DEVELOPMENT OF TRANSIT BUS COMPONENT FAILURE STATISTICS FROM CONVENTIONAL BUS CARD RECORDS

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FINAL REPORT

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16. Abstract

A fundamental requirement for the application of reliability engineering techniques is the existence of information on component failure probability density functions. This information is routinely generated in life-testing programs conducted by some industries, but little failure data has been collected or analyzed by the transit industry. This report illustrates procedures for developing failure distributions from conventional bus card record-keeping systems. Using actual data from a major U.S. transit property, the report demonstrates the computational steps necessary to convert failure and survivor counts into cumulative failure probabilities when the components of interest have variable accumulated mileages. The procedure is applicable even if some components have not been run to failure. The use of the resulting distribution to set or evaluate maintenance and replacement targets is also illustrated.

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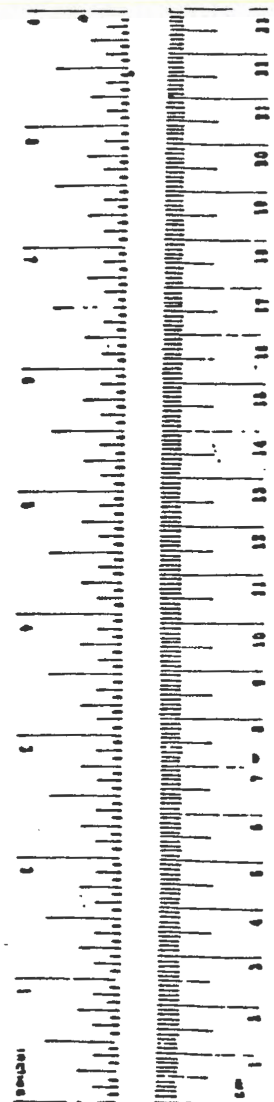
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

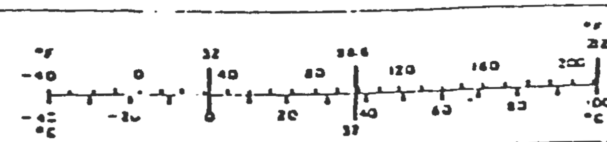
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

[illegible]



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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I Introduction

A. Purpose

The purpose of this report is to demonstrate the feasibility and utility of determining the probabilities of failure for various major bus components and systems from existing maintenance records. These probabilities are of interest in management decision-making because they can be used to determine inspection mileages for the components, (inspections being a key factor in an effective preventive maintenance program) and optimal replacement intervals (see Foerster et al, 1981). The process for determining the failure probability distributions is demonstrated using maintenance data from the Alameda-Contra Costa Transit District. This process is perfectly general and is suitable for application at other systems where maintenance records are available.

B. Framework of Report

The report is divided into five major sections. Section II describes the development of the data base which is used to demonstrate the process. Included in this section is a general background of the Alameda-Contra Costa Transit District and a detailed description of data obtained from their existing maintenance record system. Section III describes the process of analyzing the data. This includes the determination of the miles to failure for each component, the development of survival counts for each component, and the utilization of this information to determine failure probabilities as a function of mileage and the derivation of cumulative failure probability distributions. Section IV gives a summary and evaluation of the data developed in the analysis. Section V contains a discussion of the results and provides examples of the types of conclusions which may be drawn from the analysis of failure data. Finally, Section VI restates the procedure for extracting data from existing records, analyzing the data and evaluating maintenance intervals from the information obtained. This gives a basic outline of the procedures that are needed to implement the failure analysis methodology at other transit systems.

C. Overall Conclusions

The procedures and applications illustrated in the remainder of the report demonstrate that:

1. Standard bus maintenance record keeping procedures are compatible with the requirements of reliability analysis techniques.

2. The data needed are easy to extract from existing records.

3. The analytical methods required can be applied using widely available general purpose computer packages.

4. Graphical displays facilitate the analysis of the failure data.

5. The results of the analysis can provide insight into the appropriateness of existing or proposed maintenance policies.

II. Development of Data Base From Existing Maintenance Records

A. Background

The Alameda-Contra Costa Transit District, hereafter referred to as A/C Transit, operates a fleet of 813 buses in the Oakland, California area; most of the vehicles are GM coaches. A/C transit routes provide service to three general areas. Routes run between Oakland and downtown San Francisco, Oakland and its surrounding suburbs, and Oakland and the Concord-Pleasant Hills area some 30 miles away.

The A/C transit district maintains buses at four divisions located in and around Oakland. Buses are assigned to a division and serviced at that division's garage. Exceptions to this would be major breakdowns while a bus was in service, in which case the repair would be done at or by the nearest division.

A/C Transit inspects major components such as differentials, generators, starters, air compressors, blowers and brake valves and diaphragms on a regular basis according to prearranged guidelines (Table 1). These components are then changed as the foreman deems necessary. Inspections and repairs are also initiated by operator reports of obvious defects or possible problems which are discovered during the operation of the bus.

After a foreman decides that the replacement of a component is necessary and the component is replaced, a Mechanical Department Work Report is filled out listing the bus number, the date of the repair, the unit or units replaced and the reasons(s) for the repair. This information is then transferred monthly to a bus maintenance history record along with the end-of-month mileage. It is from these bus histories that the data base for this project was developed.

B. Description of Data

Of the 813 buses in operation at A/C transit as of November, 1980, 263 were randomly selected for the study. All buses chosen were GMC V-6 Detroit diesels, models SDH-4501, TDH-5304, TDH-4516, TDH-5301, TDH-5305, TDH-4517, TDH-4519, T6H-4523 and T6H-5305. The information gathered for most buses covered five to ten years of operation, although 15 full bus histories were taken and 40 shorter two to three year histories were obtained.

Data concerning the replacement of 17 major components was obtained from these histories. These components are listed in Table 2. With the exception of engine work done under the major or semi-overhaul categories, all units are considered replaced in totality when they are reported on the bus history. Distinctions are not made as to whether the unit being replaced failed because of an internal defect, normal wear, or an accident; these could not be determined from these records. Also, no distinction is made as to whether a component is a new or rebuilt part.

Table 1

A/C Transit Unit Exchange Program

Inspection Mileages

Vehicle Number	Trans. Hyd. Trans.	Diff.	Gener.	Starter	Air. Comp.	Blower	Semi-O'Haul	Brake Appl. Valve	Quick Release Valve	Brake Diaph-ragm	Brake Relay Valve	Air Change Shutter-Stat	Change Comp. Head Casket	Shift Gov-ernor
100-179 (A/C	See Note	400,000	275,000	150,000	250,000	300,000	250,000	250,000	–	100,000	250,000	–	–	36,000
180-299	" "	400,000	275,000	150,000	250,000	300,000	250,000	250,000	–	100,000	250,000	–	–	36,000
300-364	" "	700,000	275,000	150,000	250,000	300,000	250,000	250,000	–	*100,000	250,000	–	–	36,000
400-449	" "	400,000	275,000	150,000	250,000	300,000	250,000	250,000	–	100,000	250,000	–	–	36,000
500-624	" "	400,000	275,000	150,000	250,000	300,000	250,000	250,000	–	100,000	250,000	–	–	36,000
625-680	" "	700,000	275,000	150,000	250,000	300,000	250,000	250,000	–	** 75,000	250,000	–	–	–
700-764	" "	450,000	275,000	150,000	250,000	300,000	250,000	250,000	–	**100,000	250,000	–	–	36,000
765-809	" "	700,000	275,000	150,000	250,000	300,000	250,000	250,000	–	**100,000	250,000	–	–	36,000
825-864														
900-929	" "	700,000	275,000	150,000	250,000	300,000	250,000	250,000	–	** 75,000	250,000	–	–	36,000
930-989	" "	700,000	275,000	150,000	250,000	300,000	250,000	250,000	–	100,000	250,000	–	–	36,000
XMC-77	" "	250,000	275,000	60,000	250,000	–	200,000	250,000	–	100,000	250,000	100,000	–	36,000
2000-2049	" "	*200,000	250,000	60,000	250,000	200,000	200,000	250,000	200,000	150,000	250,000	100,000	–	18,000
2100-2120	" "	*200,000	250,000	60,000	250,000	200,000	200,000	250,000	–	100,000	250,000	100,000	–	18,000

NOTES

Convertors will be changed only as required for leaking seals and noise. Clutches to be changed at 25,000 miles on coaches 175, 176, 177, 178 and 17

Where one brake diaphragm on an axle needs changing, always change the other diaphragm on the same axle.

*Differentials will be changed only as required for leaking and noisy.

**Coaches #330 thru 364, 625 thru 680 and 780 thru 809 and 900 thru 929 have the DD-3 Brake diaphragms installed on rear wheels, and should be changed every 75,000 miles.

The table above shows minimum unit mileages at which units on coaches should be thoroughly inspected and checked to determine if at this mileage the units should be removed for overhaul. After inspection, if it is thought possible to obtain additional mileage before overhaul without the possibility of damage to the unit, then the unit should be flagged for each additional major inspection, and again re-inspected thoroughly to see if the unit in question will be able to continue to run satisfactorily. It is during this high mileage period that the Superintendent and his foremen must watch those units very closely. Should it be necessary to remove a unit for mileage under those indicated, the yellow defect tag should show in detail the reason therefore. Semi-overhauls should be based on engine mileage and performance.

Source: R.H. Bertz, A/C Transit Unit Exchange Program

Table 2 Bus Components Studied
Engine (Major Overhaul)
Engine (Semi Overhaul)
Differential
Transmission
Clutch
Starter
Generator
Blower
Air Compressor
Front Brake Diaphragm
Rear Brake Diaphragm
Brake Applicator Valve
Brake Relay Valve
Right Front Brake
Left Front Brake
Right Rear Brake
Left Rear Brake

The data obtained for each replacement of the 17 components under study was as follows:

1. The division to which the bus was assigned (2, 3, or 4).*
2. The bus identification number.
3. The date of replacement.
4. The mileage at the end of the month in which the unit was changed.
5. The unit which failed
6. The reason given for initiating the inspection which lead to the unit replacement.

The reasons for initiating an inspection were coded as follows:

1. Mileage - Routine check as per pre-arranged schedule
2. Operator - Operator initiated inspection stemming from problem encountered while bus was in use
3. Inspector - Mechanic initiated check
4. Breakdown/Road Call - Major breakdown requiring service on site.
0. NA - Information not available

III <u>Analysis of Data</u>

This section describes the procedures used for the initial analysis of the data. Detailed discussion of these results are in the following sections. The analysis was done using the Statistical Analysis System (SAS) Version 79.5.

A. Development of Failure Mileage

The basic items of interest in this study are the failure rate of each component and the functional relationship between the probability of failure for any given unit and the number of miles operated. Thus the main focus in the analysis of the data is the mileage that each unit attained before it was replaced because failure seemed likely or because the unit actually failed. <u>For convenience, we will use the term "failed" interchangably with "replaced in anticipation of failure."</u>

The miles to failure for each component was computed as follows. For each type of unit in each bus the incidents of failure were sorted in chronological order and the mileage for the first incident of failure was subtracted from the second, the second from the third and so on to determine the mileage between replacements. This convention is reasonable since A/C routinely inspects units both at set mileages and upon the basis of operator reports and closely monitors their performance. Thus any replacement is likely to indicate that the unit has reached or is about to reach the end of its useful life.

* Due to time and monetary constraints, information could not be obtained from division 6 which services 10% of A/C transit's fleet. We feel that this exclusion does not negatively affect the validity of the data or conclusions developed from it.

At this point, in order to facilitate analysis, the miles to failure were categorized into intervals of tens of thousands of miles. For example, if the miles to failure for one observation of a unit were 27,850, then the interval in which it failed, which will now be referred to as its FI (or failure interval) value, would be:

$$\frac{27850}{10000} = 2.785 \qquad \text{Rounding, FI} = 3$$

Because of the system of rounding employed, this FI value of 3 means that the unit failed (or was replaced) somewhere between 25,001 and 35,000 miles. Thus for all values of FI 0, FI x 10000 is the middle of the 10000 mile interval in which the unit was replaced or failed. (FI = 0 indicates that the unit failed during the first 5,000 miles of operation).

One feature about this method should be mentioned: because of the record-keeping procedure, the mileages used to determine the miles to failure were the end-of-month mileages for the month in which the unit failed. Thus the mileage at failure may differ somewhat from the end of month mileage. In the most extreme cases this difference, for a unit that failed at the beginning of the month, would be the average monthly mileage for that bus. This average monthly mileage for the buses studied ranged from 3000 - 4300 miles.

The frequency of a unit failing during a given interval can be meaningfully displayed in histograms (charts 1-17 in Appendix A) Most of these exhibit the characteristic properties of classic failure curves. That is, an initial period of high failure due to manufacturing defects is followed by a stable rate of failure due to random processes, with a marked increase in failures as the unit approaches its design limit and wear and tear begin to take their toll.

Exhibit 1 depicts a frequency bar chart for failures of the clutch. This chart is similar to chart 5 in Appendix A. The large number of failures in the 0-15,000 mile interval probably represents the failures due to defects. Later failures represent the result of random failures.

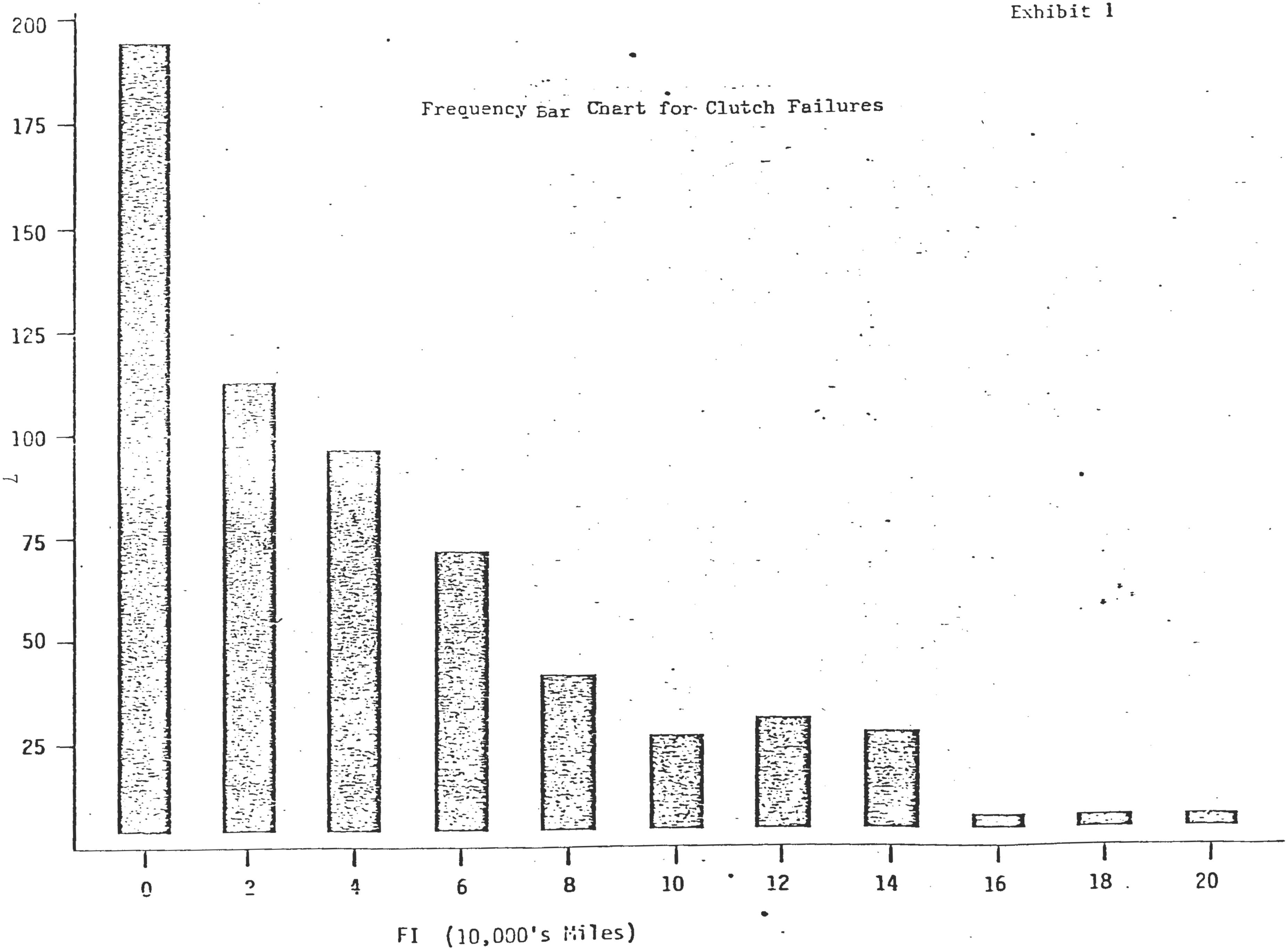
B. Determination of Survival Counts

The analysis so far has centered on unit failures and their frequencies. Much more meaningful information can be obtained from the probabilites of failure for each unit. In order to calculate these probabilities, however, the number of units surviving into and beyond the interval when a failure occurred has to be determined. This is particularly important when analyzing operational data because not all units operate to the point of failure. The following section describes the procedure used to determine the number of these surviving units.

First, for those buses for which full histories were obtained, a case representing replacement at zero miles was created for each unit.

Exhibit 1

Frequency Bar Chart for Clutch Failures



This provided a starting point from which the 17 original units on the bus could be observed. This was necessary because bus records typically contain only instances of servicing and failure, not normal operation. For instance, if the differential on a bus was the original factory part which had never failed, and its original installation or manufacture had not been noted, it would not be counted among the survivors.

The second step in determining the number of survivors and the mileage reached was to determine when a unit was replaced for the last time on a particular bus and to extrapolate, using the last available mileage (regardless of unit), the number of miles to which the unit had survived at the date of data collection. For each unit of each bus the last occurrence of a replacement was found. The corresponding mileage was then subtracted from the last mileage recorded for that bus. From the date of the mileage which corresponded to the last time the bus was being serviced, an estimate of the miles operated from that day to the day of data collection on April 30, 1981 could be made. This was done by calculating the number of intervening days and multiplying by 133.33 miles/day. (This figure is that used by A/C transit as its daily average operating mileage for its entire fleet). A sample calculation illustrating this process is shown in Example 1, Appendix D.

Through this process, the mileage and frequency distribution for the surviving units was obtained by the same method used for units that failed. These miles of survival have been categorized into intervals in exactly the same way that the miles to failure were categorized. The results of this process can be seen in Appendix B. Charts 1-17 in the Appendix represent the frequency of a unit surviving to that interval. Exhibit 2 is an example of the frequency bar chart for surviving clutches. This chart is similar to chart 5 in Appendix B.

C. Development of Failure Probabilities as a Function of Mileage

Using the frequencies of unit failure and unit survival the conditional failure probability distribtion functions for each of the 17 units can be determined. This probabilty of failure in any FI interval, given that the units survived into the interval, can be stated as:

$$P(\text{failure} \mid M_i \leq x < M_{i+1}) = \frac{a}{a + b + c} = P(f \mid FI)$$

where M_i and M_{i+1} are the mileage corresponding to the beginning and end of any interval FI. (For example if FI = 1 then M_i = 5000 and M_{i+1} = 15000); and

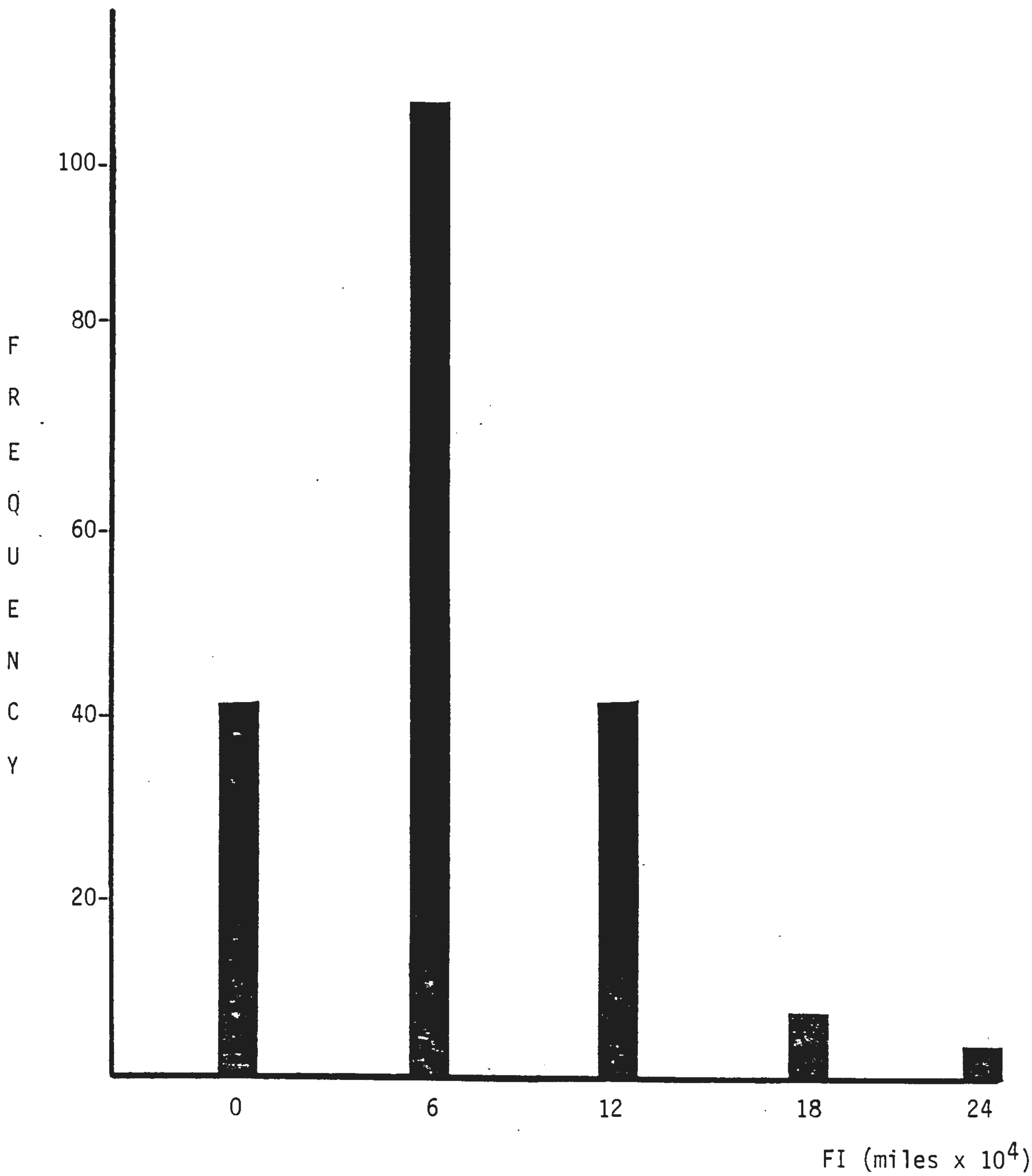
x is the miles that the unit has run

a is the number of failures in the M_i to M_{i+1} interval

b is the number of units which failed for $X \quad M_{i+1}$

c is the number of units which survived beyond the M_i - M_{i+1} interval and which were never observed to fail.

Exhibit 2: Frequency Bar Chart for Surviving Clutches



The probability of a unit surviving to M_{i+1} given that it has not failed prior to M_i is 1 - P(f FI). These numbers can be found in tables 1-17 of Appendix C. A complete example of this calculation can be found in Appendix D, Example 2. The complete results of these calculations for each unit are in Appendix C.

D. Development of Cumulative Failure Probability Functions.

The cumulative failure probabilty distribution function for each unit may now be determined from the above conditional distribution function.

Let:

P(f FI) = Prob (Failure in interval FI given that the unit has survived to mileage FI), and

P_0 = Prob (failure in 1st interval)

Then by simple probability theory,

P_i = Prob (failure before or in the ith interval),
= (Probability that the unit survived to interval i) x (Probability that unit failed in interval i) + (Probability unit failed before interval I)

Or

$$P_i = (1 - P_{i-1})P\ (f \quad FI{=}i) + P_{i-1}$$

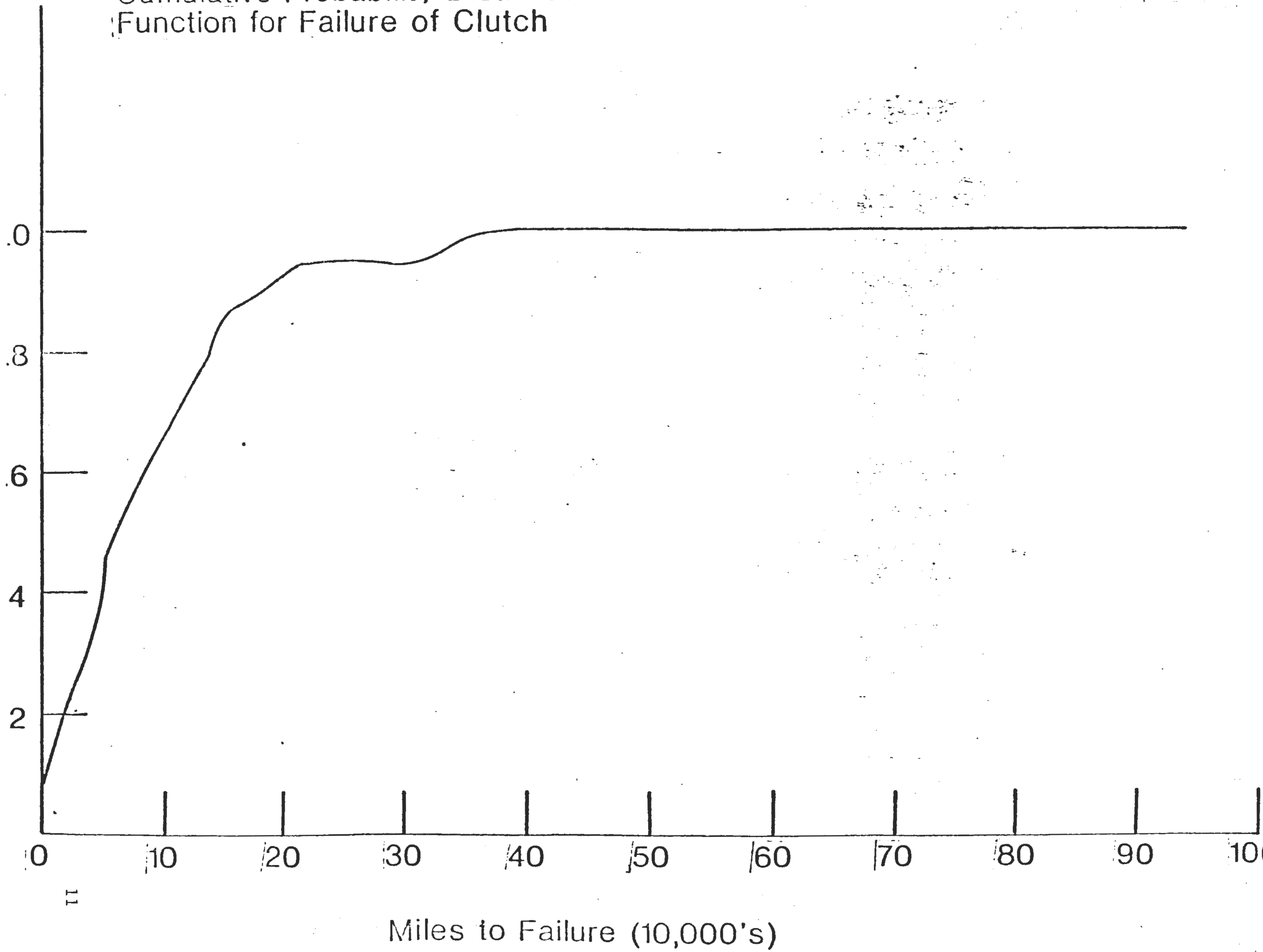
These cumulative probabilities are listed in Appendix C, along with the conditional probabilities. A sample calculation is given in Appendix D, Example 3. Graphs 1-17 of Appendix C give a visual representation of these cumulative probability functions.

Exhibit 3 depicts the cumulative probability distribution function for clutches. As seen in the exhibit the curve rises steeply between 0-60,000 miles, levels off slightly between 60,000-170,000 miles and gradually approaches 1 beyond 170,000 miles.

IV Discussion and Evaluation of the Data

This section contains detailed discussions of the results obtained from the analysis of the primary data. While the discussions put forth in this section center around A/C Transit, it should be noted that they are presented as examples of the types of conclusions which may be drawn from an application of the previously described analysis of maintenance data. The first subsection contains general comments about the quality of the data base and recommendations for improving record keeping procedures. The second subsection discusses the calculation of mean miles to failure and associated confidence intervals for each component. The third subsection contains an evaluation of the reliability of the failure probability density functions.

Cumulative Probability Distribution
Function for Failure of Clutch



A Data

The overall quality and consistency of the data obtained from A/C Transit reflects well kept maintenance records. The data does show, however, some trends which may be indicative of scheduling or record keeping problems. While the rather random method of selecting buses for the study leads to a somewhat uneven distribution of the data among the three divisions and makes strict comparisons of maintenance actions with numbers of vehicles assigned to each division difficult, the relative proportion of work done on specific units at each division should be close to the overall percentage of the total work done at the division. As an example of this type of analysis, division 2 accounted for 43% of the observations in the data base. Division 2 was responsible for 54% of all work done on differentials, 55% of the work done on air compressors, rear brake diaphragms, and front brakes, and only 32% of the rear brake work. Similar, but much less striking examples of this pattern can be found in Table 3 which shows the frequency of unit replacements by division, with the row percentages representing the proportion of unit replacements done at a particular division. The discrepancies noted may be caused by a lack of manpower or parts at one or more of the divisions, scheduling problems, or substantial differences in wear patterns between divisions; different terrain, route type and usage may also account for some of the discrepancies. Alternatively, record keeping variances may account for part of the apparently disproportionate work loads. These considerations are beyond the scope and purpose of this report, but should be considered as an area for further study.

An analysis of the reasons listed for work being done provides little useful information. As can be seen from the frequencies in Table 4, those replacements which had no reason given accounted for 68% of all the observations. Much of the missing data results from the one year retention period assigned to defect records, and the separation of bus cards and unit room records. Another explanation may be ambiguity about procedures. For example, if a driver informs a mechanic of a possible problem and during the course of investigating the complaint several parts are found to need replacement, it is unclear what reason should be listed for their replacement: operator initiated? or inspection? These questions too are beyond our current purpose of illustrating procedures for developing component failure statistics.

B. Mean Miles to Failure and Confidence Intervals

Table 5 displays the mean, standard deviation, variance, and number of observed failures for each of the 17 components being studied. Since the chances of a unit failing at exactly this estimated mean are close to zero, a more useful statistic, which can be derived from the information in Table 5, is the confidence interval. The confidence interval, as the name implies, is an interval centered around an estimated mean which has a known probability of including the true population mean. Using the assumption that the failures would be normally distributed if a large enough sample could be obtained, a 95% confidence interval was constructed for each component. That is, assuming normality, there is a .95 probability that the interval

Table 3
Frequency of Unit
Replacement by Division

UNIT	FREQUENCY PERCENT ROW PCT COLUMN PCT	Division 2	Division 3	Division 4	TOTAL
1 Major Overhaul		32	32	7	71
		0.33	0.33	0.07	0.72
		45.07	45.07	9.86	
		0.78	0.91	0.33	
2 Semi Overhaul		108	56	29	193
		1.10	0.57	0.30	1.97
		55.96	29.02	15.03	
		2.57	1.50	1.38	
3 Differential		42	30	6	78
		0.43	0.31	0.06	0.80
		53.85	38.46	7.69	
		1.00	0.86	0.29	
4 Transmission		200	212	79	491
		2.04	2.16	0.81	5.01
		40.73	43.18	16.09	
		4.77	6.05	3.77	
5 Clutch		360	310	165	835
		3.67	3.16	1.68	8.52
		43.11	37.13	19.76	
		8.58	8.84	7.86	
6 Starter		267	238	85	590
		2.72	2.43	0.87	5.02
		45.25	40.34	14.41	
		6.36	6.79	4.05	
7 Generator		164	111	66	341
		1.67	1.13	0.67	3.48
		48.09	32.55	19.35	
		3.91	3.17	3.15	
8 Blower		140	94	31	265
		1.43	0.96	0.32	2.70
		52.83	35.47	11.70	
		3.34	2.68	1.48	
9 Air Compressor		173	87	52	312
		1.77	0.89	0.53	3.18
		55.45	27.88	16.67	
		4.12	2.48	2.48	
10 Front Brake		245	129	99	474
Diaphragm		2.01	1.32	1.01	4.84
		51.90	27.22	20.89	
		5.86	3.68	4.72	
11 Rear Brake		302	148	98	548
Diaphragm		3.08	1.51	1.00	5.59
		55.11	27.01	17.88	
		7.20	4.22	4.67	
12 Brake Applicator		121	55	45	221
Value		1.23	0.56	0.46	2.26
		54.75	24.89	20.35	
		2.88	1.57	2.14	
13 Brake Relay		89	52	42	133
Value		0.91	0.53	0.43	1.87
		8.63	28.42	22.95	
		2.12	1.48	2.00	
14 Right Front		315	154	102	571
Brake		3.21	1.57	1.04	5.83
		55.17	25.97	17.86	
		7.51	4.39	4.86	
15 Left Front		313	154	102	569
Brake		3.19	1.57	1.04	5.81
		55.01	27.07	17.9	
		7.46	4.39	4.85	
16 Right Rear		659	820	542	2021
Brake		3.19	1.57	1.04	20.52
		55.01	27.07	17.93	
		7.45	4.39	4.85	
17 Left Rear Brake		665	824	548	2037
		6.79	8.41	5.59	20.79
		32.65	40.45	26.90	
		15.85	23.50	26.12	
TOTAL		4196	3506	2098	9800
		42.82	35.78	21.41	100.00

Table 4
Frequency of Unit Replacement
by Reason for Replacement

FREQUENCY / PERCENT / ROW PCT / COL PCT / UNIT (REASON)	Missing	Mileage	Operator Initiated	Inspection	Breakdown	TOTAL
1 Major Overhaul	53	7	0	10	1	71
	0.54	0.07	0.00	0.10	0.01	0.72
	74.55	9.86	0.00	14.08	1.41	
	0.79	1.18	0.00	0.42	1.03	
2 Semi-Overhaul	139	28	0	26	0	1.93
	1.42	0.29	0.00	0.27	0.00	1.97
	72.02	14.51	0.00	13.47	0.00	
	2.07	4.71	0.00	1.10	0.00	
3 Differential	62	0	0	15	1	78
	0.63	0.00	0.00	0.15	0.01	0.80
	79.49	0.00	0.00	19.23	1.28	
	0.92	0.00	0.00	0.63	1.03	
4 Transmission	384	8	1	81	17	491
	3.92	0.08	0.01	1.83	0.17	5.01
	78.21	1.63	0.20	16.50	3.46	
	5.71	1.34	7.14	3.42	17.53	
5 Clutch	534	13	1	162	25	835
	6.47	0.13	0.01	1.65	0.26	8.52
	75.93	1.55	0.12	19.40	2.99	
	9.43	2.18	7.14	6.84	25.77	
6 Starter	456	55	2	65	11	590
	4.55	0.57	0.02	0.66	0.11	6.02
	77.29	9.49	0.34	11.02	1.86	
	5.78	9.41	14.29	2.74	11.34	
7 Generator	252	20	0	59	10	341
	2.57	0.20	0.00	0.60	0.10	3.48
	73.90	5.87	0.00	17.30	2.93	
	3.75	3.36	0.00	2.49	10.31	
8 Blower	204	21	0	32	8	265
	2.08	0.21	0.00	0.33	0.08	2.70
	76.98	7.92	0.00	12.08	3.02	
	3.03	3.53	0.00	1.35	8.25	
9 Air Compressor	226	35	0	45	6	312
	2.31	0.36	0.00	0.46	0.06	3.18
	72.44	11.22	0.00	14.42	1.92	
	3.36	5.88	0.00	1.90	6.19	
10 Front Brake Diaphagm	340	93	0	41	0	474
	3.47	0.95	0.00	0.42	0.00	4.84
	71.73	19.62	0.00	8.65	0.00	
	5.06	15.63	0.00	1.73	0.00	
11 Rear Brake Diaphragm	378	89	1	78	2	548
	3.86	0.91	0.01	0.80	0.02	5.59
	68.98	16.24	0.18	14.23	0.36	
	5.62	14.96	7.14	3.29	2.06	
12 Brake Applicator Value	157	27	0	25	2	221
	1.70	0.28	0.00	0.25	0.02	2.26
	75.57	12.22	0.00	11.31	0.90	
	2.48	4.54	0.00	1.06	2.06	
13 Brake Relay Value	115	49	1	18	0	183
	1.17	0.50	0.01	0.18	0.00	1.87
	62.54	26.78	0.55	9.84	0.00	
	1.71	8.24	7.14	0.75	0.00	
14 Right Front Brake	439	13	2	116	1	571
	4.48	0.13	0.02	1.18	0.01	5.83
	76.88	2.28	0.35	20.32	0.18	
	6.48	2.35	14.29	4.90	1.03	
15 Left Front Brake	436	14	2	116	1	569
	4.45	0.14	0.02	1.18	0.01	5.81
	75.53	2.46	0.35	10.39	0.18	
	6.48	2.35	14.29	4.90	1.03	
16 Right Rear Brake	1212	64	2	737	6	2021
	12.37	0.65	0.02	7.52	0.06	20.62
	59.97	2.86	0.10	36.48	0.29	
	18.28	9.75	14.29	31.36	6.19	
17 Left Rear Brake	1228	58	2	743	6	2037
	12.53	0.59	0.02	7.58	0.06	20.79
	60.28	2.86	0.10	36.48	0.30	
	18.28	9.75	14.29	31.36	6.19	
TOTAL	6725	595	14	2369	97	9800
	68.62	6.07	0.14	24.17	0.99	100.00

Table 5
Component Failure Statistics

Component/ System	Mean miles to failure	Standard Deviation	number of observed failures	95% Confidence Interval Lower Limit	95% Confidence Interval Upper Limit
*Major overhauls	339,099	354,183	20	183,871	494,327.4
Semi overhauls	190,386	95,266	86	170,252	210,521.7
*differential	169,301	117,017	31	128,107	210,494.6
transmission	86,499	84,617	302	76,956	96,043.49
clutch	52,847	62,447	621	47,935	57,759.18
starter	87,613	73,664	367	80,077	95,150.49
generator	102,365	98,039	195	88,604	116,125.94
blower	137,510	99.364	135	120,748	154,272.04
air compressor	123,760	95,377	161	109,027	138,493.20
brake diaphragm (front)	75,869	70,818	255	67,177	84,562.02
brake diaphragm (rear)	63,668	64,437	333	56,747	70,589.75
brake applicator valve	100,545	98,169	114	82,524	118,566.52
brake relay valve	175,974	105,883	73	151,685	200,264.79
**right front brake	60,108	74,875	381	52,589	67,626.92
**left front brake	60,585	75,205	378	53,003	68,166.97
**right rear brake	19,466	32,962	1773	17,932	21,000.96
**left rear brake	19,412	32,427	1789	17,910	20,915.65

* Many of the vehicle histories indicated that overhauls and differential replacements had not occured. The mean values for these two systems, therefore, should not be viewed as descriptive of the entire fleet of vehicles.

** Front and rear brakes are changed in pairs; discrepancies may be due to sample variations.

contains the true population mean. These intervals are listed in Table 5. Sample calculations and formulae used are given in Example 4 of Appendix D.

C. Evaluation of the Probability Distribution Functions for Component Failures

Two items should be noted with regard to the probability distribution functions whose derivation was discussed in section III D. The limited number of observed failures for major overhauls and differentials, 20 and 31 respectively, provide inadequate samples with which to derive a complete probability distribution. These components are discussed in qualitative terms throughout this discussion. Any quantitative use of this information should be discouraged since the failure probability distributions are not complete.

The second point which should be noted is that several of the cumulative distribution functions for the failure of a component do not reach the value of 1 which would be expected. The reason for this is twofold. First, convergence to 1 is only assured as the running time of each component approaches infinity. While most of the components have sample sizes large enough for relatively accurate estimations of their probabilities of failure, they have not necessarily been run long enough to guarantee convergence of the probability distribution to 1.0. Secondly, although the time frame covered in the data that is used in this report is a large one, averaging ten years per bus, it is by no means large enough to extend beyond the life of the odd component that far exceeds its expected performance. The occasional component that survives far beyond its expected lifetime because of a fortuitous combination of manufacturing, operation, and routine maintenance conditions would be observed on the extreme right of the cumulative probability curves if enough data over an extended time period could be obtained. An example of this can be seen in graph 5, Appendix C in one clutch that was reported to have run almost a million miles before failure. This extends the graph substantially beyond the point where approximately 97% of the clutches would already have failed. Extreme cases such as this should be viewed suspiciously since inaccurate records may fail to note a replacement and thus generate a "super-component". In all other cases these extreme lifetimes have been omitted from the graphs but can be found in the tables listing the probabilities of failure by intervals which are also in Appendix C.

V. Examples of Use of the Results in Analysis of Management Decision

This section of the report provides examples of the types of conclusions which may be drawn from results previously described and their implications with regard to inspection schedules.

A. Evaluation of Current Intervals

One way to use the data from the previous analysis in conjunction with currently existing maintenance guidelines is illustrated in Table 6. Table 6 lists ten of the seventeen components under study. These are the ten components for which A/C transit currently has specified minimum unit mileages to inspection and/or replacement. The mileages, listed

Table 6
Comparison of Probabilities of Failure
With Existing Inspection Guidelines

Component	A/C minimum miles to initial inspection*	corresponding FI value	cumulative failure probability
Semi Overhaul	250,000	25	0.5695
Differential	400,000-700,000**	40-20	
Starter	150,000	15	0.7749
Generator	275,000	27	0.8650
Blower	300,000	30	0.8211
Air Compressor	250,000	25	0.8362
Front Brake Diaphragm	100,000	10	0.6119
Rear Brake Diaphragm	75,000	7	0.5469
Brake Applicator Valve	250,000	25	0.8120
Brake Relay Valve	250,000	25	0.6807

*See Table 1 Section II
** Varies by model
** The cumulative probability differential failure is 0.6614 at 350,000 miles. This component is only changed upon failure.

for each component, are taken from Table (1 A/C Transit's unit change table). Table 6 also includes the cumulative probability of failure before or in the interval FI that correspond to the minimum inspection/replacement mileage set by A/C transit. Comparison of these values by component suggests that the mileages specified by A/C Transit for the inspection of their units may be too high in some cases in light of the maintenance history of the fleet.

Specifically, the minimum miles indicated for the inspection of the generator, air compressor, brake applicator value, and blower coincide with .86, .84, .81, and .82 probabilities of failure at or before the minimum inspection/replacement mileage, respectively. The 150,000 mile figure for the starter corresponds to a cumulative probability of failure of .77. Thus, according to the A/C schedule, the first inspections of these parts occur after 77-86% of them have already failed.

The mileages for the brake relay valve, front brake diaphragm, and semi-overhaul, which correspond to .68, .61, and .57 cumulative failure probabilities, respectively, represent slightly better assumptions about the lifetime mileage of these components, but even these figures indicate that the parts may not be inspected until more than half have failed. The mileages indicated for the inspection of the differential, namely the 400,000-700,000 range, vary by bus model. The small number of observed differential failures make quantifiable comparisons tenuous. It does appear, however, that these mileage figures may also be overestimated since the mean miles to failure for the limited observed sample was 169,000, less than one half of the lowest mileage listed in the exchange table.

The mileage indicated for the inspection of the rear brake diaphragms is supported by historical data. The 75,000 mile figure corresponds to a .55 cumulative probability of failure. Thus, assuming that inspection should be undertaken when the probability of a unit failing is approximately between .3 and .5, the figure appears fairly accurate.

The interpretive process can be facilitated by graphical presentation of the data. For example, Exhibit 4 shows the cumulative probability of failure for starters as a function of mileage, along with the current inspection interval. The graphical display indicates that the current inspection schedule is associated with a .77 likelihood of failure before inspection. Management might choose to alter its inspection policy in light of this result if starter failures are particularly troublesome.

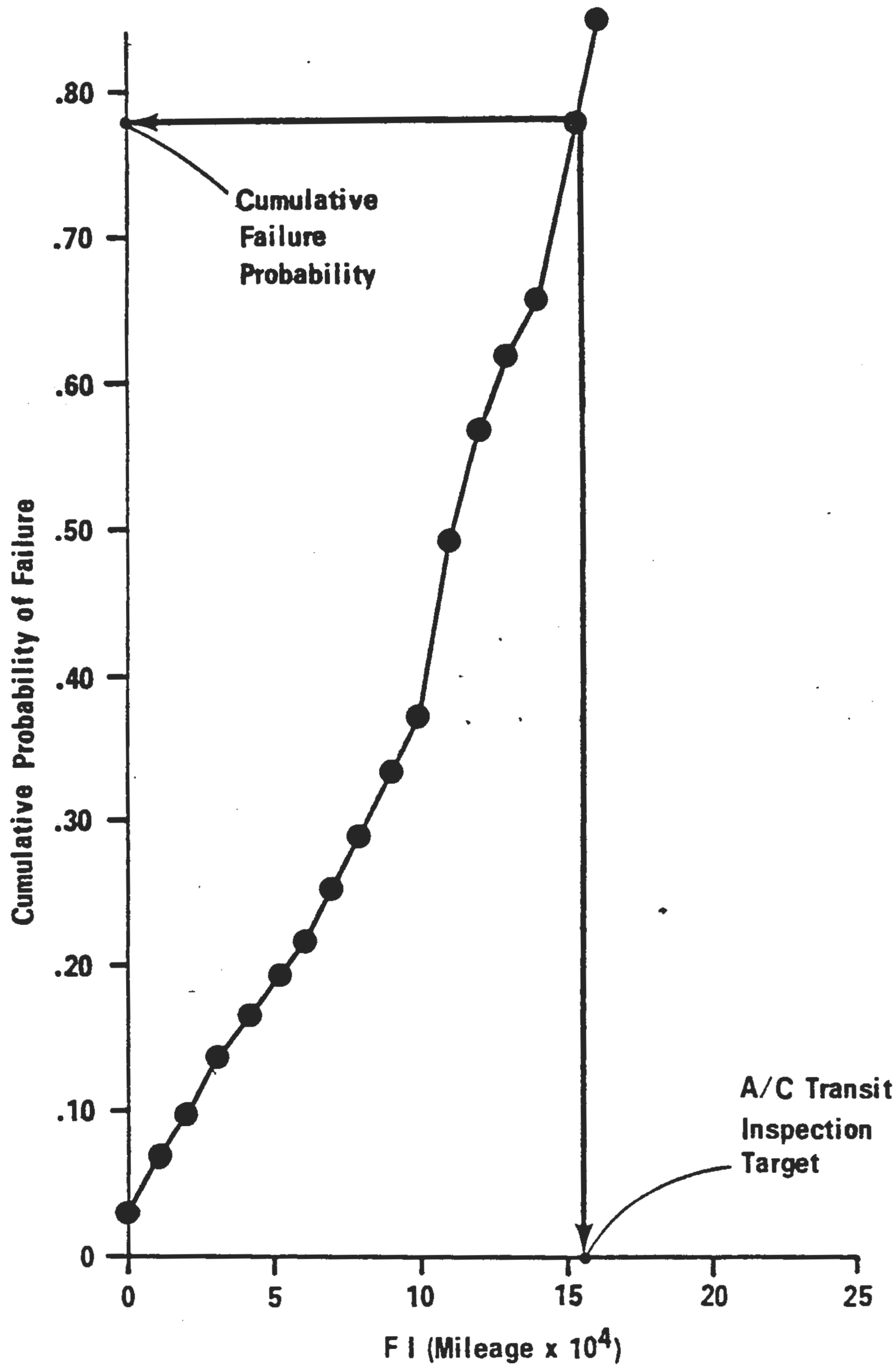
B. Using Failure Probability to Set Intervals

The cumulative failure probabilities just mentioned can be used to set service intervals directly. This method is based on using the cumulative probability of failure as a basis for determining an optimal mileage interval for the inspection of components. This method could be used to check existing inspection standards or to develop new guidelines.

The probabilities of failure used to determine the inspection intervals will vary between systems depending on the resources, failure modes, management policies, and assumptions made about the system under consideration. A .3 to .5 probability of failure was used for illus-

EXHIBIT 4

USE OF CUMULATIVE FAILURE GRAPHS TO EVALUATE INSPECTION TARGETS



trative purposes under the assumption that the initial inspection of a part and its possible replacement should be carried out before the probability of failure reaches 0.5. This is reasonable if the main reasons for inspecting units are safety and preventive maintenance in order to avoid breakdowns and excessive overtime of maintenance crews.

What constitutes a reasonable criterion depends on how critical the unit is to the operation of the system. This probability should also be high enough to justify the inspection costs and the possible replacement costs of the unit. These costs for A/C transit were not available at the time of this study. While the target value may vary for some of the units in this study, the .3 probability of failure was chosen as an illustrative value. This is not to say that it is a definitive criterion at which inspections should begin; rather it is a reasonable starting point.

Once the probabilities for the inspection intervals are decided, the mileages for inspection may be determined from the graphs of the cumulative probabilities of failure for each component. These mileages can be read directly from the graphs, given the probabilities desired. This is illustrated with reference to starters in Exhibit 5. This Figure again shows the cumulative failure probability function, but this time emphasis is given to the mileages associated with the .3 and .5 probability of failure. These indicate that a 85,000-110,000 starter inspection mileage window would be used under a policy calling for inspection at the stated cumulative failure probabilities. Table 7 gives an example of the type of inspection guideline which may be developed from this method of maintenance data analysis. The intervals shown represent the mileages at which 30-50% of the units are expected to have failed. For an effective preventive maintenance program, based on the previous assumptions and on the historical data from A/C Transit, the initial inspection of the various units should occur at or near the beginning of the interval and definitely before the upper bound is reached. Due to the lack of information available, no recommendations can be given for major overhauls and differentials. In the case of differentials, however, inspections may be required at more frequent intervals than those stated on the unit change table.

C. Use of Data to Analyze Cost-Failure Tradeoffs

A third use of the failure distributions is the setting of cost-effective service policies which specifically take into account the costs, both monetary and demand related, of breakdown vs. preventive maintenance. This requires consideration of manpower availability, component and labor costs, and peak hour requirements as well as failure data. The approach has been documented by Herniter et al (1977) and analyzed by Foerster et al (1981) in prior work. The major problem with the technique was found to be failure data availability. The procedures used for keeping records at A/C Transit and the methods for developing the needed failure distributions discussed in this report suggest that the method can be operationalized easily and without the need for additional recordkeeping activities.

EXHIBIT 5

USE OF CUMULATIVE FAILURE GRAPH TO SET INSPECTION TARGETS

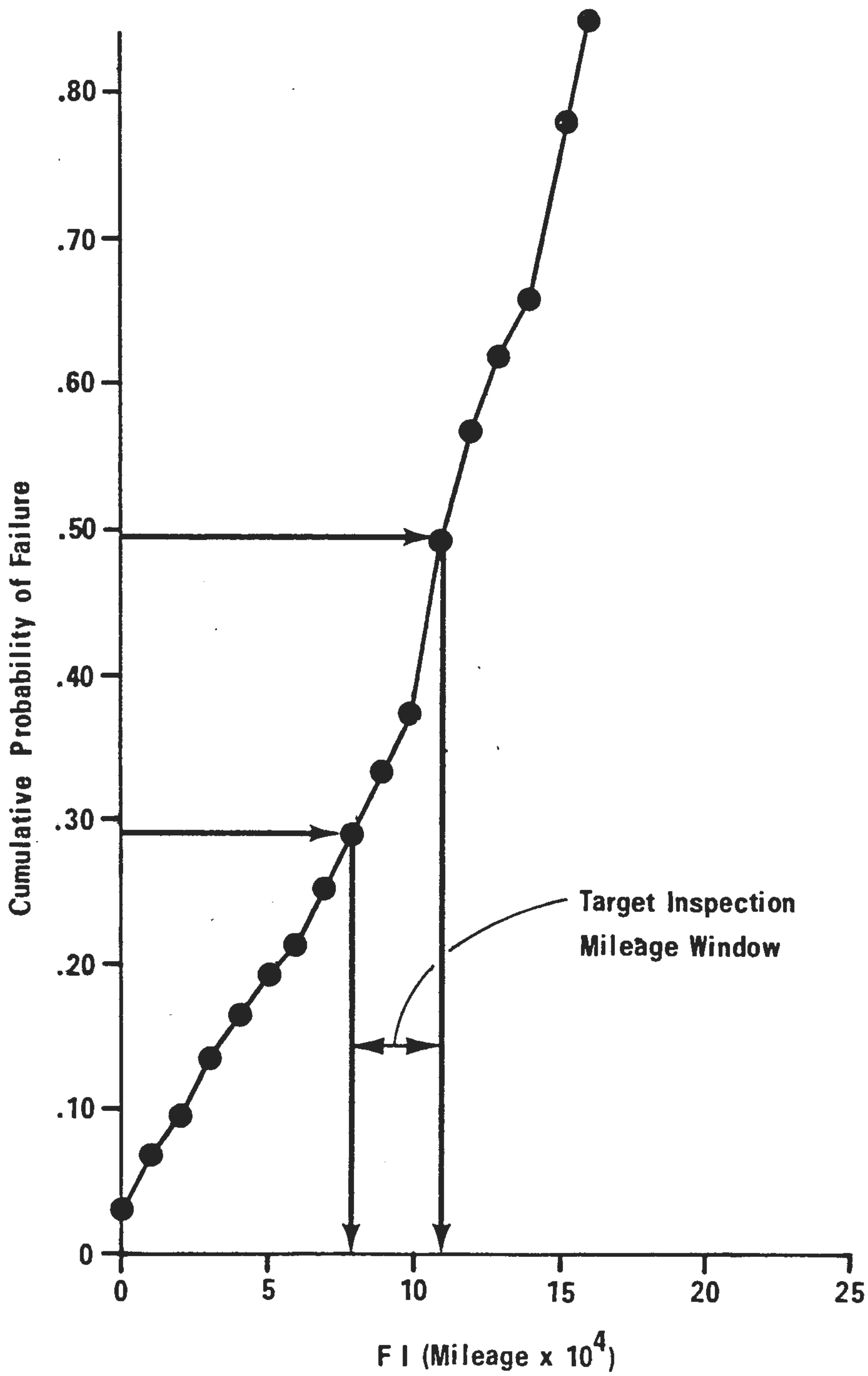


TABLE 7
Example of Recommended Mileage Intervals
with Associated Cumulative Probabilities
of Failure Between .3 and .5

Component	Recommended Inspection Interval (miles)	Cumulative Probability of Failure
Semi Overhaul	190,000-220,000	.31 -.45
*Transmission	60,000- 95,000	.33 -.48
*Clutch	30,000- 50,000	.36 -.49
Starter	80,000-110,000	.32 -.51
Generator	80,000-150,000	.34 -.51
Blower	120,000-170,000	.34 -.48
Air Compressor	110,000-160,000	.33 -.46
Front Brake Diaphragm	80,000- 95,000	.33 -.48
Rear Brake Diaphragm	50,000- 60,000	.30 -.51
Brake Applicator Valve	80,000-140,000	.28 -.43
Brake Relay Valve	180,000-230,000	.31 -.46
* Right Front Brake	40,000- 60,000	.30 -.49
* Left Front Brake	40,000- 60,000	.30 -.49
* Right Rear Brake	10,000- 15,000	.41 -.51
* Left Rear Brake	10,000- 15,000	.41 -.51

* = changed and inspected as needed under current policy

V Guidelines for Implementation

Implementation of the methods used in this report is relatively simple, following the steps as outlined in the preceeding sections. A summary of these steps follows.

A. Data Base Selection

The quality of the data base will be a key factor that determines the reliability of the conclusions formed by this analysis. The following points should be considered in selecting a data base.

1. The data base should cover a time span sufficiently large enough to insure the replacement of most of the units under consideration in the majority of buses surveyed.

2. The data base should be built upon a reliable maintenance record keeping system. The information needed to follow the procedures given in this report include a bus identification number, date of replacement, unit replaced, and mileage either at replacement or at the end of the month in which the unit was replaced, the former being preferable. Information regarding place of maintenance and reason for maintenance should be included if general trends in maintenance scheduling are of interest.

3. The date base should contain information taken from buses which are relatively representative of the entire fleet. That is, the buses surveyed should not be exclusively from any one geographic or division of the system but should be selected randomly on a system-wide basis.

B. Development of Failure Curves

The initial analysis of the data may be done using any standard statistical analysis package that has sorting, recoding, variable-lagging, and new record creation capabilities. The steps required are the same regardless of the package used. These steps are:

1. Historical starting points are created for all units in buses for which full maintenance histories have been obtained. These starting points consist of a record of replacement at zero mileage in order to take into account the original equipment on the buses.

2. Determine how many miles each observed unit ran before failure or replacement occurred. This is done by sorting the data by bus number, then by unit within each bus, then by ascending mileage within each unit. The miles to failure can then be obtained by calculating the differences in the mileage between the replacements of units as discussed in section 3A.

3. After the miles to failure for each observation have been determined, the mean miles to failure for each component, the number of observations for each unit, and the standard deviation are calculated.

4. The observed miles to failure are categorized into intervals of 10,000 miles by dividing the miles to failure for each observation by 10,000. A consistent method of rounding should be used so that all observations may be placed in an integer interval.

5. The frequency of observations within each interval is then determined for each unit under consideration.

6. Next, the number of surviving units observed and the miles they survived are determined. This is accomplished by calculating the difference between the mileage of the last observation of a unit on a bus and the last mileage recorded for the bus and adding the estimated miles the bus was run between the last recorded mileage and the time of data collection as shown in example 1 appendix D.

7. The survival mileages are then categorized into 10,000 mile intervals as in step 4.

8. The frequencies of observations of surviving units within each interval are then determined for each unit.

9. A 95% confidence interval for the mean miles to failure is constructed for each unit showing less than 1%* of survivors in the top mileage category as described in example 4 of appendix D.

10. The conditional probability distribution function for each unit is then calculated for each 10,000 mile interval. This is done by dividing the number of units which failed in an interval by this number plus the number of units which survived past this interval plus the number of units which failed after this interval. This follows the sample calculation in example 2 of Appendix D.

11. The cumulative probability distribution functions for each unit can then be determined from the probabilities calculated in step 10. A sample calculation of this is given in Example 3 of Appendix D.

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*chosen to represent an arbitrarily small number

C. Determination of Maintenance Intervals

The determination of mileage intervals at which specified maintenance inspections and/or replacement should occur is currently a rather hueristic process involving managerial judgement with respect to the optimal balance of acceptable probability of failure and the cost of servicing the vehicles. The steps described below give the information necessary to compare different inspection mileages and the associated cumulative probabilities of failure at or before the inspection target. It is left to the individual to determine the acceptable probability interval that will be used to find the mileage recommendations, but the data derived from the failure analysis can influence this decision. The steps necessary to obtain the comparisons are as follows:

1. The currently used standards should be checked for reasonableness. This can be done by finding the cumulative probability of failure of each unit under currently used inspection guidelines. If these probabilities of failure seem unreasonably high for first inspections, then this process should be continued to determine new intervals. If the inspection mileages accurately reflect the operational goals of the system, then no further analysis is required.

2. If acceptable probabilities of failure are not found in the above step, then candidate mileage intervals may be determined by deciding on acceptable probabilities of failure and working backwards from the cumulative probability distribution functions for each unit to find the corresponding inspection mileage.

3. If time estimates and cost data are available, true cost-minimizing solutions can be found using suitable computer programs.

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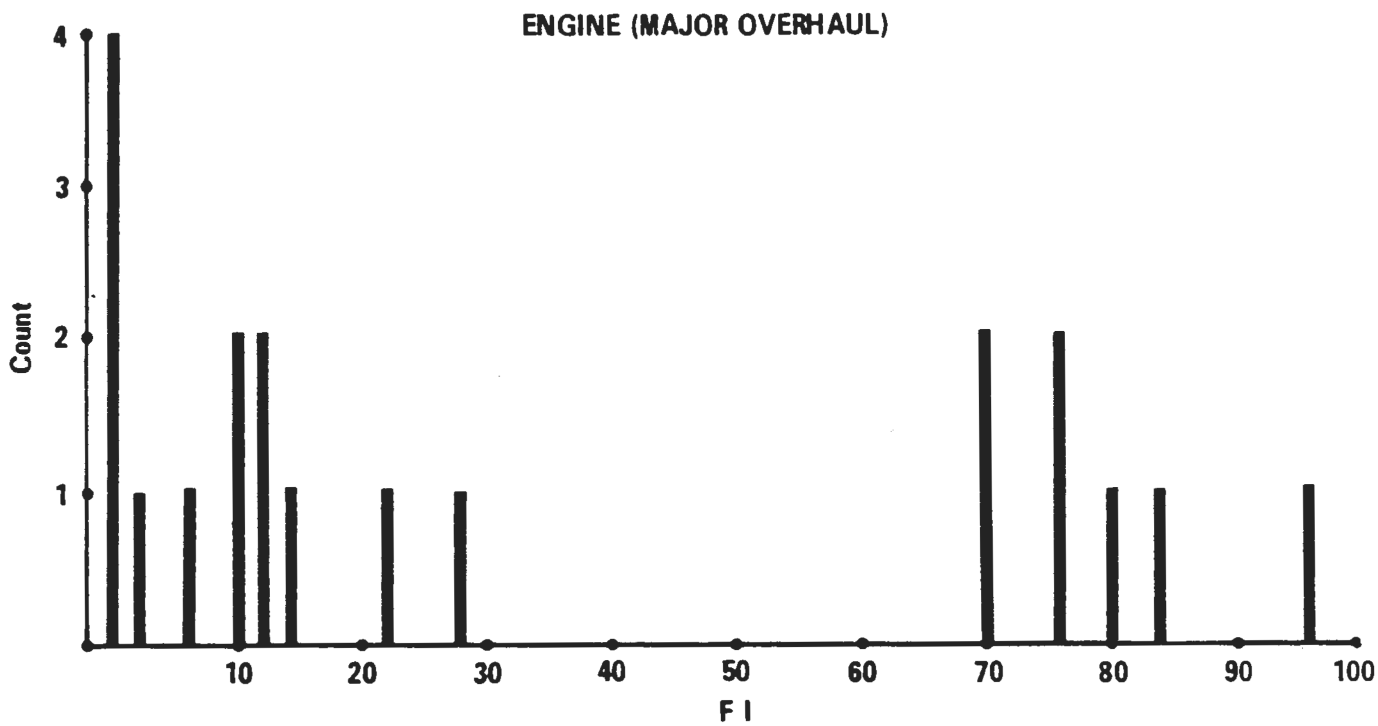
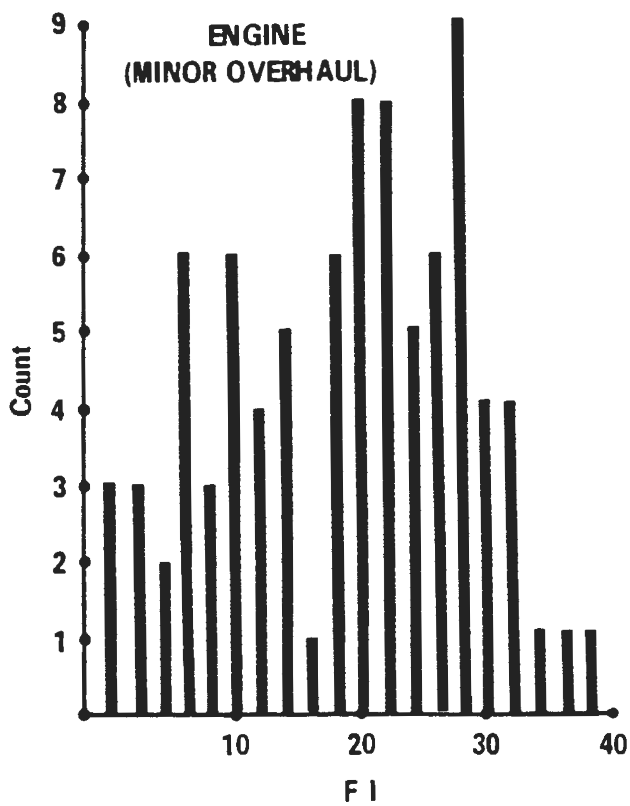
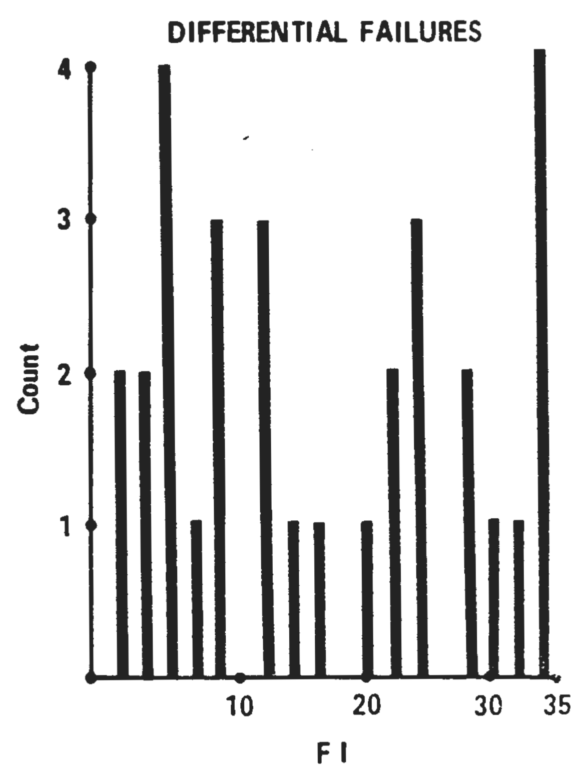
Appendix A

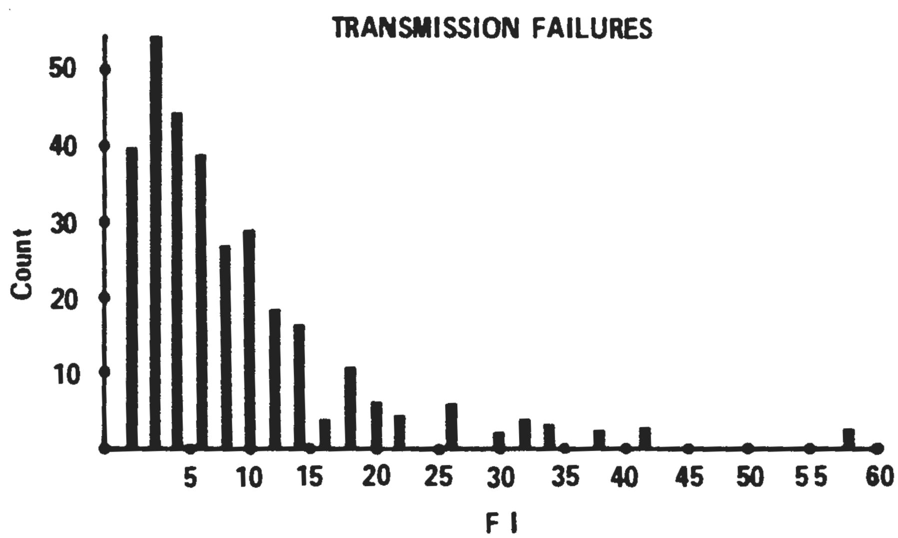
Frequency of Failures

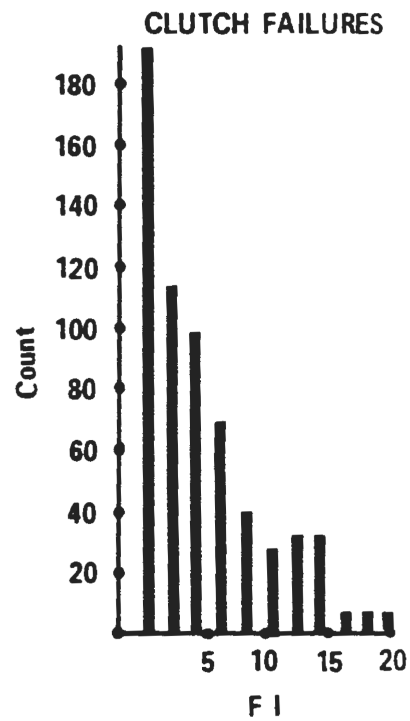
Each of the seventeen graphs in this Appendix presents the number of components failing in a particular FI (failure interval). The midpoint indicated on the graphs is the middle of the 10,000 mile interval in which the units failed. For instance if the midpoint of an interval containing five failures is listed as 40, this indicates that the five units failed between 395,000 and 405,000 miles.

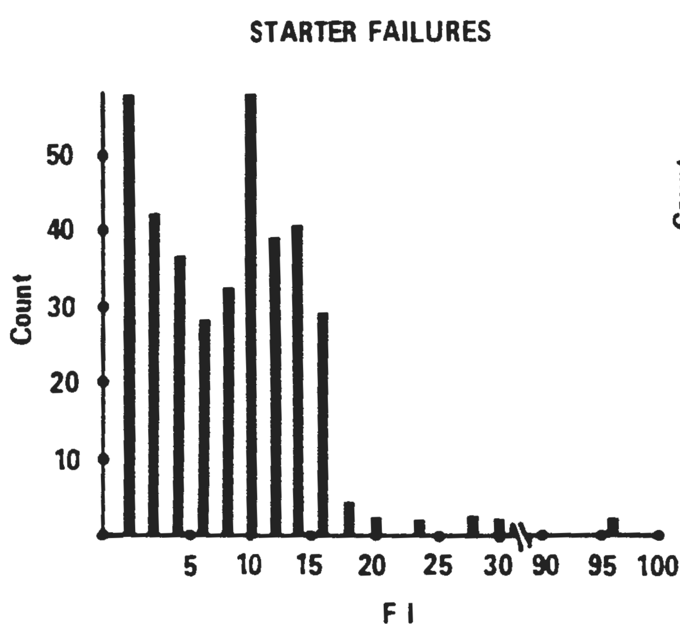

ENGINE (MAJOR OVERHAUL)
Count
4
3
2
1
10
20
30
40
50
60
70
80
90
100
F I

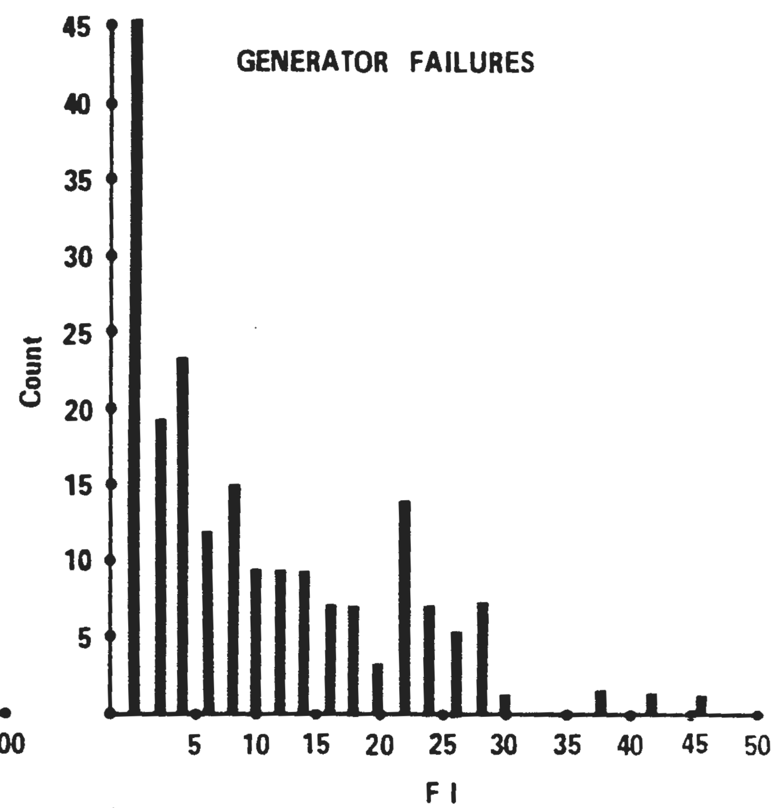

ENGINE
(MINOR OVERHAUL)
Count
9
8
7
6
5
4
3
2
1
10
20
30
40
F I

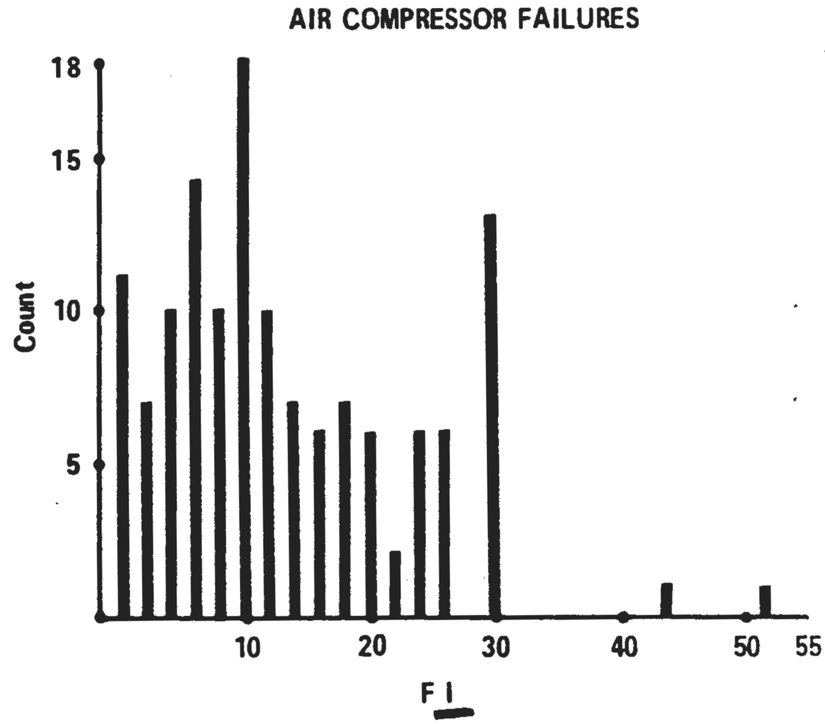

DIFFERENTIAL FAILURES
Count
4
3
2
1
10
20
30
35
F I

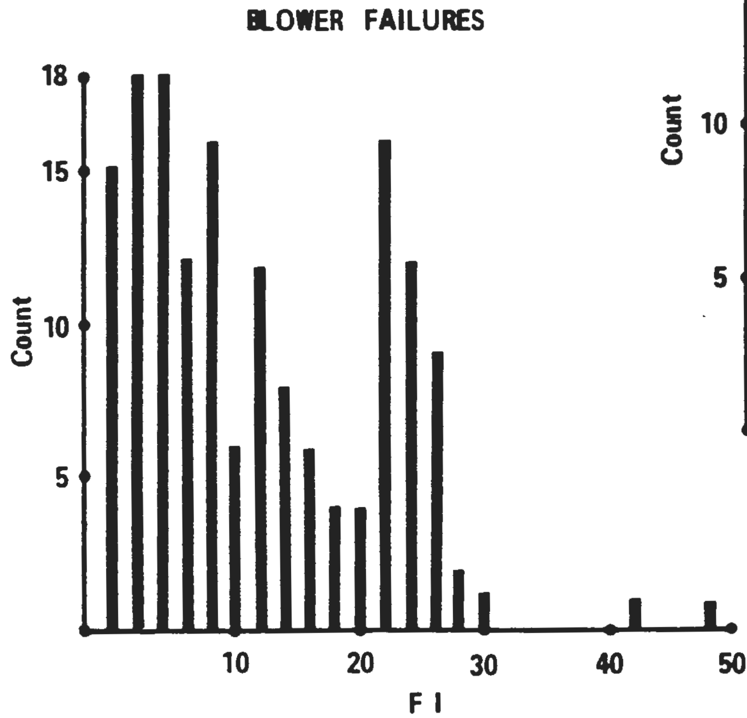

TRANSMISSION FAILURES
Count
50
40
30
20
10
5 10 15 20 25 30 35 40 45 50 55 60
F I

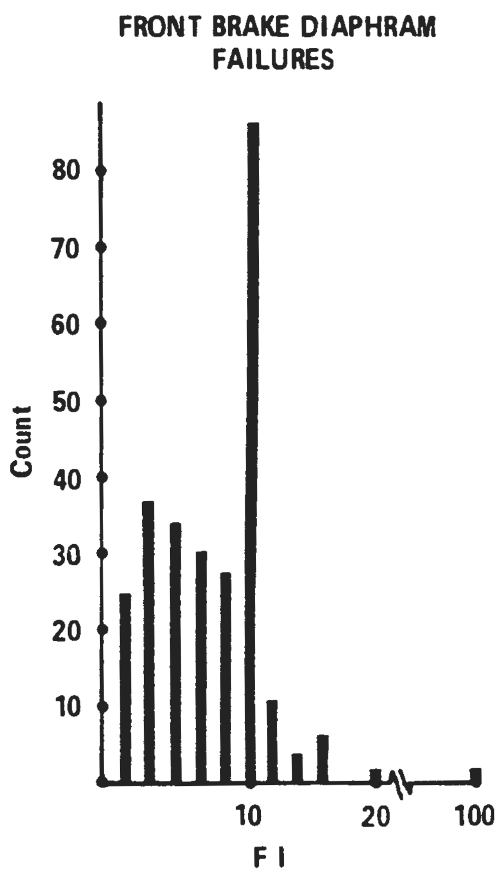

CLUTCH FAILURES
Count
180
160
140
120
100
80
60
40
20
5 10 15 20
F I

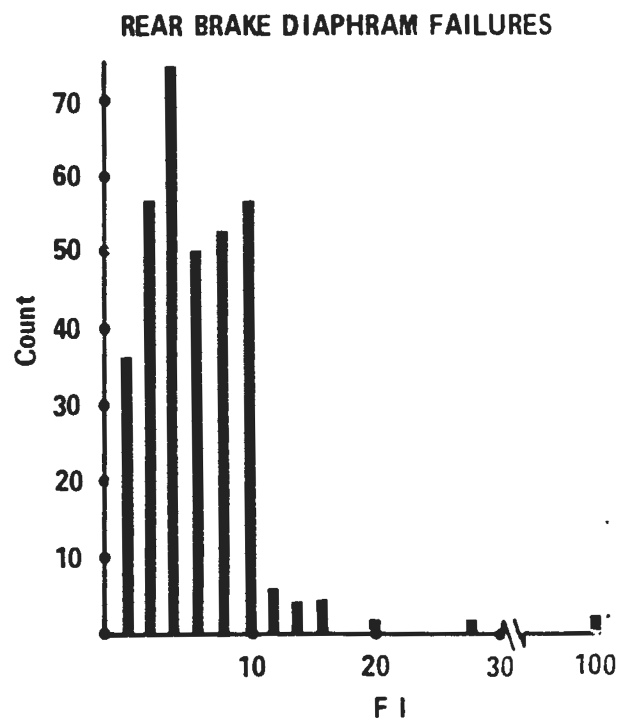

STARTER FAILURES
Count
50
40
30
20
10
5 10 15 20 25 30 90 95 100
F I

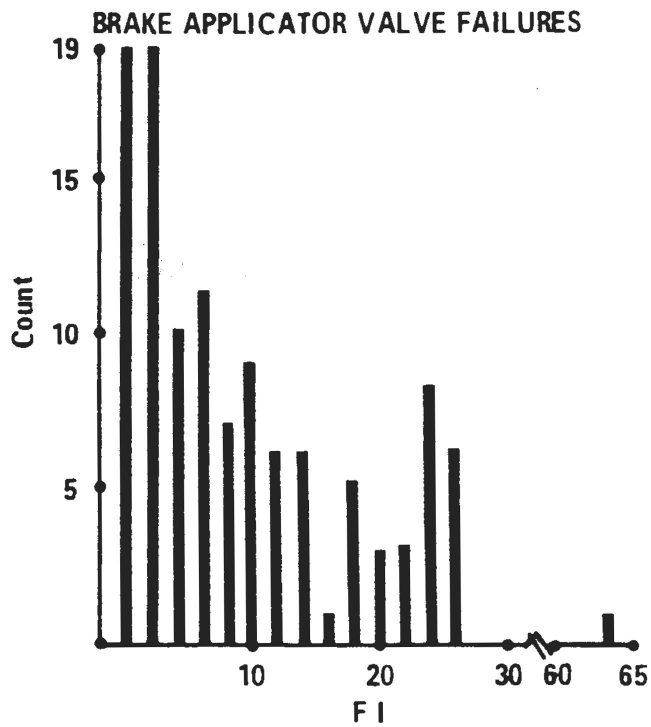

GENERATOR FAILURES
Count
45
40
35
30
25
20
15
10
5
5 10 15 20 25 30 35 40 45 50
F I

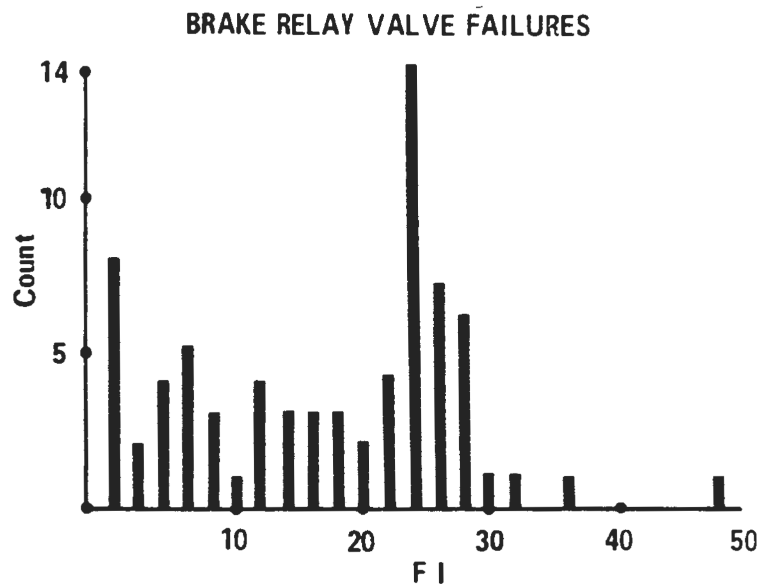

AIR COMPRESSOR FAILURES
Count
18
15
10
5
10
20
30
40
50
55
F I

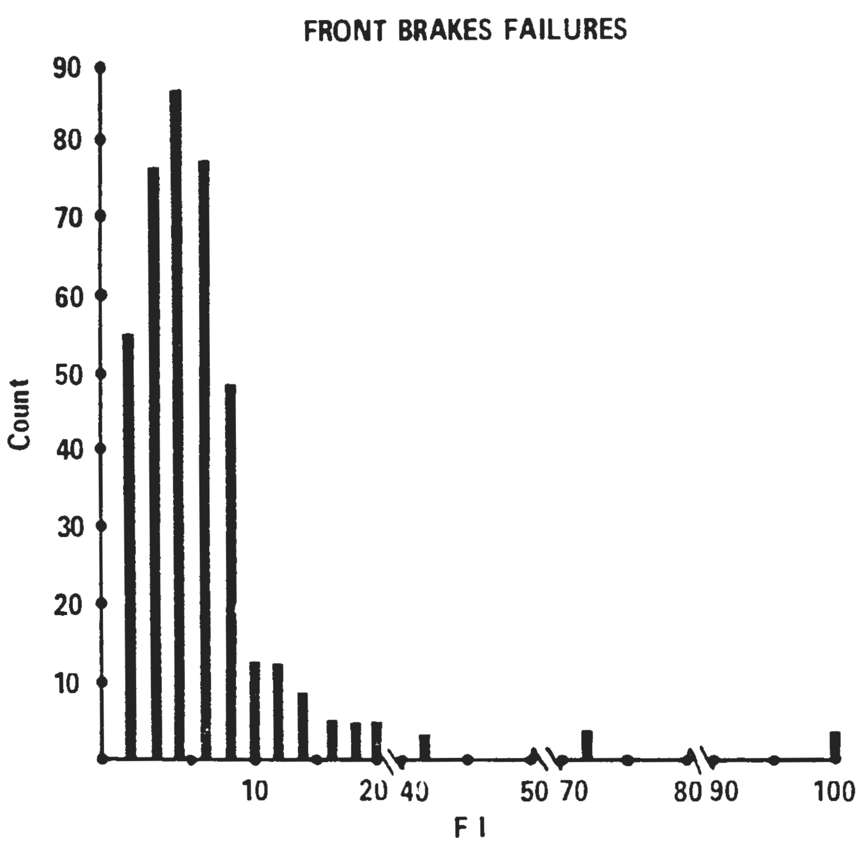

BLOWER FAILURES
Count
18
15
10
5
10
20
30
40
50
F I

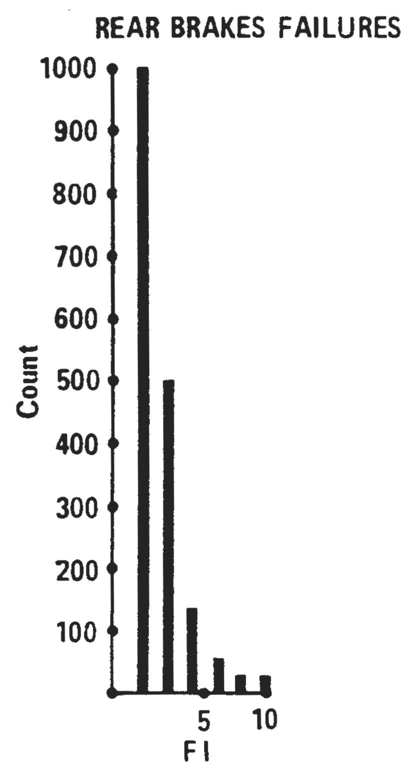

FRONT BRAKE DIAPHRAM FAILURES
Count
80
70
60
50
40
30
20
10
10
20
100
F I


REAR BRAKE DIAPHRAM FAILURES
Count
70
60
50
40
30
20
10
10
20
30
100
F I


BRAKE APPLICATOR VALVE FAILURES
Count
19
15
10
5
10
20
30
60
65
F I

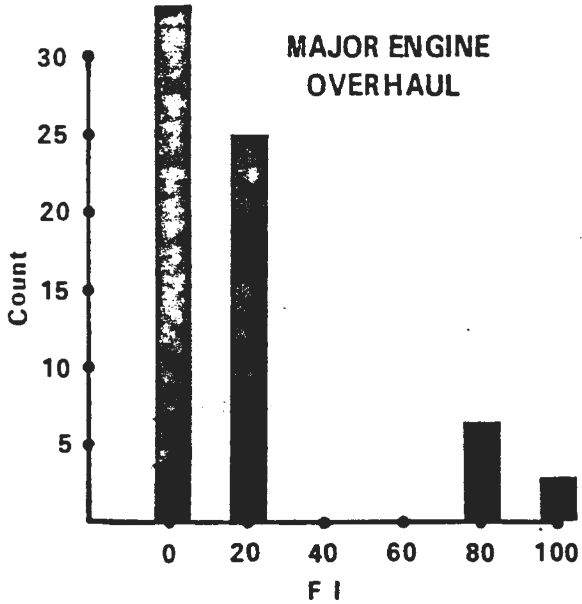

BRAKE RELAY VALVE FAILURES
Count
14
10
5
10
20
30
40
50
F I

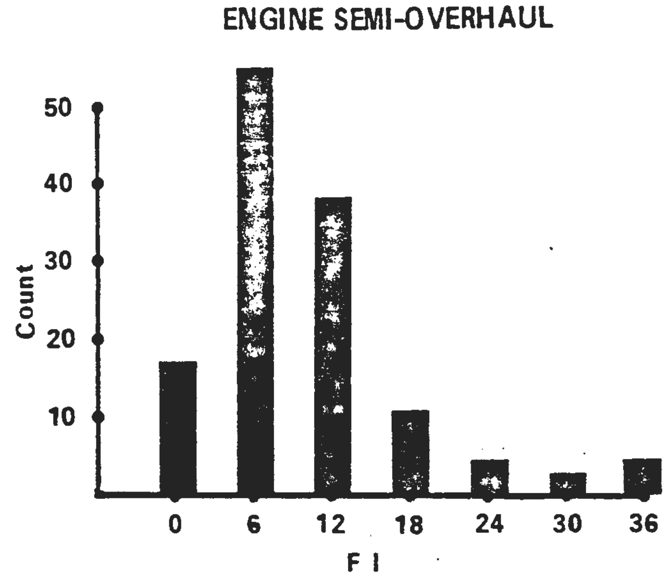

FRONT BRAKES FAILURES
Count
90
80
70
60
50
40
30
20
10
10
20
40
50
70
80
90
100
F I

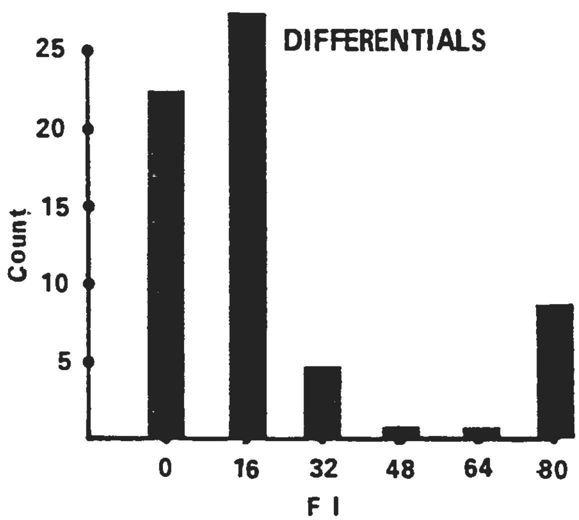

REAR BRAKES FAILURES
Count
1000
900
800
700
600
500
400
300
200
100
5
10
F I

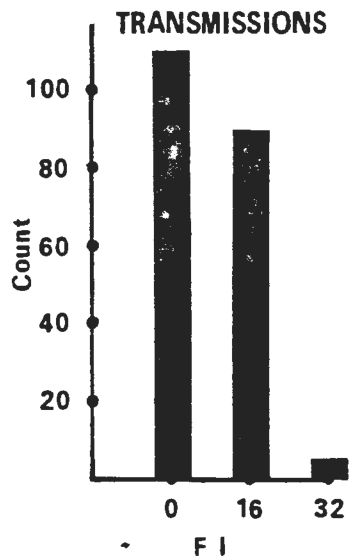
Appendix B
Survivor Frequency

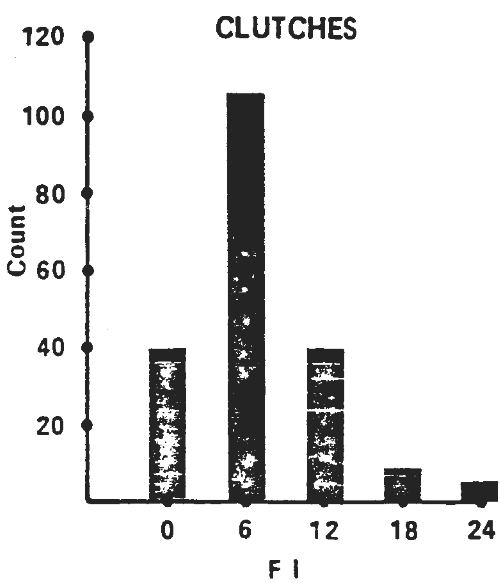
The following graphs indicate the number of vehicle components which had reached mileages associated with the listed FI intervals at the time of data collection without experiencing failure.

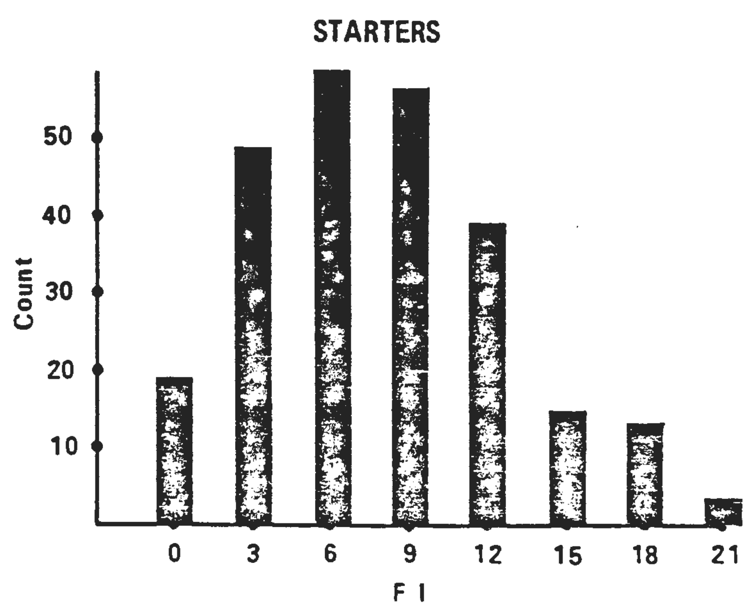

MAJOR ENGINE OVERHAUL
Count
30
25
20
15
10
5
0
20
40
60
80
100
F I

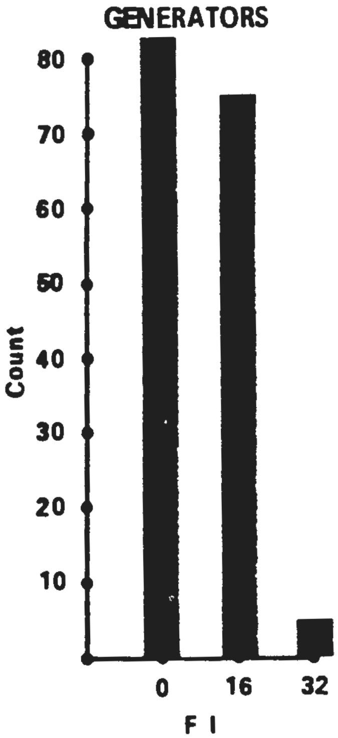

ENGINE SEMI-OVERHAUL
Count
50
40
30
20
10
0
6
12
18
24
30
36
F I

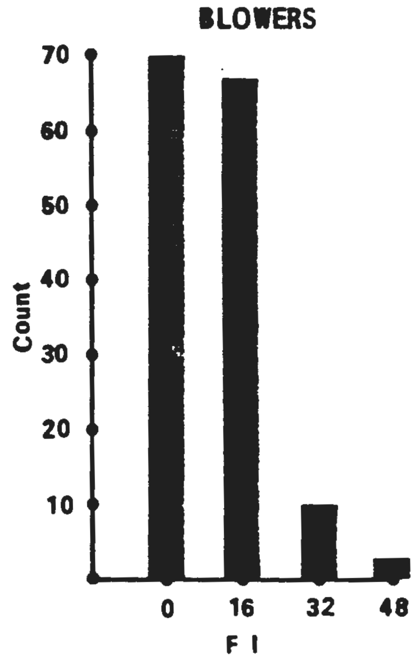

DIFFERENTIALS
Count
25
20
15
10
5
0
16
32
48
64
80
F I

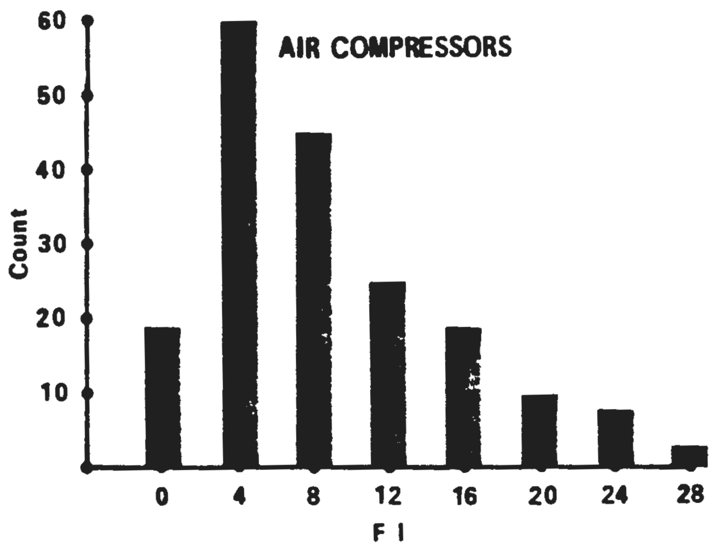

TRANSMISSIONS
Count
100
80
60
40
20
0
16
32
F I

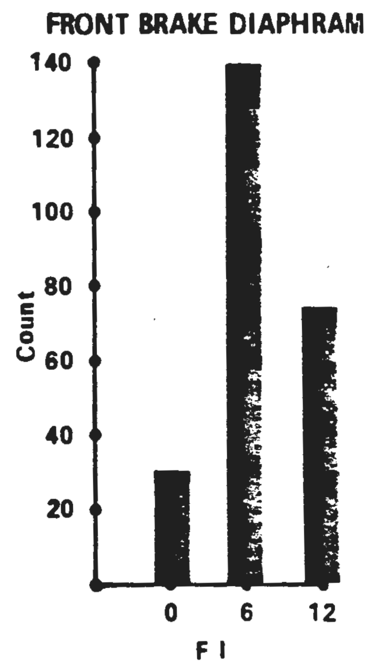

CLUTCHES
Count
120
100
80
60
40
20
0
6
12
18
24
F I

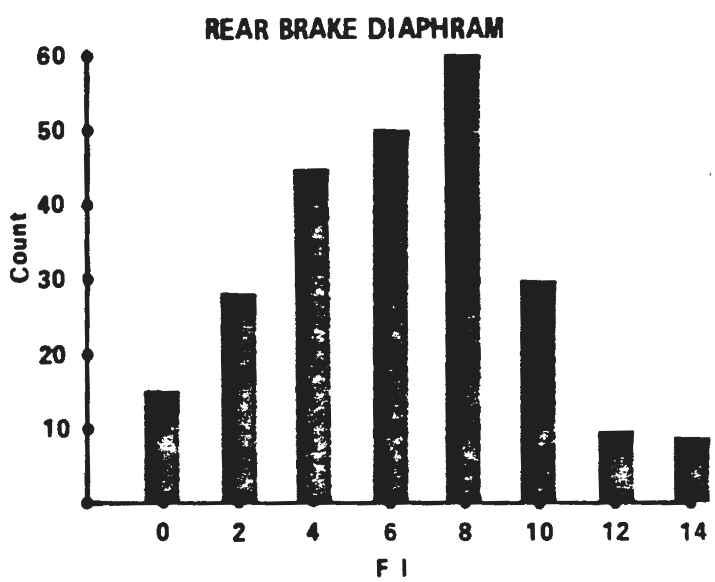

STARTERS
Count
50
40
30
20
10
0
3
6
9
12
15
18
21
F I

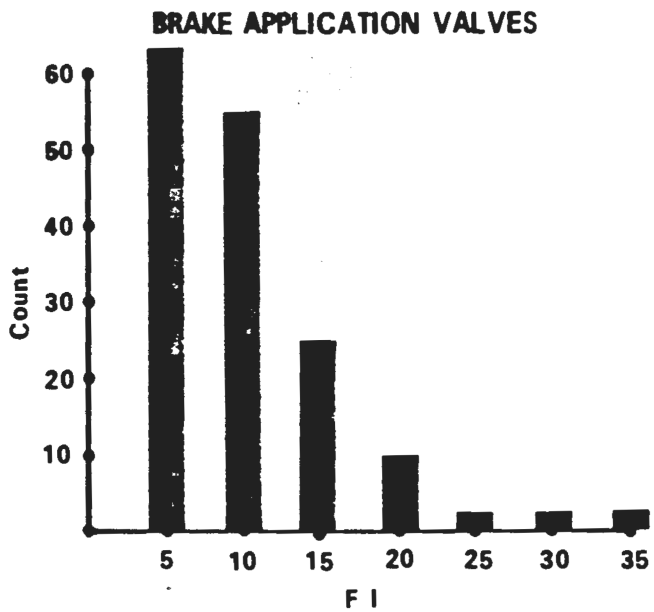

GENERATORS
Count
80
70
60
50
40
30
20
10
0
16
32
F I

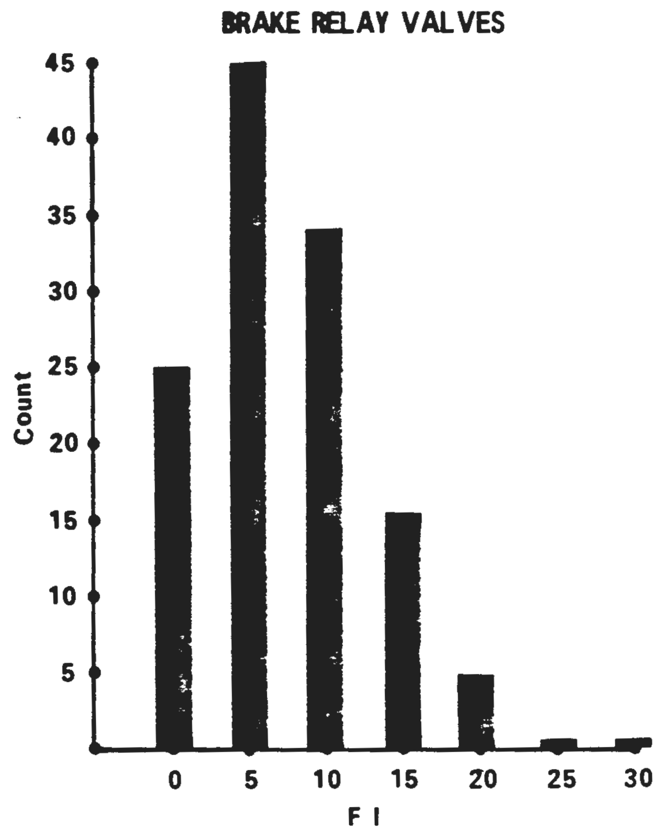

BLOWERS
Count
70
60
50
40
30
20
10
0
16
32
48
F I

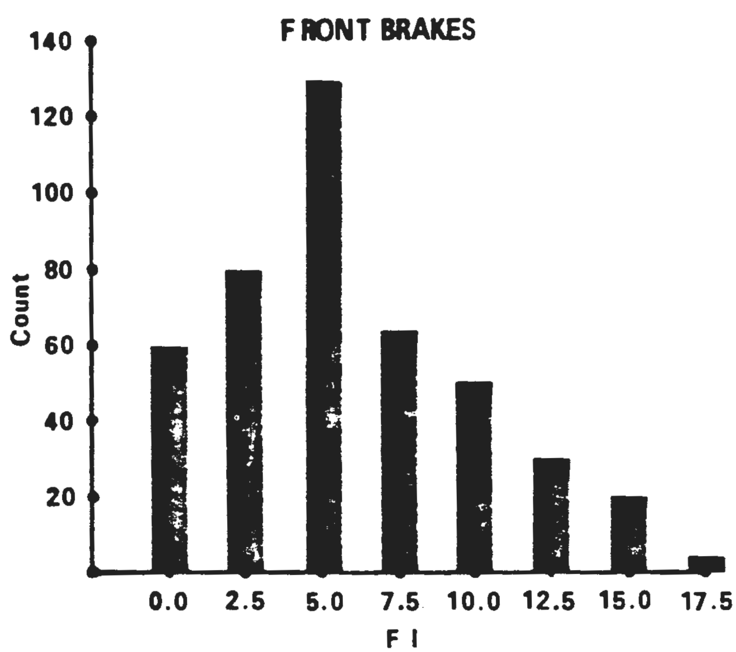

AIR COMPRESSORS
Count
60
50
40
30
20
10
0
4
8
12
16
20
24
28
F I

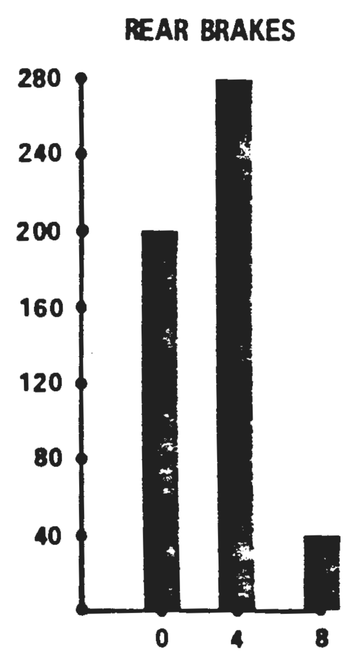

FRONT BRAKE DIAPHRAM
Count
140
120
100
80
60
40
20
0
6
12
F I


REAR BRAKE DIAPHRAM
Count
60
50
40
30
20
10
0
2
4
6
8
10
12
14
F I


BRAKE APPLICATION VALVES
Count
60
50
40
30
20
10
5
10
15
20
25
30
35
F I


BRAKE RELAY VALVES
Count
45
40
35
30
25
20
15
10
5
0
5
10
15
20
25
30
F I


FRONT BRAKES
Count
140
120
100
80
60
40
20
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
F I


REAR BRAKES
280
240
200
160
120
80
40
0
4
8

Appendix C

Probability Distribution Functions for the Failure of units in any given interval and Cumulative Probability Distribution Functions for the Failure of units before or in a given interval.

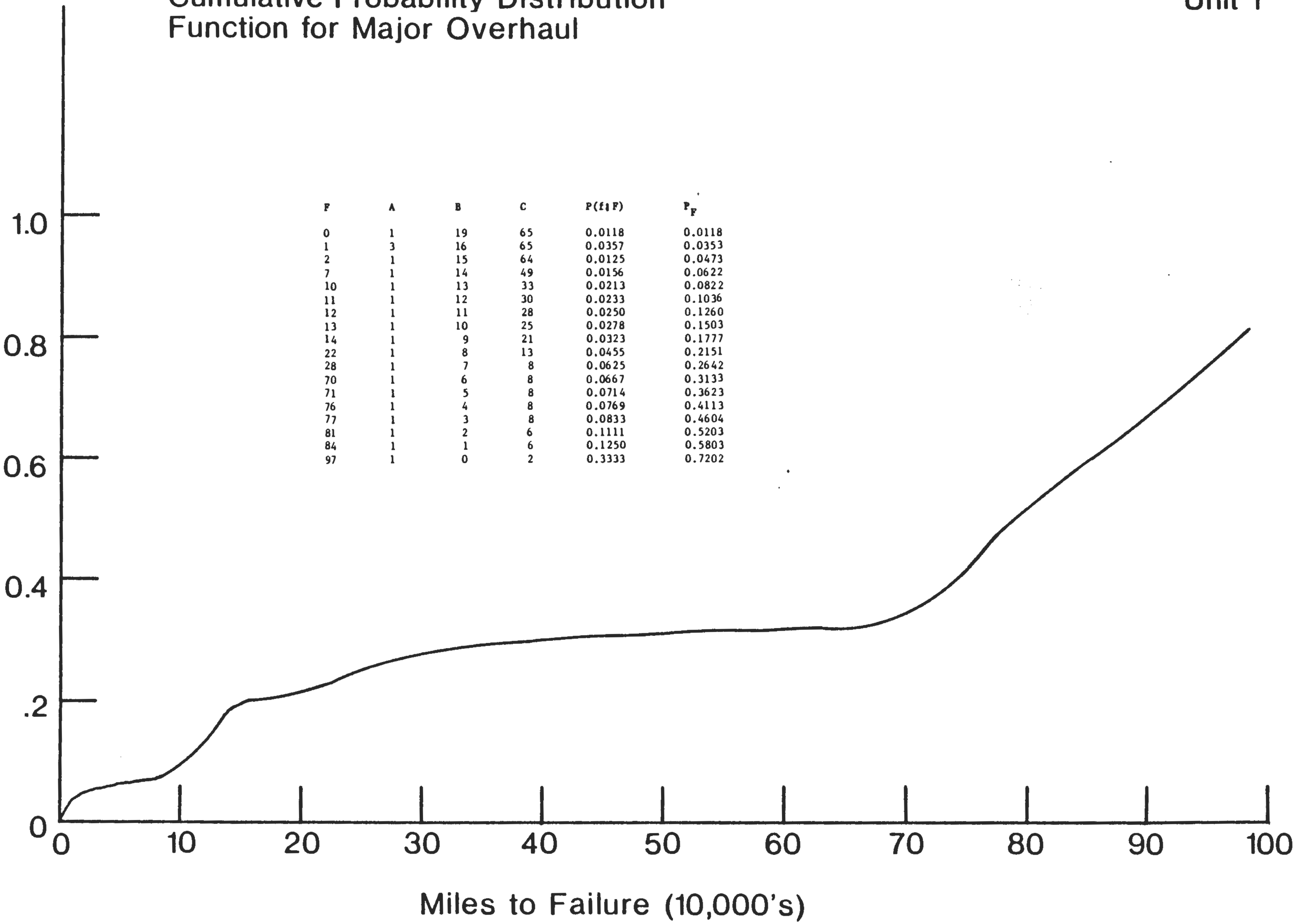
The following abbreviations are used throughout this Appendix.

FI	=	mileage interval midpoint ($x10^4$)
P (f|FI)	=	Probability of failure in interval FI given that the unit survived to interval FI.
P_{FI}	=	Probability of unit failure in or before interval FI; cumulative probabilities.
A	=	# of units that failed in FI
B	=	# of units that failed after FI
C	=	# of units that survived beyond FI and were near observed to fail.

Note: Vertical lines indicate threshold mileages for components routinely inspected by A/C Transit

Cumulative Probability Distribution Function for Major Overhaul

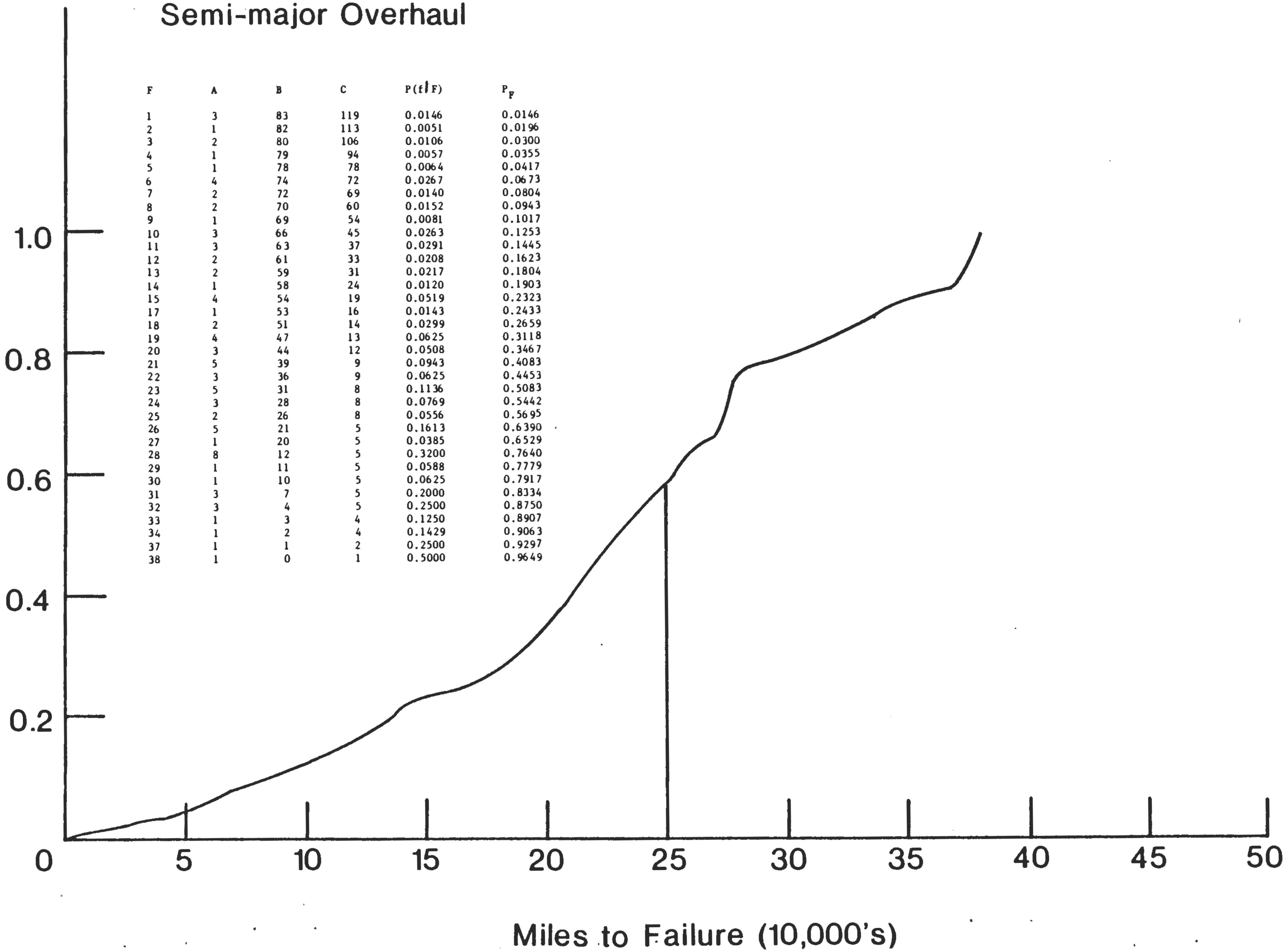
Unit 1



F	A	B	C	P(f|F)	P_F
0	1	19	65	0.0118	0.0118
1	3	16	65	0.0357	0.0353
2	1	15	64	0.0125	0.0473
7	1	14	49	0.0156	0.0622
10	1	13	33	0.0213	0.0822
11	1	12	30	0.0233	0.1036
12	1	11	28	0.0250	0.1260
13	1	10	25	0.0278	0.1503
14	1	9	21	0.0323	0.1777
22	1	8	13	0.0455	0.2151
28	1	7	8	0.0625	0.2642
70	1	6	8	0.0667	0.3133
71	1	5	8	0.0714	0.3623
76	1	4	8	0.0769	0.4113
77	1	3	8	0.0833	0.4604
81	1	2	6	0.1111	0.5203
84	1	1	6	0.1250	0.5803
97	1	0	2	0.3333	0.7202

Cumulative Distribution Function for Semi-major Overhaul

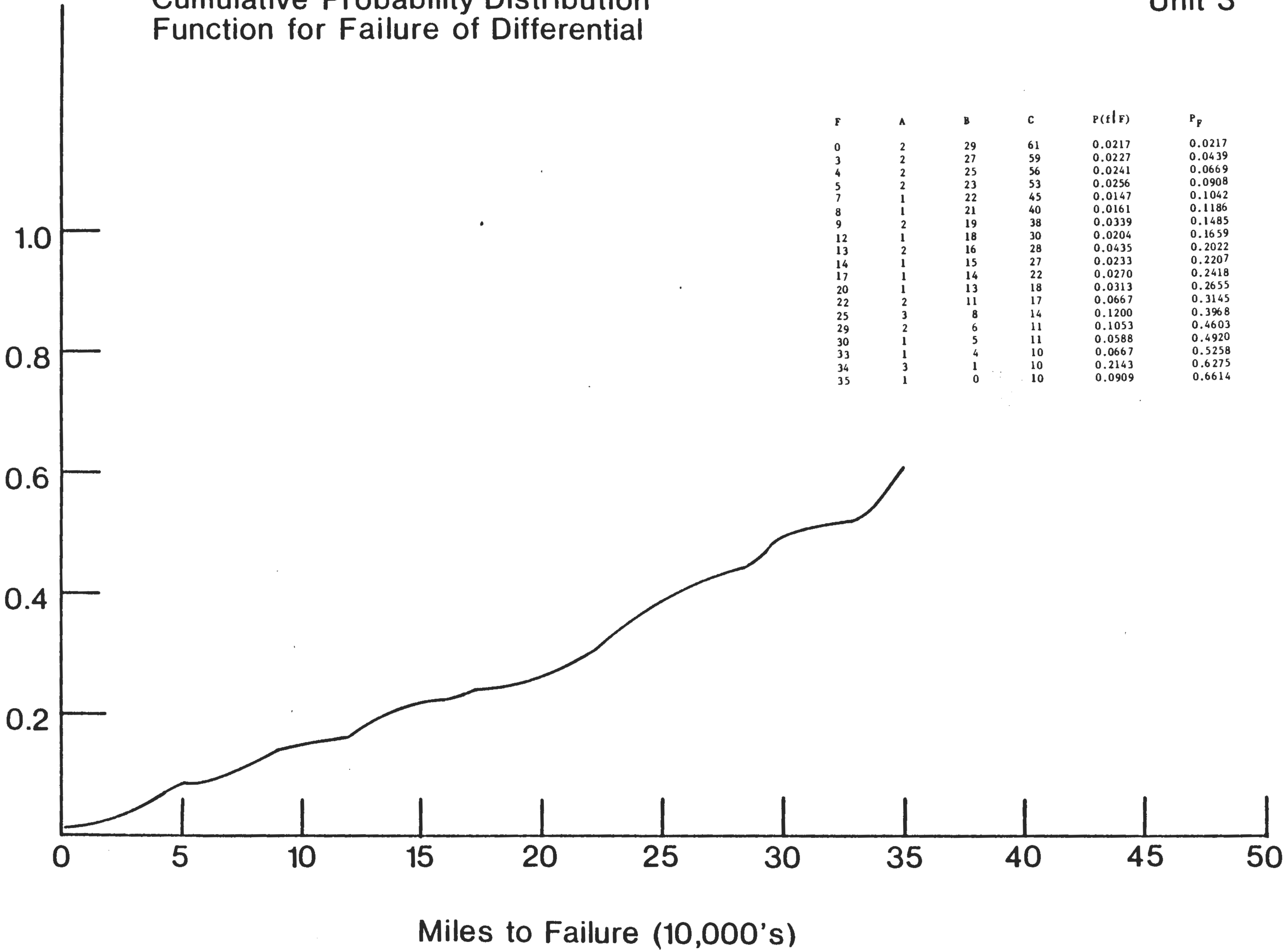
Unit 2



F	A	B	C	P(f|F)	P_F
1	3	83	119	0.0146	0.0146
2	1	82	113	0.0051	0.0196
3	2	80	106	0.0106	0.0300
4	1	79	94	0.0057	0.0355
5	1	78	78	0.0064	0.0417
6	4	74	72	0.0267	0.0673
7	2	72	69	0.0140	0.0804
8	2	70	60	0.0152	0.0943
9	1	69	54	0.0081	0.1017
10	3	66	45	0.0263	0.1253
11	3	63	37	0.0291	0.1445
12	2	61	33	0.0208	0.1623
13	2	59	31	0.0217	0.1804
14	1	58	24	0.0120	0.1903
15	4	54	19	0.0519	0.2323
17	1	53	16	0.0143	0.2433
18	2	51	14	0.0299	0.2659
19	4	47	13	0.0625	0.3118
20	3	44	12	0.0508	0.3467
21	5	39	9	0.0943	0.4083
22	3	36	9	0.0625	0.4453
23	5	31	8	0.1136	0.5083
24	3	28	8	0.0769	0.5442
25	2	26	8	0.0556	0.5695
26	5	21	5	0.1613	0.6390
27	1	20	5	0.0385	0.6529
28	8	12	5	0.3200	0.7640
29	1	11	5	0.0588	0.7779
30	1	10	5	0.0625	0.7917
31	3	7	5	0.2000	0.8334
32	3	4	5	0.2500	0.8750
33	1	3	4	0.1250	0.8907
34	1	2	4	0.1429	0.9063
37	1	1	2	0.2500	0.9297
38	1	0	1	0.5000	0.9649

Cumulative Probability Distribution Function for Failure of Differential

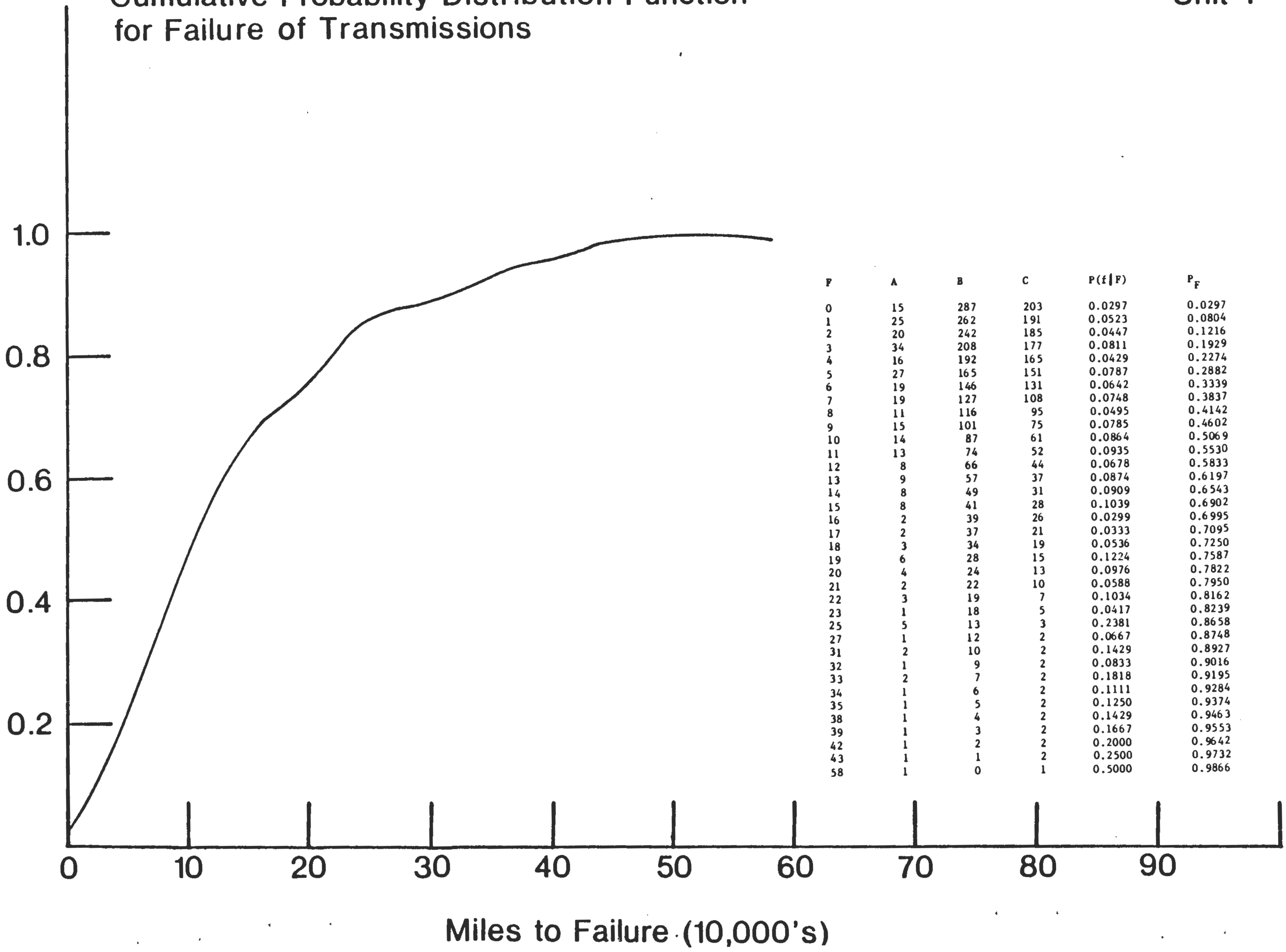
Unit 3



F	A	B	C	P(f|F)	P_F
0	2	29	61	0.0217	0.0217
3	2	27	59	0.0227	0.0439
4	2	25	56	0.0241	0.0669
5	2	23	53	0.0256	0.0908
7	1	22	45	0.0147	0.1042
8	1	21	40	0.0161	0.1186
9	2	19	38	0.0339	0.1485
12	1	18	30	0.0204	0.1659
13	2	16	28	0.0435	0.2022
14	1	15	27	0.0233	0.2207
17	1	14	22	0.0270	0.2418
20	1	13	18	0.0313	0.2655
22	2	11	17	0.0667	0.3145
25	3	8	14	0.1200	0.3968
29	2	6	11	0.1053	0.4603
30	1	5	11	0.0588	0.4920
33	1	4	10	0.0667	0.5258
34	3	1	10	0.2143	0.6275
35	1	0	10	0.0909	0.6614

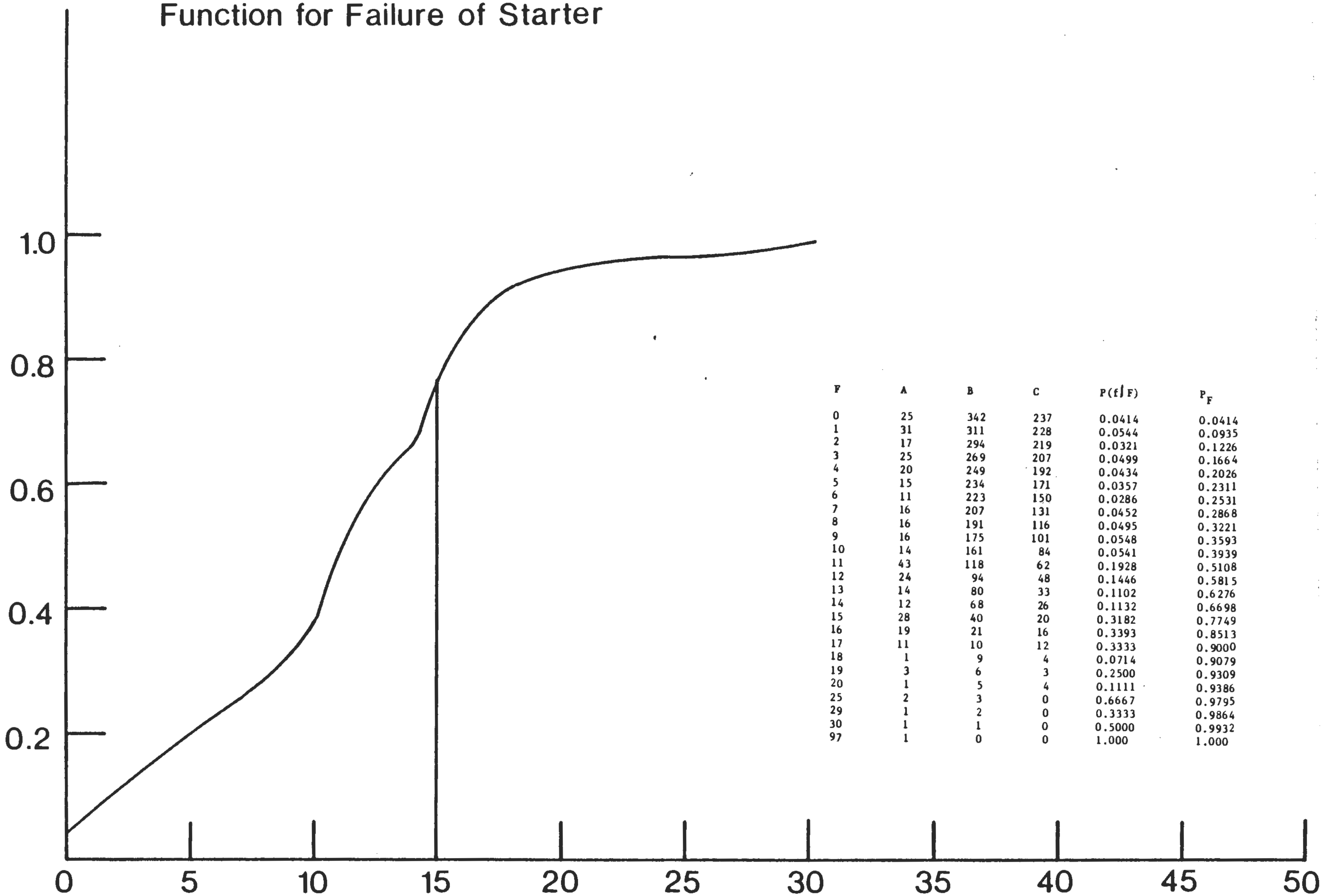
Cumulative Probability Distribution Function for Failure of Transmissions

Unit 4



F	A	B	C	P(f|F)	P_F
0	15	287	203	0.0297	0.0297
1	25	262	191	0.0523	0.0804
2	20	242	185	0.0447	0.1216
3	34	208	177	0.0811	0.1929
4	16	192	165	0.0429	0.2274
5	27	165	151	0.0787	0.2882
6	19	146	131	0.0642	0.3339
7	19	127	108	0.0748	0.3837
8	11	116	95	0.0495	0.4142
9	15	101	75	0.0785	0.4602
10	14	87	61	0.0864	0.5069
11	13	74	52	0.0935	0.5530
12	8	66	44	0.0678	0.5833
13	9	57	37	0.0874	0.6197
14	8	49	31	0.0909	0.6543
15	8	41	28	0.1039	0.6902
16	2	39	26	0.0299	0.6995
17	2	37	21	0.0333	0.7095
18	3	34	19	0.0536	0.7250
19	6	28	15	0.1224	0.7587
20	4	24	13	0.0976	0.7822
21	2	22	10	0.0588	0.7950
22	3	19	7	0.1034	0.8162
23	1	18	5	0.0417	0.8239
25	5	13	3	0.2381	0.8658
27	1	12	2	0.0667	0.8748
31	2	10	2	0.1429	0.8927
32	1	9	2	0.0833	0.9016
33	2	7	2	0.1818	0.9195
34	1	6	2	0.1111	0.9284
35	1	5	2	0.1250	0.9374
38	1	4	2	0.1429	0.9463
39	1	3	2	0.1667	0.9553
42	1	2	2	0.2000	0.9642
43	1	1	2	0.2500	0.9732
58	1	0	1	0.5000	0.9866

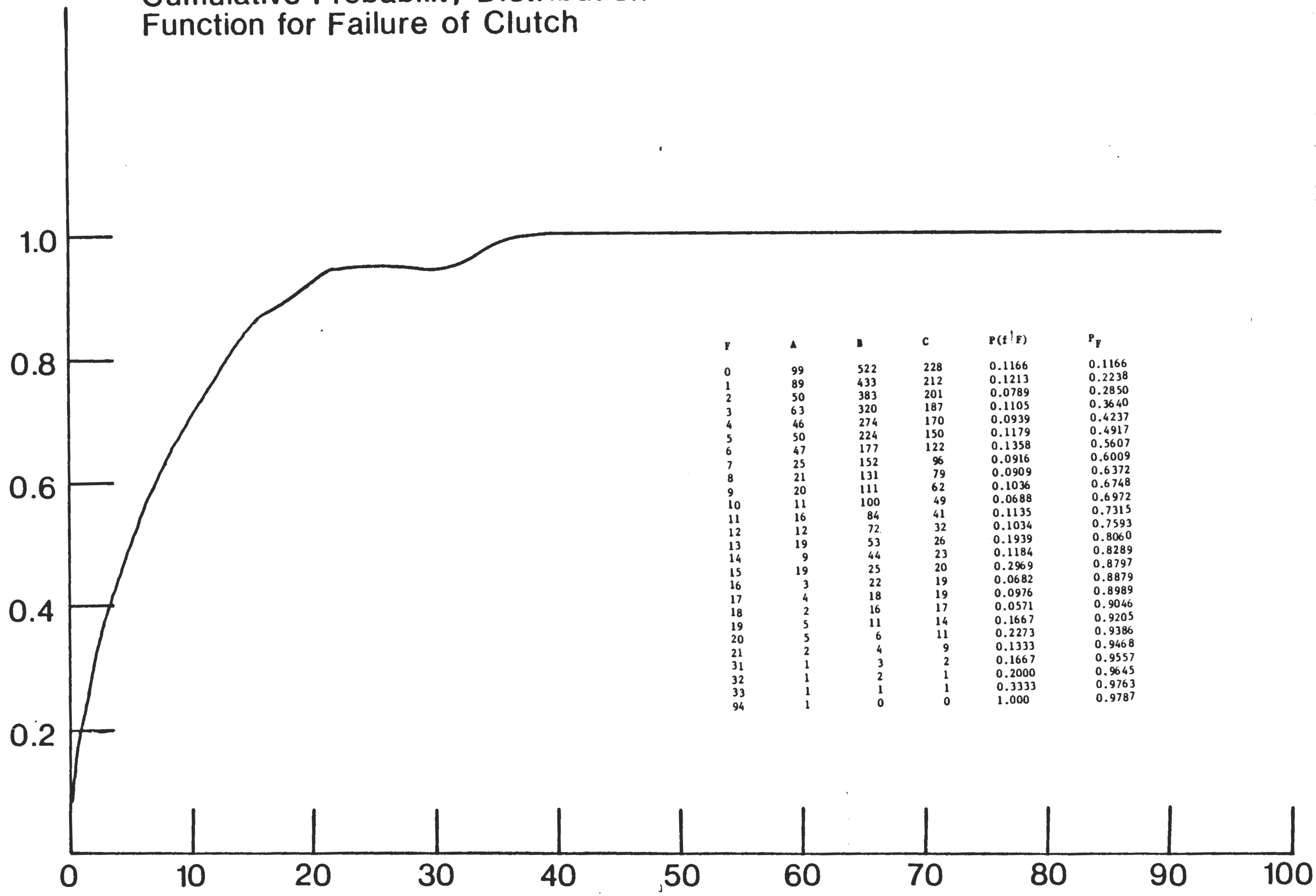
Cumulative Probability Distribution Function for Failure of Starter



F	A	B	C	P(f|F)	P_F
0	25	342	237	0.0414	0.0414
1	31	311	228	0.0544	0.0935
2	17	294	219	0.0321	0.1226
3	25	269	207	0.0499	0.1664
4	20	249	192	0.0434	0.2026
5	15	234	171	0.0357	0.2311
6	11	223	150	0.0286	0.2531
7	16	207	131	0.0452	0.2868
8	16	191	116	0.0495	0.3221
9	16	175	101	0.0548	0.3593
10	14	161	84	0.0541	0.3939
11	43	118	62	0.1928	0.5108
12	24	94	48	0.1446	0.5815
13	14	80	33	0.1102	0.6276
14	12	68	26	0.1132	0.6698
15	28	40	20	0.3182	0.7749
16	19	21	16	0.3393	0.8513
17	11	10	12	0.3333	0.9000
18	1	9	4	0.0714	0.9079
19	3	6	3	0.2500	0.9309
20	1	5	4	0.1111	0.9386
25	2	3	0	0.6667	0.9795
29	1	2	0	0.3333	0.9864
30	1	1	0	0.5000	0.9932
97	1	0	0	1.000	1.000

Miles to Failure (10,000's)

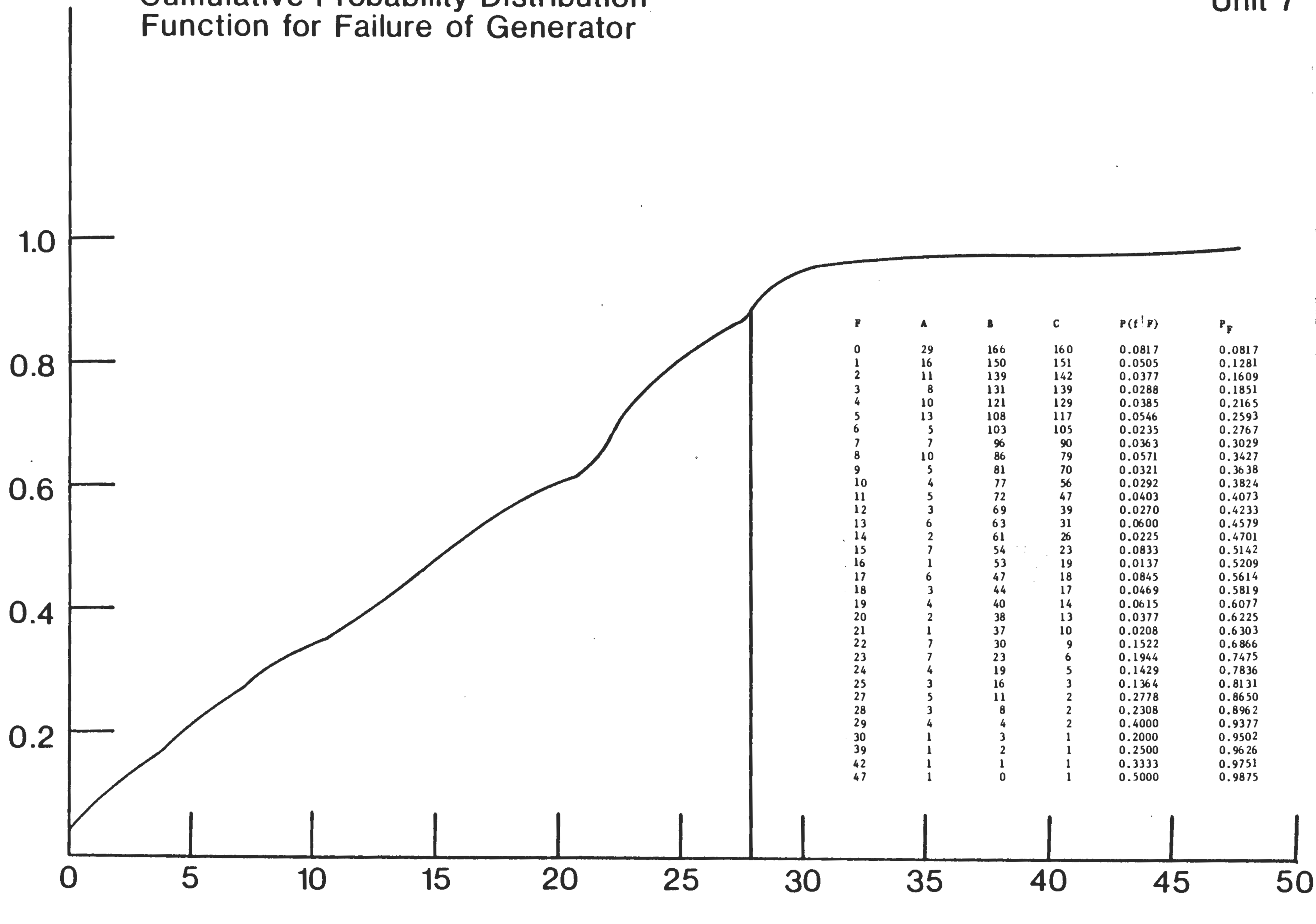
Cumulative Probability Distribution Function for Failure of Clutch



F	A	B	C	P(f ¦ F)	P_F
0	99	522	228	0.1166	0.1166
1	89	433	212	0.1213	0.2238
2	50	383	201	0.0789	0.2850
3	63	320	187	0.1105	0.3640
4	46	274	170	0.0939	0.4237
5	50	224	150	0.1179	0.4917
6	47	177	122	0.1358	0.5607
7	25	152	96	0.0916	0.6009
8	21	131	79	0.0909	0.6372
9	20	111	62	0.1036	0.6748
10	11	100	49	0.0688	0.6972
11	16	84	41	0.1135	0.7315
12	12	72	32	0.1034	0.7593
13	19	53	26	0.1939	0.8060
14	9	44	23	0.1184	0.8289
15	19	25	20	0.2969	0.8797
16	3	22	19	0.0682	0.8879
17	4	18	19	0.0976	0.8989
18	2	16	17	0.0571	0.9046
19	5	11	14	0.1667	0.9205
20	5	6	11	0.2273	0.9386
21	2	4	9	0.1333	0.9468
31	1	3	2	0.1667	0.9557
32	1	2	1	0.2000	0.9645
33	1	1	1	0.3333	0.9763
94	1	0	0	1.000	0.9787

Miles to Failure (10,000's)

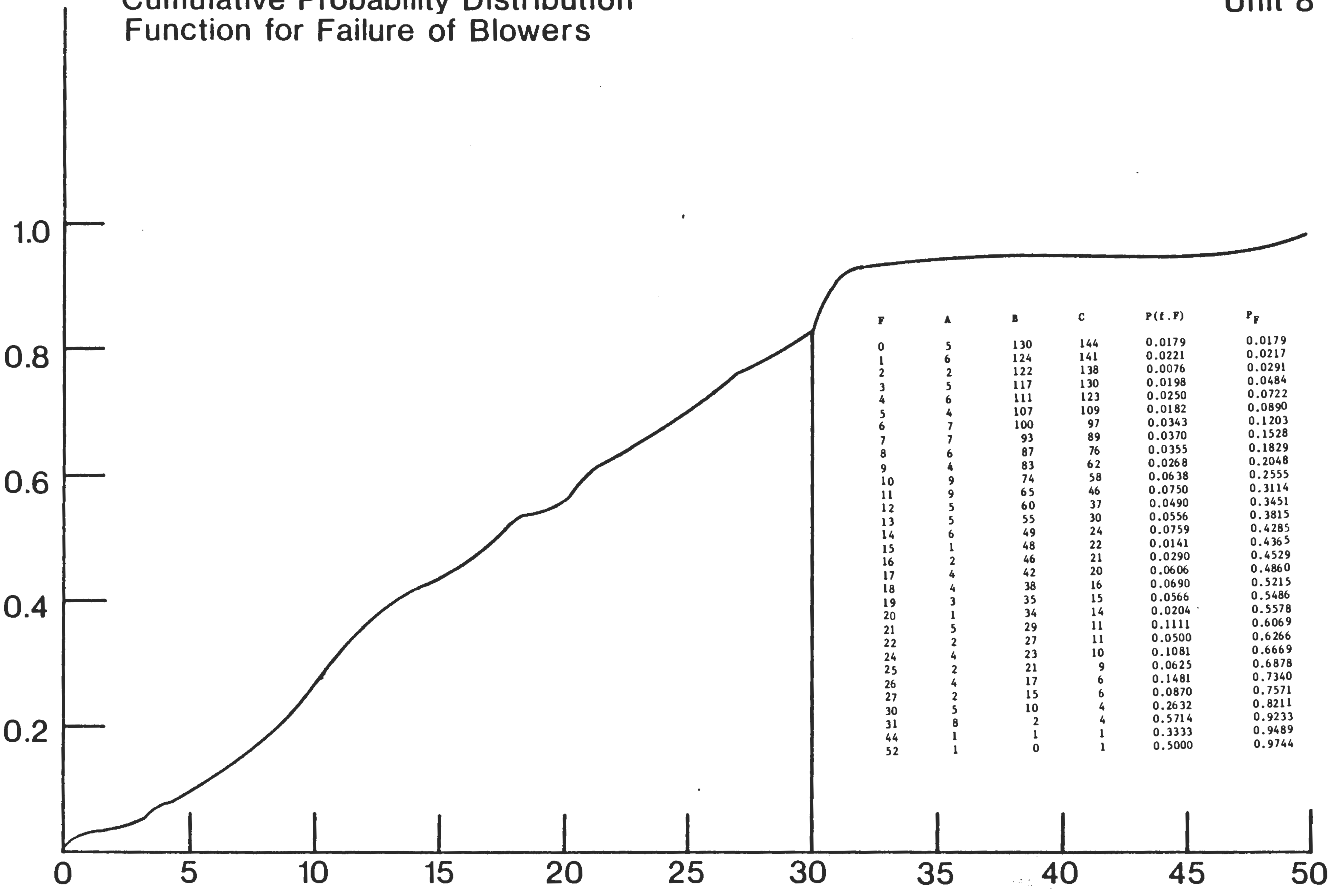
Cumulative Probability Distribution Function for Failure of Generator



F	A	B	C	P(f | F)	P_F
0	29	166	160	0.0817	0.0817
1	16	150	151	0.0505	0.1281
2	11	139	142	0.0377	0.1609
3	8	131	139	0.0288	0.1851
4	10	121	129	0.0385	0.2165
5	13	108	117	0.0546	0.2593
6	5	103	105	0.0235	0.2767
7	7	96	90	0.0363	0.3029
8	10	86	79	0.0571	0.3427
9	5	81	70	0.0321	0.3638
10	4	77	56	0.0292	0.3824
11	5	72	47	0.0403	0.4073
12	3	69	39	0.0270	0.4233
13	6	63	31	0.0600	0.4579
14	2	61	26	0.0225	0.4701
15	7	54	23	0.0833	0.5142
16	1	53	19	0.0137	0.5209
17	6	47	18	0.0845	0.5614
18	3	44	17	0.0469	0.5819
19	4	40	14	0.0615	0.6077
20	2	38	13	0.0377	0.6225
21	1	37	10	0.0208	0.6303
22	7	30	9	0.1522	0.6866
23	7	23	6	0.1944	0.7475
24	4	19	5	0.1429	0.7836
25	3	16	3	0.1364	0.8131
27	5	11	2	0.2778	0.8650
28	3	8	2	0.2308	0.8962
29	4	4	2	0.4000	0.9377
30	1	3	1	0.2000	0.9502
39	1	2	1	0.2500	0.9626
42	1	1	1	0.3333	0.9751
47	1	0	1	0.5000	0.9875

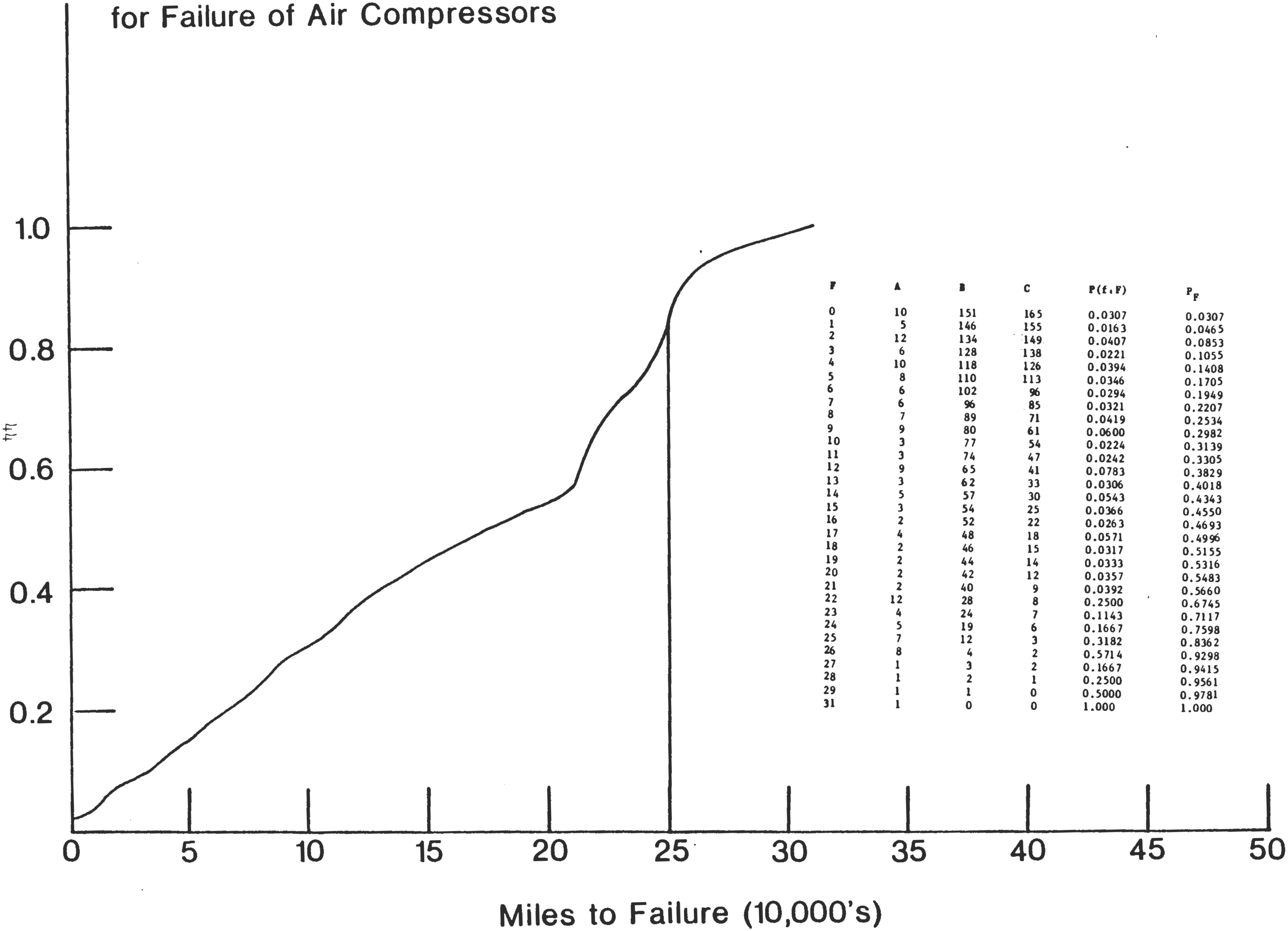
Cumulative Probability Distribution Function for Failure of Blowers

Unit 8



F	A	B	C	P(f.F)	P_F
0	5	130	144	0.0179	0.0179
1	6	124	141	0.0221	0.0217
2	2	122	138	0.0076	0.0291
3	5	117	130	0.0198	0.0484
4	6	111	123	0.0250	0.0722
5	4	107	109	0.0182	0.0890
6	7	100	97	0.0343	0.1203
7	7	93	89	0.0370	0.1528
8	6	87	76	0.0355	0.1829
9	4	83	62	0.0268	0.2048
10	9	74	58	0.0638	0.2555
11	9	65	46	0.0750	0.3114
12	5	60	37	0.0490	0.3451
13	5	55	30	0.0556	0.3815
14	6	49	24	0.0759	0.4285
15	1	48	22	0.0141	0.4365
16	2	46	21	0.0290	0.4529
17	4	42	20	0.0606	0.4860
18	4	38	16	0.0690	0.5215
19	3	35	15	0.0566	0.5486
20	1	34	14	0.0204	0.5578
21	5	29	11	0.1111	0.6069
22	2	27	11	0.0500	0.6266
24	4	23	10	0.1081	0.6669
25	2	21	9	0.0625	0.6878
26	4	17	6	0.1481	0.7340
27	2	15	6	0.0870	0.7571
30	5	10	4	0.2632	0.8211
31	8	2	4	0.5714	0.9233
44	1	1	1	0.3333	0.9489
52	1	0	1	0.5000	0.9744

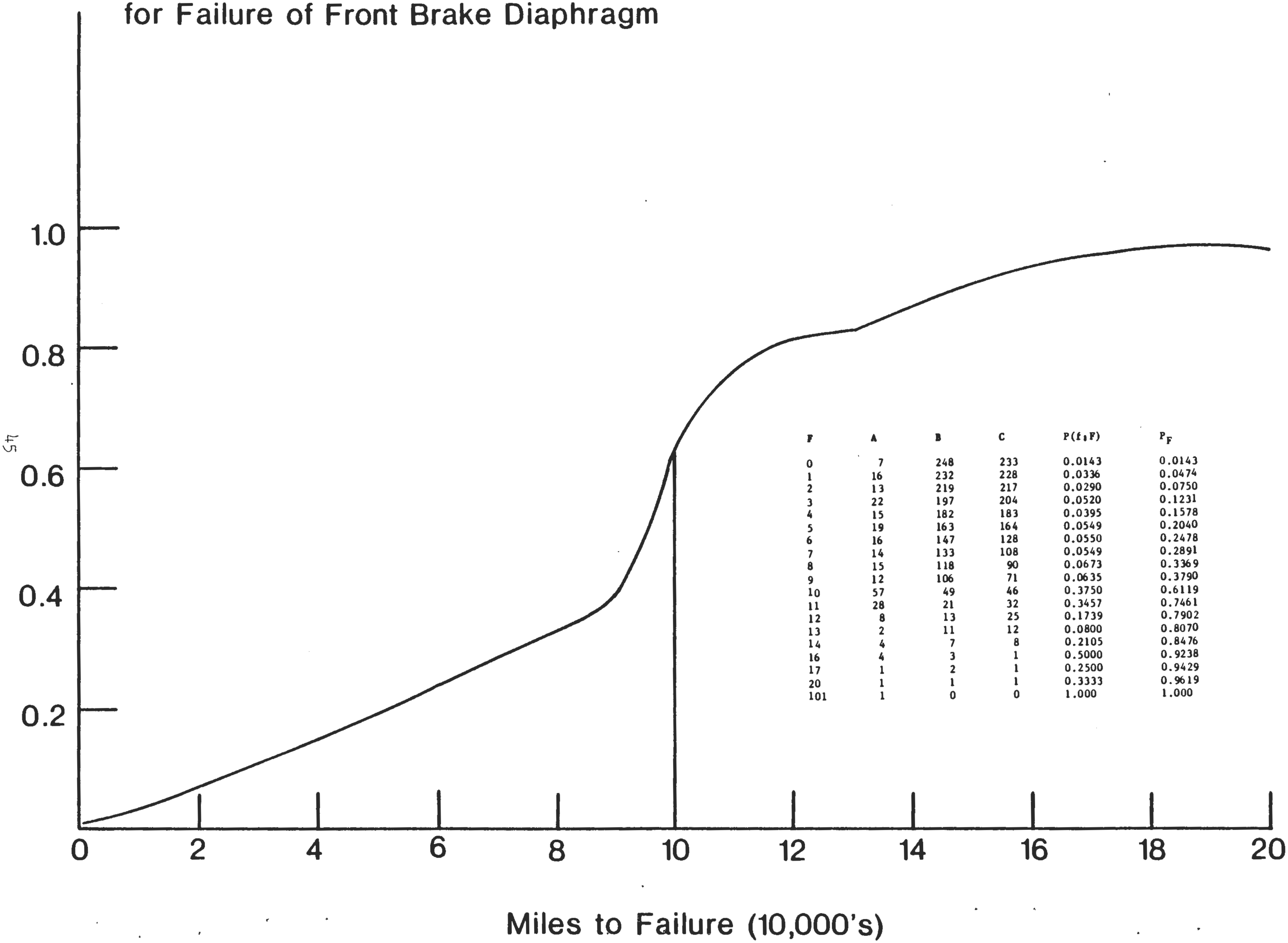
Cumulative Probability Distribution Function for Failure of Air Compressors



F	A	B	C	P(f, F)	P_F
0	10	151	165	0.0307	0.0307
1	5	146	155	0.0163	0.0465
2	12	134	149	0.0407	0.0853
3	6	128	138	0.0221	0.1055
4	10	118	126	0.0394	0.1408
5	8	110	113	0.0346	0.1705
6	6	102	96	0.0294	0.1949
7	6	96	85	0.0321	0.2207
8	7	89	71	0.0419	0.2534
9	9	80	61	0.0600	0.2982
10	3	77	54	0.0224	0.3139
11	3	74	47	0.0242	0.3305
12	9	65	41	0.0783	0.3829
13	3	62	33	0.0306	0.4018
14	5	57	30	0.0543	0.4343
15	3	54	25	0.0366	0.4550
16	2	52	22	0.0263	0.4693
17	4	48	18	0.0571	0.4996
18	2	46	15	0.0317	0.5155
19	2	44	14	0.0333	0.5316
20	2	42	12	0.0357	0.5483
21	2	40	9	0.0392	0.5660
22	12	28	8	0.2500	0.6745
23	4	24	7	0.1143	0.7117
24	5	19	6	0.1667	0.7598
25	7	12	3	0.3182	0.8362
26	8	4	2	0.5714	0.9298
27	1	3	2	0.1667	0.9415
28	1	2	1	0.2500	0.9561
29	1	1	0	0.5000	0.9781
31	1	0	0	1.000	1.000

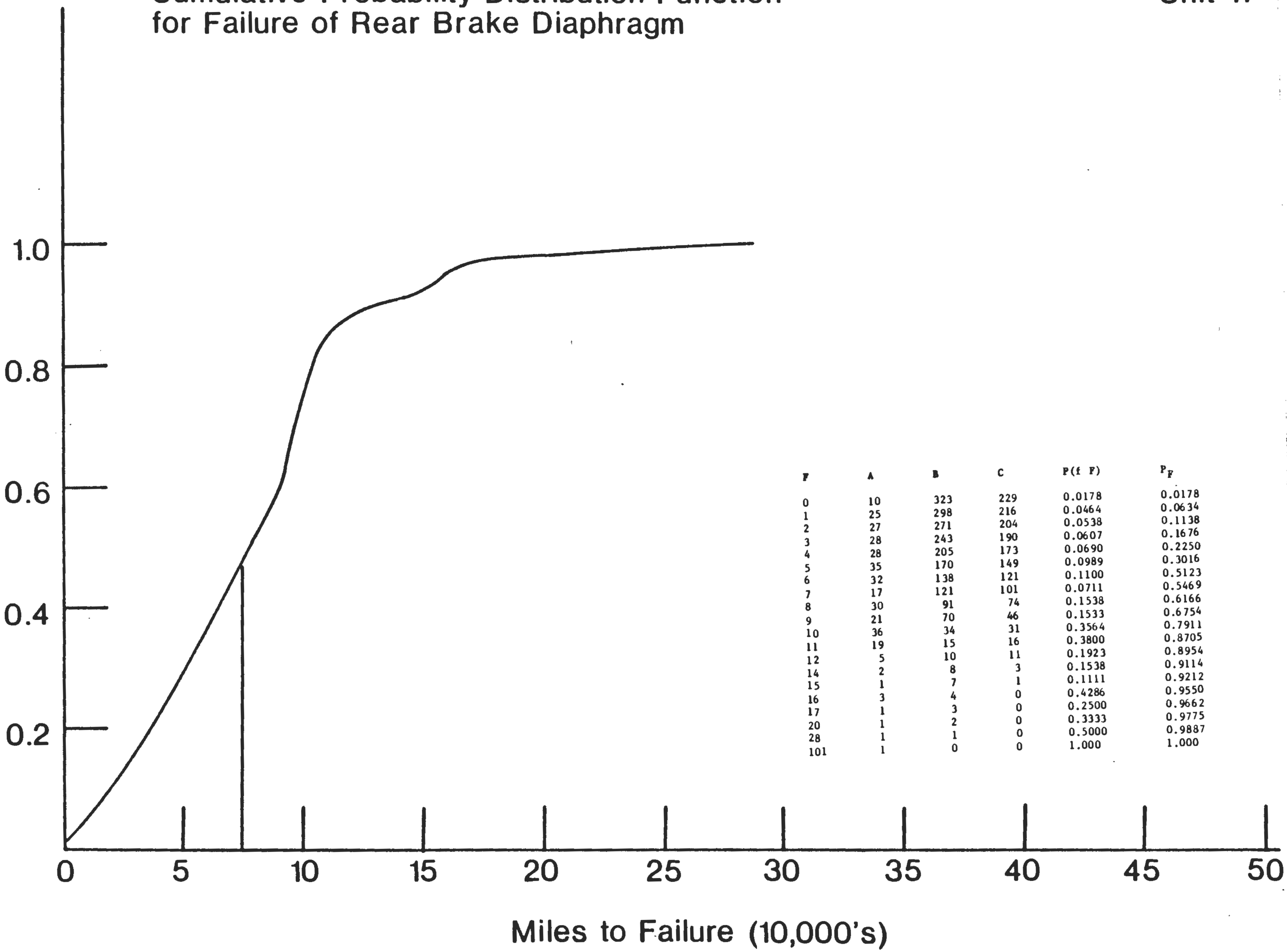
Cumulative Probaability Distribution Function for Failure of Front Brake Diaphragm

Unit 10



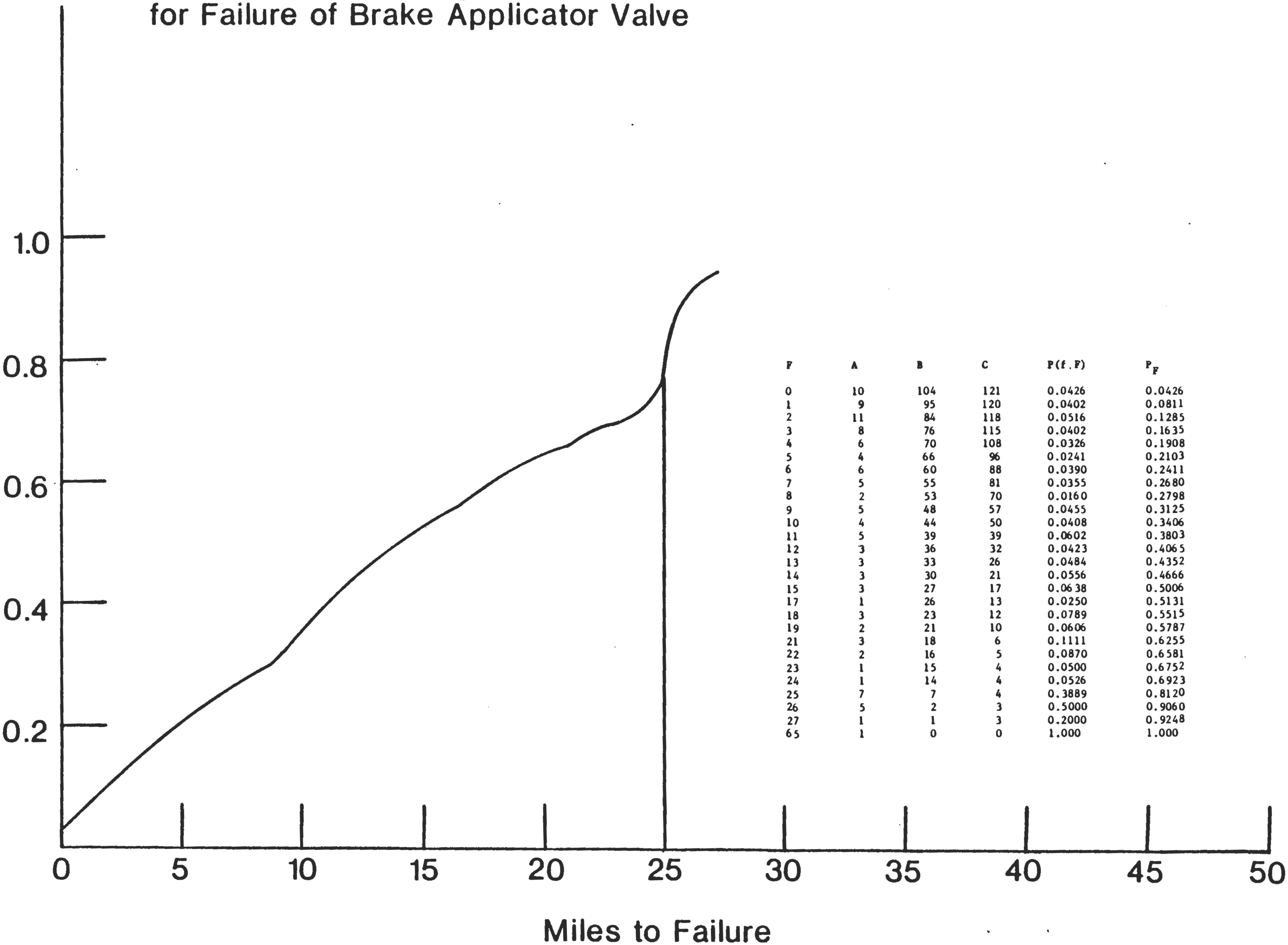
F	A	B	C	P(f;F)	P_F
0	7	248	233	0.0143	0.0143
1	16	232	228	0.0336	0.0474
2	13	219	217	0.0290	0.0750
3	22	197	204	0.0520	0.1231
4	15	182	183	0.0395	0.1578
5	19	163	164	0.0549	0.2040
6	16	147	128	0.0550	0.2478
7	14	133	108	0.0549	0.2891
8	15	118	90	0.0673	0.3369
9	12	106	71	0.0635	0.3790
10	57	49	46	0.3750	0.6119
11	28	21	32	0.3457	0.7461
12	8	13	25	0.1739	0.7902
13	2	11	12	0.0800	0.8070
14	4	7	8	0.2105	0.8476
16	4	3	1	0.5000	0.9238
17	1	2	1	0.2500	0.9429
20	1	1	1	0.3333	0.9619
101	1	0	0	1.000	1.000

Cumulative Probability Distribution Function for Failure of Rear Brake Diaphragm



F	A	B	C	P(f F)	P_F
0	10	323	229	0.0178	0.0178
1	25	298	216	0.0464	0.0634
2	27	271	204	0.0538	0.1138
3	28	243	190	0.0607	0.1676
4	28	205	173	0.0690	0.2250
5	35	170	149	0.0989	0.3016
6	32	138	121	0.1100	0.5123
7	17	121	101	0.0711	0.5469
8	30	91	74	0.1538	0.6166
9	21	70	46	0.1533	0.6754
10	36	34	31	0.3564	0.7911
11	19	15	16	0.3800	0.8705
12	5	10	11	0.1923	0.8954
14	2	8	3	0.1538	0.9114
15	1	7	1	0.1111	0.9212
16	3	4	0	0.4286	0.9550
17	1	3	0	0.2500	0.9662
20	1	2	0	0.3333	0.9775
28	1	1	0	0.5000	0.9887
101	1	0	0	1.000	1.000

Cumulative Probability Distribution Function for Failure of Brake Applicator Valve



F	A	B	C	P(f, F)	P_F
0	10	104	121	0.0426	0.0426
1	9	95	120	0.0402	0.0811
2	11	84	118	0.0516	0.1285
3	8	76	115	0.0402	0.1635
4	6	70	108	0.0326	0.1908
5	4	66	96	0.0241	0.2103
6	6	60	88	0.0390	0.2411
7	5	55	81	0.0355	0.2680
8	2	53	70	0.0160	0.2798
9	5	48	57	0.0455	0.3125
10	4	44	50	0.0408	0.3406
11	5	39	39	0.0602	0.3803
12	3	36	32	0.0423	0.4065
13	3	33	26	0.0484	0.4352
14	3	30	21	0.0556	0.4666
15	3	27	17	0.0638	0.5006
17	1	26	13	0.0250	0.5131
18	3	23	12	0.0789	0.5515
19	2	21	10	0.0606	0.5787
21	3	18	6	0.1111	0.6255
22	2	16	5	0.0870	0.6581
23	1	15	4	0.0500	0.6752
24	1	14	4	0.0526	0.6923
25	7	7	4	0.3889	0.8120
26	5	2	3	0.5000	0.9060
27	1	1	3	0.2000	0.9248
65	1	0	0	1.000	1.000

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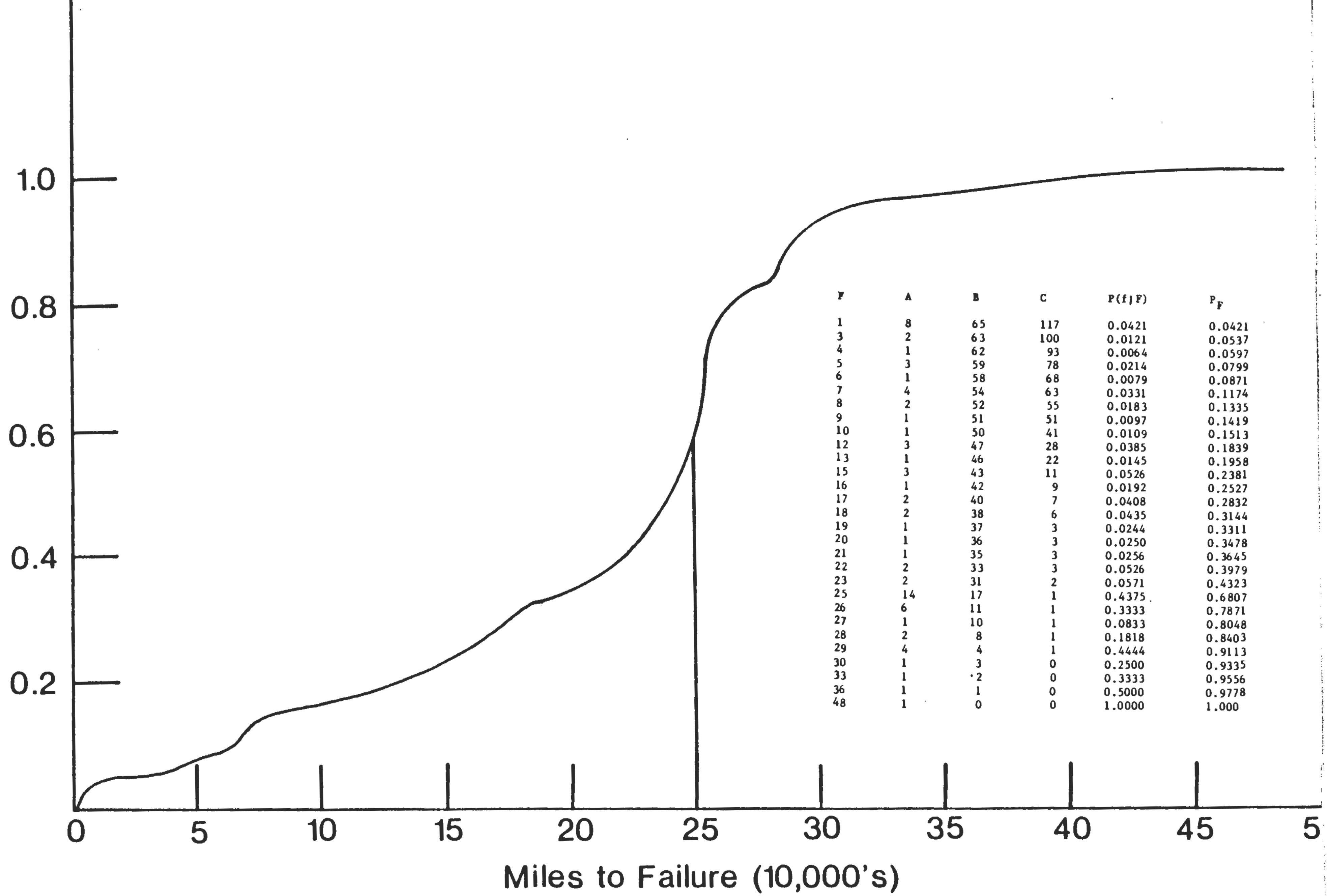
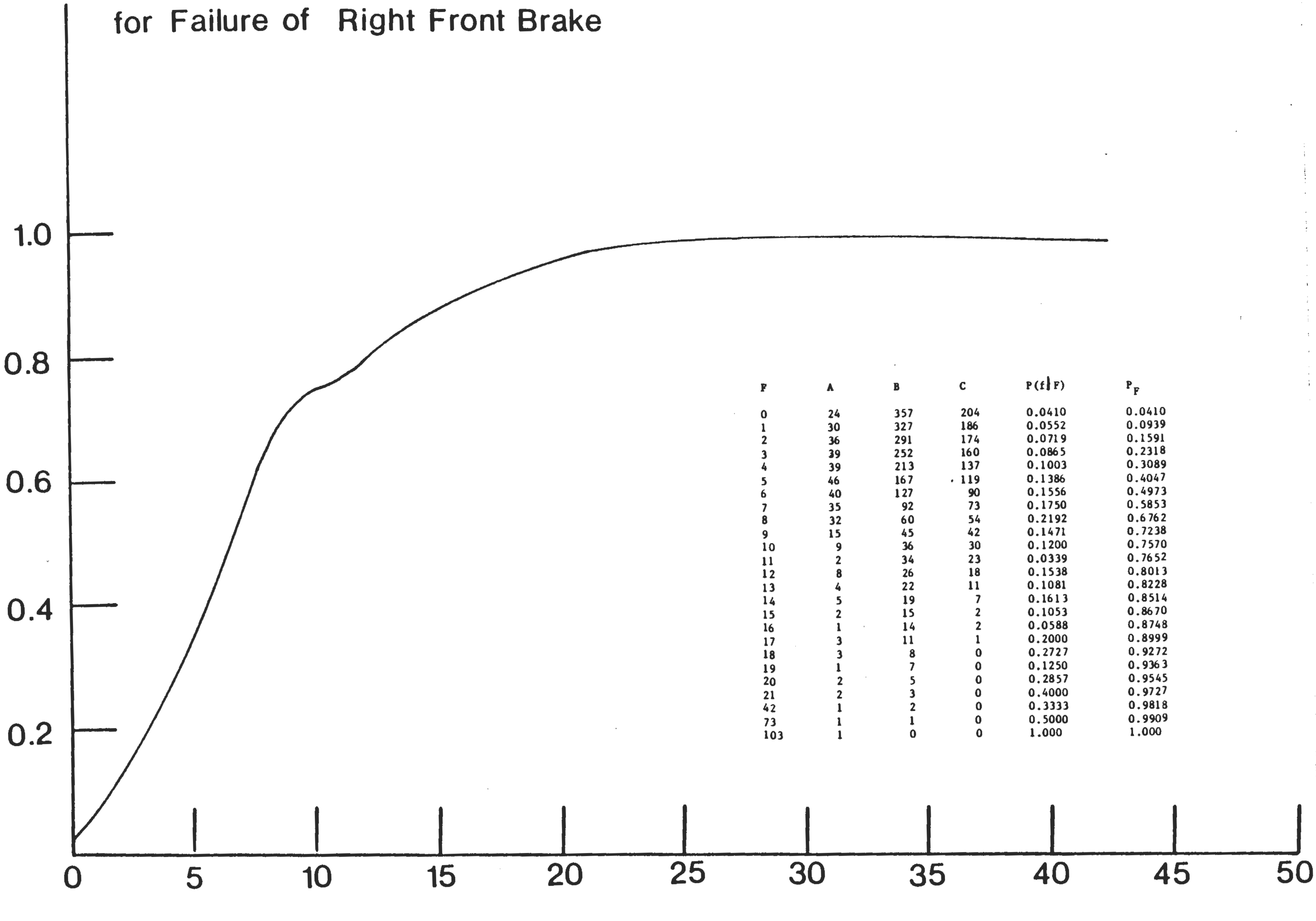
Cumulative Probability Distribution Function for Failure of Brake Relay Valve



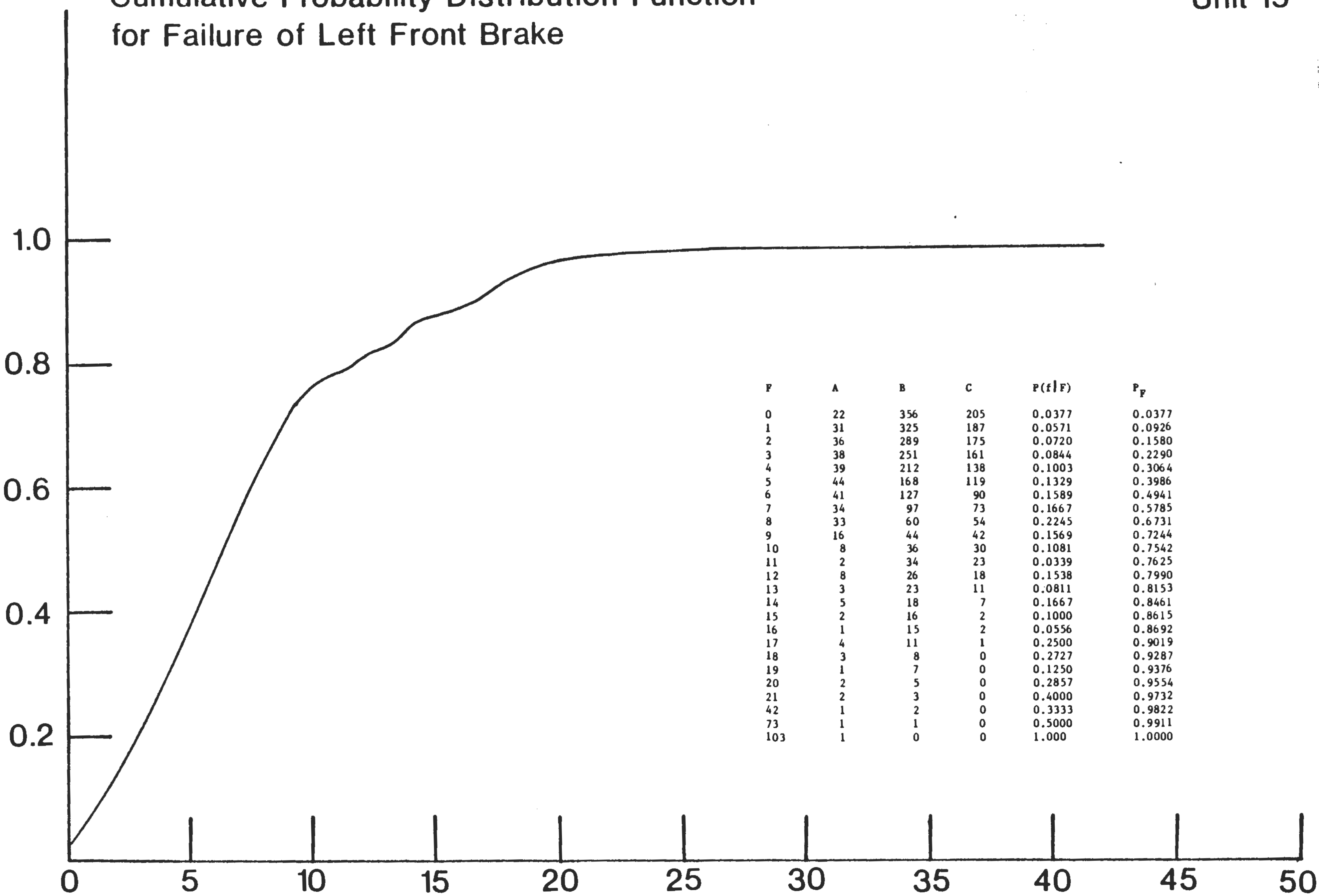
F	A	B	C	P(f/F)	P_F
1	8	65	117	0.0421	0.0421
3	2	63	100	0.0121	0.0537
4	1	62	93	0.0064	0.0597
5	3	59	78	0.0214	0.0799
6	1	58	68	0.0079	0.0871
7	4	54	63	0.0331	0.1174
8	2	52	55	0.0183	0.1335
9	1	51	51	0.0097	0.1419
10	1	50	41	0.0109	0.1513
12	3	47	28	0.0385	0.1839
13	1	46	22	0.0145	0.1958
15	3	43	11	0.0526	0.2381
16	1	42	9	0.0192	0.2527
17	2	40	7	0.0408	0.2832
18	2	38	6	0.0435	0.3144
19	1	37	3	0.0244	0.3311
20	1	36	3	0.0250	0.3478
21	1	35	3	0.0256	0.3645
22	2	33	3	0.0526	0.3979
23	2	31	2	0.0571	0.4323
25	14	17	1	0.4375	0.6807
26	6	11	1	0.3333	0.7871
27	1	10	1	0.0833	0.8048
28	2	8	1	0.1818	0.8403
29	4	4	1	0.4444	0.9113
30	1	3	0	0.2500	0.9335
33	1	2	0	0.3333	0.9556
36	1	1	0	0.5000	0.9778
48	1	0	0	1.0000	1.000

Cumulative Probability Distribution Function for Failure of Right Front Brake



F	A	B	C	P(f|F)	P_F
0	24	357	204	0.0410	0.0410
1	30	327	186	0.0552	0.0939
2	36	291	174	0.0719	0.1591
3	39	252	160	0.0865	0.2318
4	39	213	137	0.1003	0.3089
5	46	167	119	0.1386	0.4047
6	40	127	90	0.1556	0.4973
7	35	92	73	0.1750	0.5853
8	32	60	54	0.2192	0.6762
9	15	45	42	0.1471	0.7238
10	9	36	30	0.1200	0.7570
11	2	34	23	0.0339	0.7652
12	8	26	18	0.1538	0.8013
13	4	22	11	0.1081	0.8228
14	5	19	7	0.1613	0.8514
15	2	15	2	0.1053	0.8670
16	1	14	2	0.0588	0.8748
17	3	11	1	0.2000	0.8999
18	3	8	0	0.2727	0.9272
19	1	7	0	0.1250	0.9363
20	2	5	0	0.2857	0.9545
21	2	3	0	0.4000	0.9727
42	1	2	0	0.3333	0.9818
73	1	1	0	0.5000	0.9909
103	1	0	0	1.000	1.000

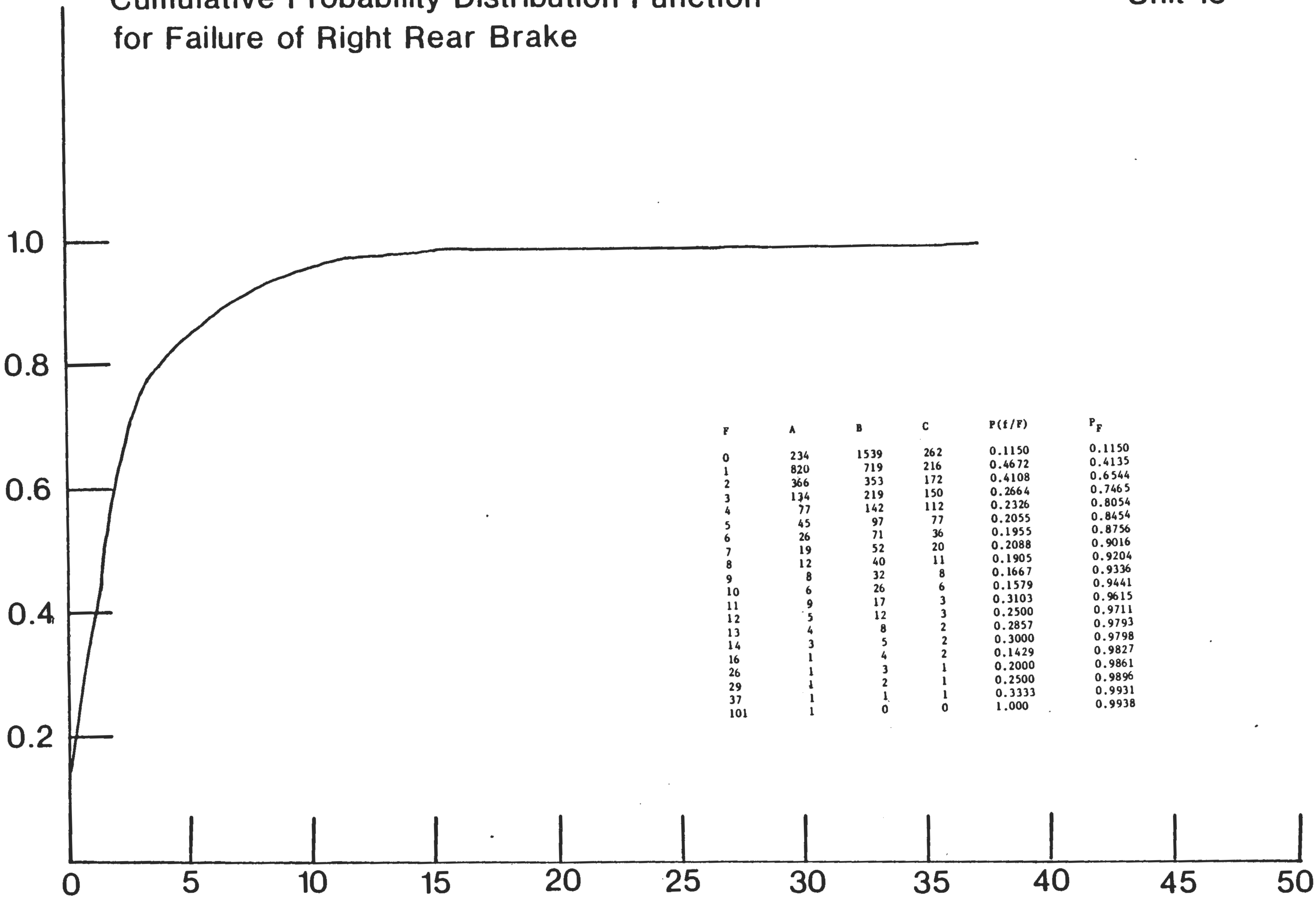
Cumulative Probability Distribution Function for Failure of Left Front Brake



Miles to Failure (10,000's)

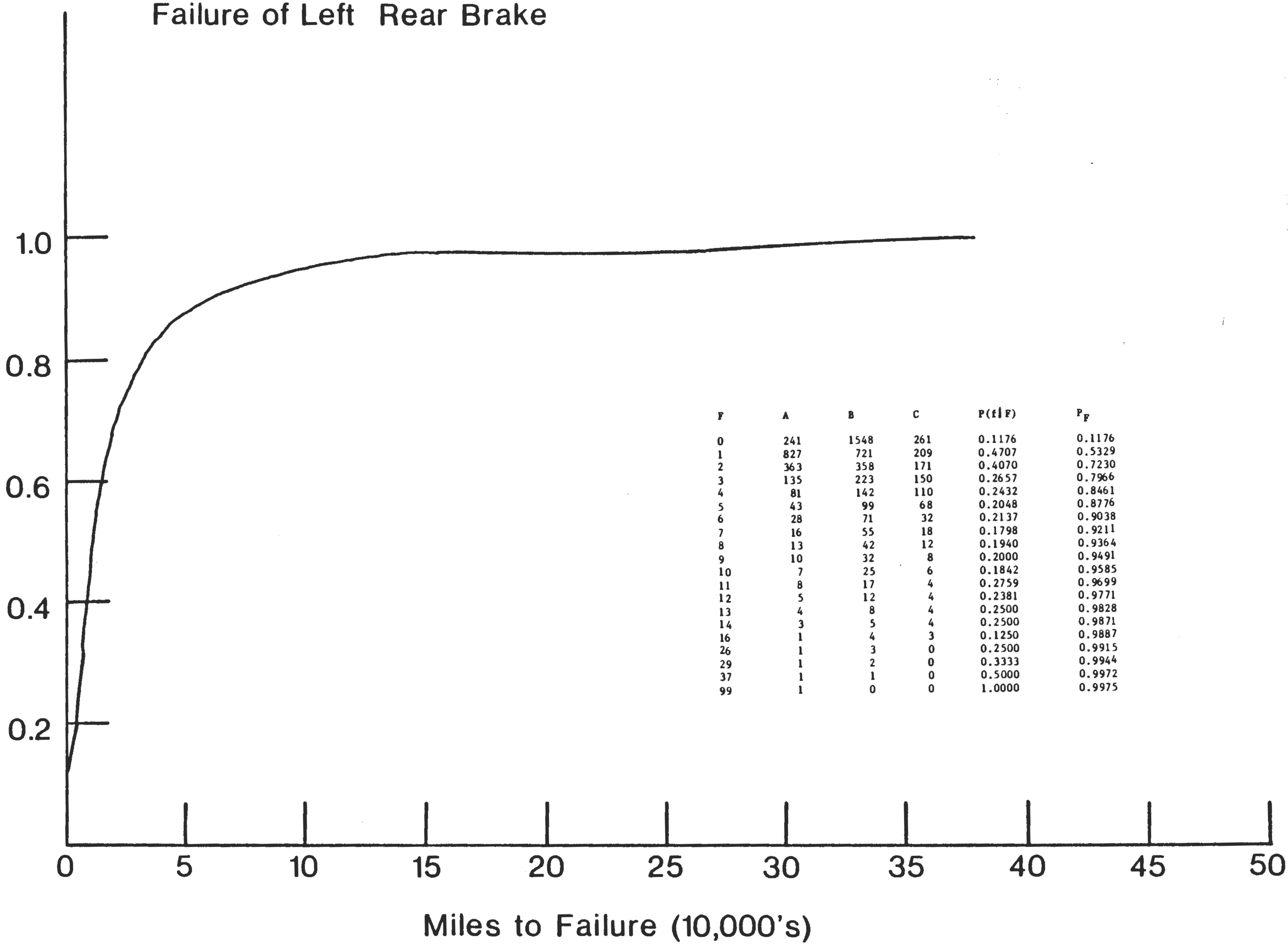
F	A	B	C	P(f|F)	P_F
0	22	356	205	0.0377	0.0377
1	31	325	187	0.0571	0.0926
2	36	289	175	0.0720	0.1580
3	38	251	161	0.0844	0.2290
4	39	212	138	0.1003	0.3064
5	44	168	119	0.1329	0.3986
6	41	127	90	0.1589	0.4941
7	34	97	73	0.1667	0.5785
8	33	60	54	0.2245	0.6731
9	16	44	42	0.1569	0.7244
10	8	36	30	0.1081	0.7542
11	2	34	23	0.0339	0.7625
12	8	26	18	0.1538	0.7990
13	3	23	11	0.0811	0.8153
14	5	18	7	0.1667	0.8461
15	2	16	2	0.1000	0.8615
16	1	15	2	0.0556	0.8692
17	4	11	1	0.2500	0.9019
18	3	8	0	0.2727	0.9287
19	1	7	0	0.1250	0.9376
20	2	5	0	0.2857	0.9554
21	2	3	0	0.4000	0.9732
42	1	2	0	0.3333	0.9822
73	1	1	0	0.5000	0.9911
103	1	0	0	1.000	1.0000

Cumulative Probability Distribution Function for Failure of Right Rear Brake



F	A	B	C	P(f/F)	P_F
0	234	1539	262	0.1150	0.1150
1	820	719	216	0.4672	0.4135
2	366	353	172	0.4108	0.6544
3	134	219	150	0.2664	0.7465
4	77	142	112	0.2326	0.8054
5	45	97	77	0.2055	0.8454
6	26	71	36	0.1955	0.8756
7	19	52	20	0.2088	0.9016
8	12	40	11	0.1905	0.9204
9	8	32	8	0.1667	0.9336
10	6	26	6	0.1579	0.9441
11	9	17	3	0.3103	0.9615
12	5	12	3	0.2500	0.9711
13	4	8	2	0.2857	0.9793
14	3	5	2	0.3000	0.9798
16	1	4	2	0.1429	0.9827
26	1	3	1	0.2000	0.9861
29	1	2	1	0.2500	0.9896
37	1	1	1	0.3333	0.9931
101	1	0	0	1.000	0.9938

Cumulative Probability Distribution for Failure of Left Rear Brake



F	A	B	C	P(f|F)	P_F
0	241	1548	261	0.1176	0.1176
1	827	721	209	0.4707	0.5329
2	363	358	171	0.4070	0.7230
3	135	223	150	0.2657	0.7966
4	81	142	110	0.2432	0.8461
5	43	99	68	0.2048	0.8776
6	28	71	32	0.2137	0.9038
7	16	55	18	0.1798	0.9211
8	13	42	12	0.1940	0.9364
9	10	32	8	0.2000	0.9491
10	7	25	6	0.1842	0.9585
11	8	17	4	0.2759	0.9699
12	5	12	4	0.2381	0.9771
13	4	8	4	0.2500	0.9828
14	3	5	4	0.2500	0.9871
16	1	4	3	0.1250	0.9887
26	1	3	0	0.2500	0.9915
29	1	2	0	0.3333	0.9944
37	1	1	0	0.5000	0.9972
99	1	0	0	1.0000	0.9975

Appendix D

Sample Calculations

Example 1

Sample Calculation of mileage accumulated by surviving unit.

bus # 107 Unit - transmission

month, day and year of last transmission replacement 10-8-80

mileage at last transmission replacement 1,239,271 = M_t

month, day and year of last replacement of any kind 3/14/81 = M_L, D_L, Y_L

mileage of last replacement of any kind 1,262,324 = M_A

date of data collection 4/30/81

average miles /day = 133.3

miles last transmission replacement has survived =

$M_A - M_t + 133.3\ ((81-Y_L) \times 365 + (4 - M_L) \times 30 + (30 - D_L)) =$

$1,262,324 - 1,239,271 + 133.3\ ((81-81) \times 365 + ((4-3) \times 30) + (30-14)) = 29184$

Example 2

Sample calculation of conditional probability distribution function for the failure of a unit in an interval FI.

Unit 5 - Clutch

FI = 5 interval = 45,000 - 55,000

a = 50 (from graph 4 appendix C, failures in interval 5)

b = 224 (from graph 4 appendix C, sum of failures in intervals FI 6.)

c = 150 (from graph 4 appendix C, sum of surviving units in intervals 5.)

P (failure in interval 5 unit survived to interval 5)

$$= P(f \mid 5) = \frac{a}{a + b + c} = \frac{50}{50+224+150} = 0.1179$$

Example 3

Sample calculation of cumulative probability distribution function for the failure of a unit before or in interval FI.

Unit 5 - Clutch

$i = 5$

$P(f \mid F = 5) = 0.1179$

$P_4 = P(\text{failure before or in interval } 4) = 0.4237$

$P_i = (1 - P_{i-1})\ P\ (f \mid F = i) + P_{i-1}$

$P_5 = (1 - 0.4237)(0.1179) + 0.4237$

$= 0.4917$

Example 4

Sample calculation of confidence interval

For further information on the construction and derivation of confidence intervals particularly as illustrated below please see Satistical Inference by Springer, Herliky, Mall, and Beggs. Richard D. Irwin Inc. 1966.

Unit 4 - transmission

mean = = 86,499.9

standard deviation = = 84,617.4

number of observations = 302

the limits of a confidence interval are defined as

$$L = \pm Z_p (\sigma / n) \qquad (1)$$

where Z_p is the standard normal variable for which the probability of Z less than Z_p is p. Thus for a 95% confidence interval (1) becomes

$$L = \pm 1.96 (\sigma / n) \qquad (2)$$

since $Z_{.025} = Z_{.975} = 1.96$

from (2) and previous information the 95% confidence interval for mean miles to transmission failure is

$$86,499.9 \pm 1.96 \frac{(84,617.4)}{302}$$

or (76,956 - 96,043)