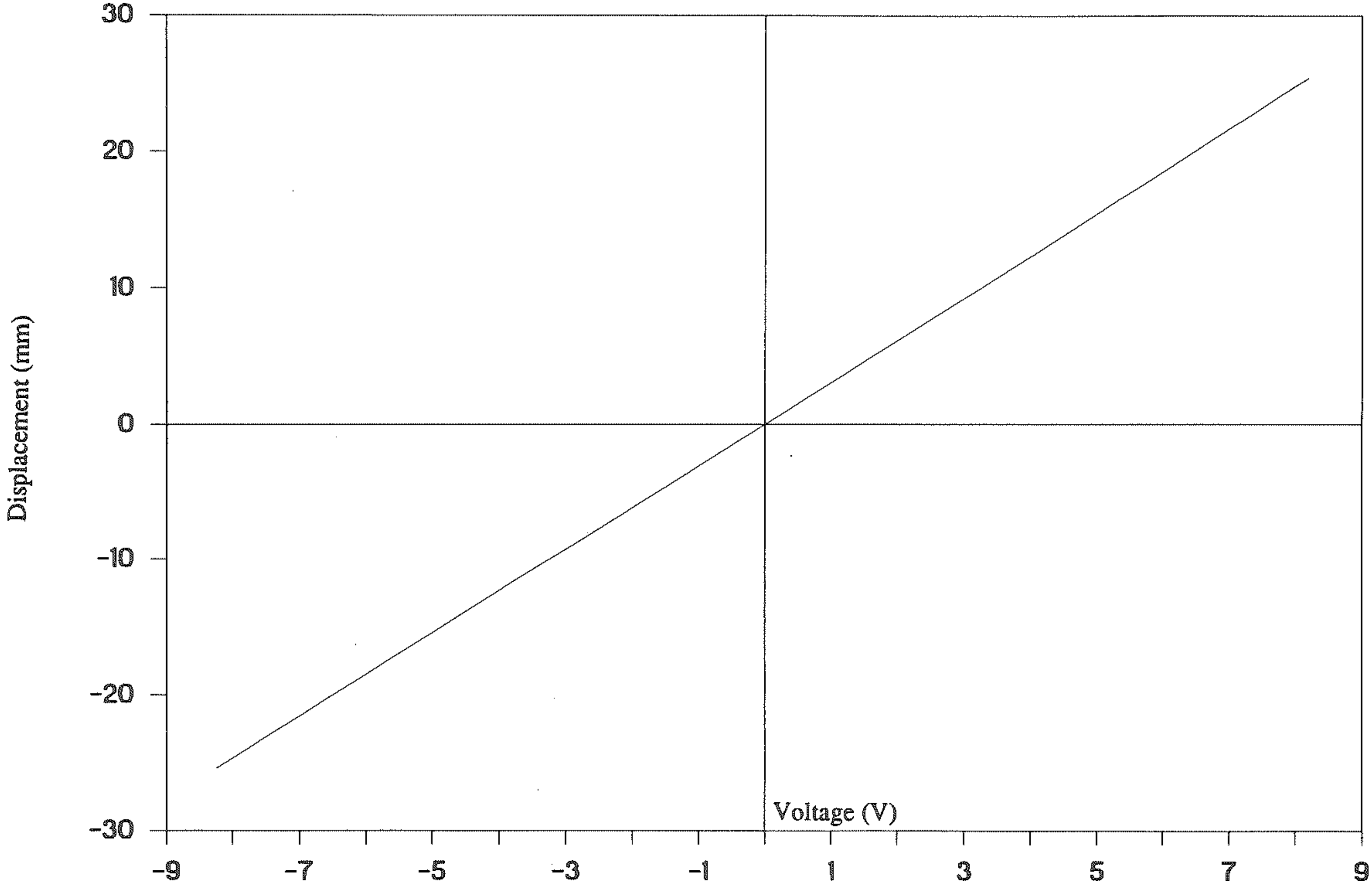


Figure 34 Calibration of DCDT 6.

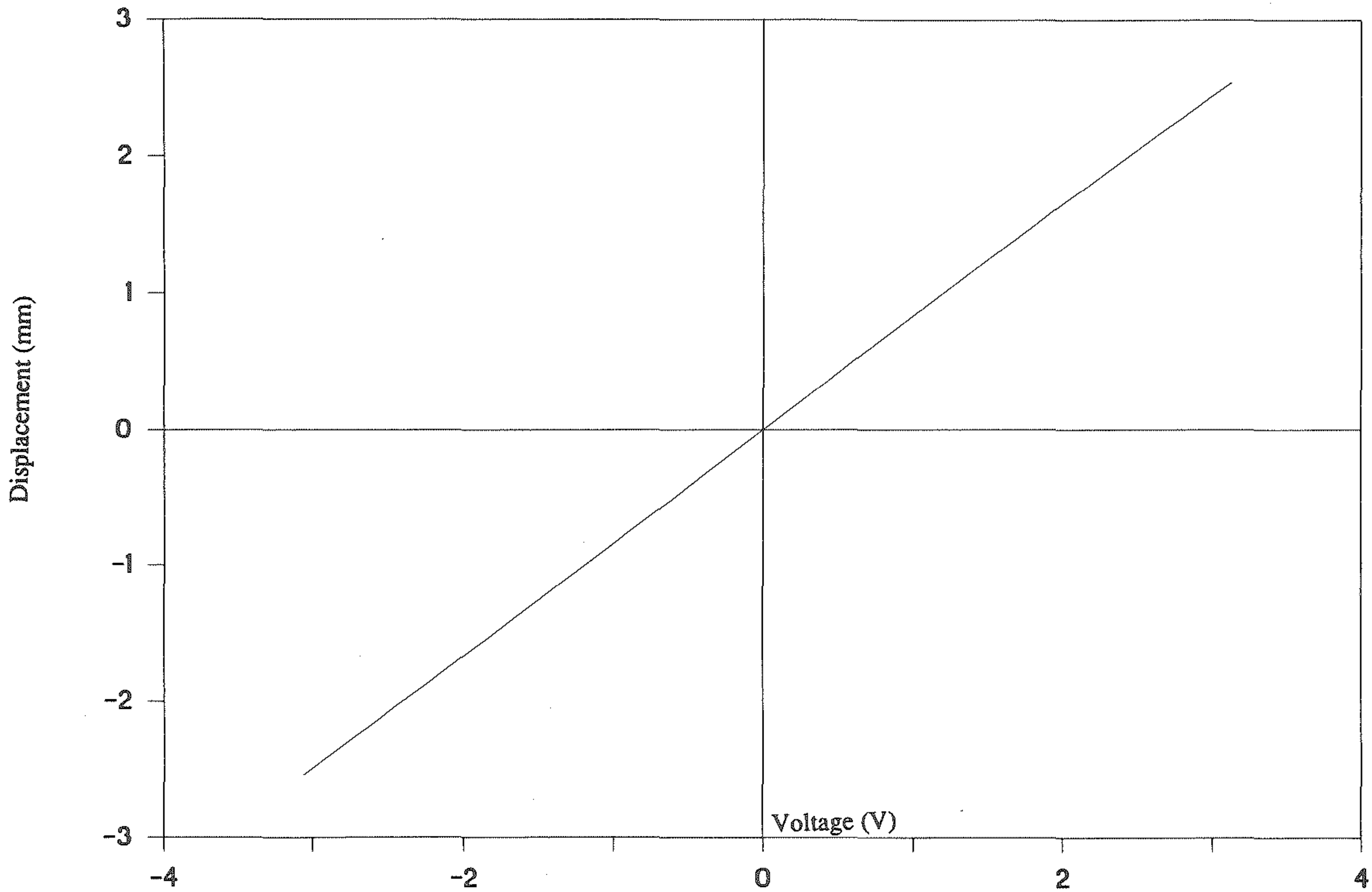


Figure 35 Calibration of DCDT 7.

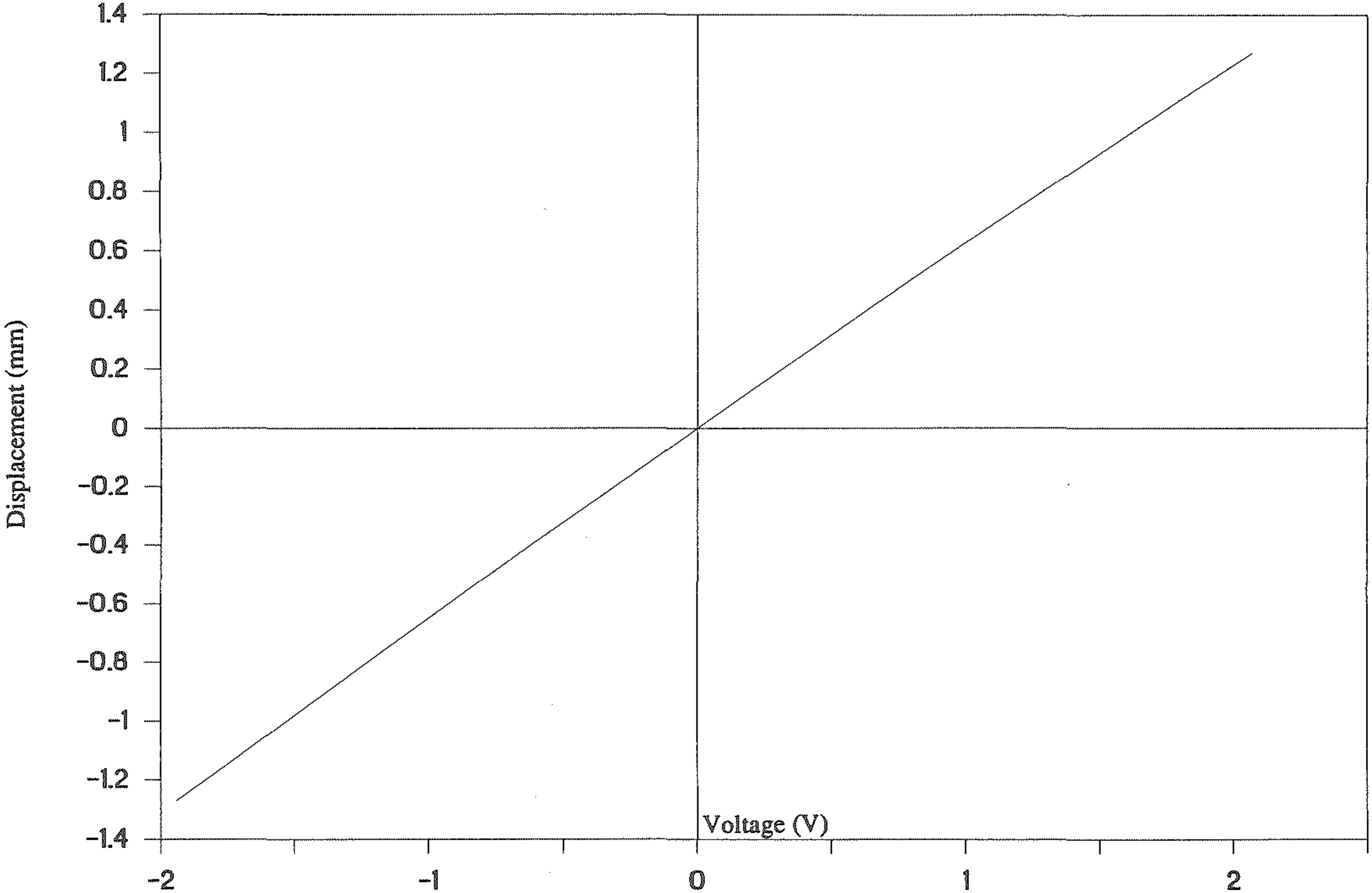


Figure 36 Calibration of DCDT 8.

Table 24. Data Acquisition And Calibration Table.

Instrument	Model No.	Range	Calibra -tion	Excitation Volt	Channel No.
MTS LOAD	66Q23A-02	0 - 450 KN	10.0	+/- 10 V.	1
MTS DISP.	LVDT	+/- 250 MM	2.0	+/- 10 V.	2
LOAD CELL	41/573-01	0 - 225 KN	500.0	+/- 10 V.	3
DCDT-1	246-000	+/- 75 MM	0.522	+/- 10 V.	4
DCDT-2	244-000	+/- 25 MM	0.121	+/- 10 V.	5
DCDT-3	244-000	+/- 25 MM	0.123	+/- 10 V.	6
DCDT-4	246-000	+/- 75 MM	0.590	+/- 10 V.	7
DCDT-5	243-000	+/- 12.5 MM	0.120	+/- 10 V.	8
DCDT-6	244-000	+/- 25 MM	0.116	+/- 10 V.	9
DCDT-7	241-000	+/- 2.5 MM	0.033	+/- 10 V.	10
DCDT-8	240-000	+/- 1.3 MM	0.030	+/- 10 V.	11

1 Kilo Pound = 4.45 Kilo Newton.

1 Inch = 25.4 Milli Meters.

7.5. Preliminary Comparisons with Analytical Investigation.

Table 23 shows the analytical vertical displacement of platform side beam toe as 14.5 millimeters (0.58 inch) for service load condition. A displacement of 11 millimeters (0.43 inch) corresponding to 480 newtons (110 pounds) load were obtained in the experiment result. This result correlates well with analysis result. The sample lift used during the preliminary testing was a reclaimed one with completed service life. Thus it is reasonable to have slack at joints and overall structurally softer then the new lift.

More precise experimental results will be obtained in Phase III when the new lifts will be used for experiment.

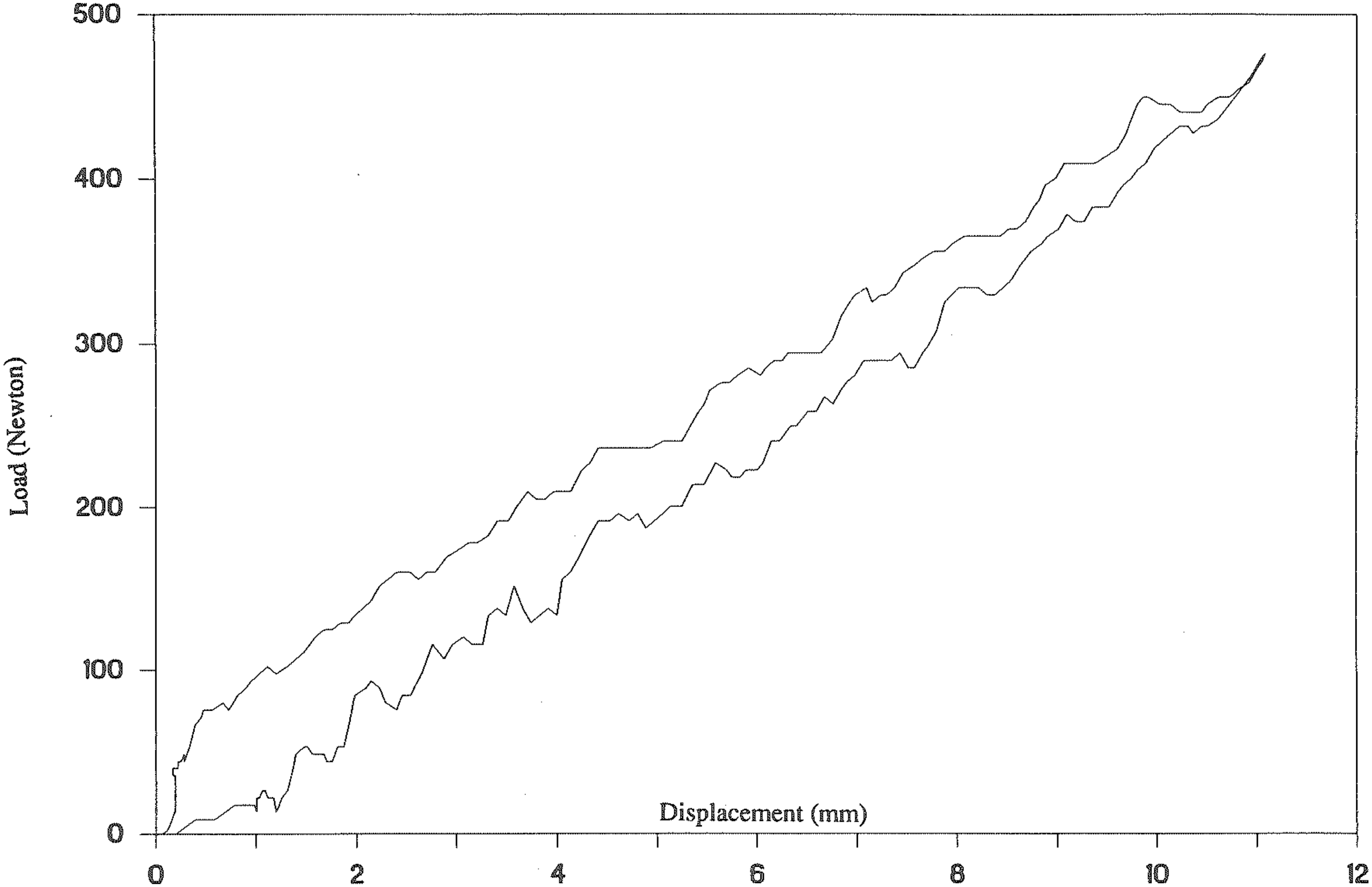


Figure 37 Load vs. Deformation of Platform.

8. CONCLUSIONS.

The work reported in this study covers the activities completed in Phase II of the wheelchair research program undertaken at Wayne State University. The activities performed can be classified under two broad categories (1) Reliability modeling based upon a statistical analysis of wheelchair repair data and (2) Structural modeling based upon a computer based finite element analysis of platform lift and step lifts. Additionally, experimental testing of platform lift structural members was initiated in preparation for the work completed in Phase III.

8.1. Reliability Modeling.

The approach presented is the continuation of the development effort of Weibull models for two types of step lifts presented in the Phase I report. This part of the research includes the incorporation of the location parameter in the model. Additionally, a separate Weibull model was developed for platform lifts of a specific type using repair data of four lifts for a three year period. The conclusions of the study are:

1) The addition of the location parameters does not make any significant difference in the estimates of the two major parameter of the Weibull distributions, Θ (characteristic life), and b (slope), particularly when the numerical value of the location parameter x_0 is very small. The data base used in the study was not broad enough to test whether the estimates of the parameters Θ and b would be significantly different, had the numerical value of the location parameter been larger.

2) The statistical analysis of a three year repair data base for a particular type of platform lift conforms the earlier finding that the distribution of the repair data measured either in Miles Between Repairs (MBR) or Time Between Repairs (TBR) follows Weibull distribution.

3) Since TBR and MBR are highly correlated, and since it is easier to collect TBR data, (compared to MBR), it is recommended that TBR distribution of repair data be used in analyzing reliability of wheelchair lifts.

4) Based upon 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 TBR and MBR.

5) Based upon 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.

8.2. Structural Modeling.

The primary objective of the structural analysis in this Phase is to describe the load demands, conduct structural analyses under these load demands and evaluate components stresses and structural deformations. The following conclusions are derived :

1. The load demands for the design of wheelchair lifts described in the specifications are not sufficient. The following additional load cases are recommended.

a). Static load cases.

i - Impact factor of 1.15 when fully deployed lift starts from zero velocity when lifting.

ii - Over extension of lift and ground contact at various critical points of the platform.

b). Dynamic load cases.

i - Bus floor motion exciting the fully stowed lift when bus is in motion.

ii - Lift integrity during bus collision.

2. The preliminary experimental results show good correlations with the analytical counter parts.

3. The structural model is sufficiently detailed for evaluating lift reliability under load cases.

4. The sample lift structure components show extensive yielding under static load cases. Thus some lift component structural strengths are insufficient.

ACKNOWLEDGEMENT.

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The authors would also like to express their appreciation to Dr.R.K.Roy of NUTEK Inc., and Prof. T.H.Maze of Iowa State University for their permission to use appropriate software packages for the analysis of repair data of wheelchair lift. The opinions and comments expressed in this paper are entirely those of the authors and do not necessarily reflect the policies and programs of the agencies mentioned above.

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APPENDIX 'A'

OPERATOR QUESTIONNAIRE SURVEY

(4) What brand(s) of lifts does your agency use or propose to use? What brand would you prefer to use, if any?

(5) Do you have specification, in addition to those developed by MDOT for ordering lifts?

(6) Is malfunctioning of wheel chair lifts considered a serious problem in your agency?

(7) Can you briefly tell us about the three most common type of lift operation problems your agency has experienced, (by bus size if possible?)

(8) On a given day, what percentage of lifts are in proper working condition?

Large ____________%, Medium ______________%, Small ________%

(9) Does your agency conduct its own maintenance of wheel chair lift or is the maintenance contracted out to a third party?

(10) Do you have a training program for your mechanics?

(11) Does the manufacturer provide your agency with a maintenance schedule? If so, does the schedule specify the type and frequency of maintenance operation? If yes, go to Question (12). If no, go to Question (13).

(12) How closely does your agency follow the manufacturer-suggested maintenance schedule?

(13) (Skip question 13 if you answered '~~Yes~~ No' to question 11.) Does your agency follow any type of preventative maintenance for the lift mechanism or is repair/maintenance initiated only in case of breakdowns?

(14) Does your agency maintain records of lift maintenance and lift failures? Are these records well-document?

(15) How many of the wheel chair-equipped buses that your agency procured most recently, have their lifts in proper working condition today?

Buses procured 3 years ago, _____ out of ____ in working condition

Buses procured 2 years ago, _____ out of ____ in working condition

Buses procured last year, _____ out of ____ in working condition

(16) In your opinion, is malfunctioning of wheel chair lifts the result of: (Please elaborate on the condition of failure).

(a) - Improper Design
(b) - Inadequate Maintenance
(c) - Improper Manufacturing Process
(d) - Improper Operation
(e) - Combination of the above

We greatly appreciate your cooperation in providing us with the above information. Please note that your individual responses will be kept confidential.

Sincerely,

Snehamay Khasnabis
Professor
Civil Engineering

Haluk Aktan
Associate Professor
Civil Engineering