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Aging and Lifetime of the M151 ¼-ton Truck

RAC

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2. This publication was prepared under a study sponsored by DCSLOG, Department of the Army. This study dealing with the M151 1/4-Ton Truck was preceded by a number of studies dealing with aging and lifetime of equipment. Studies included:

a. T-401, Economics of Maintenance and Replacement of 3/4-Ton, 2 1/2-Ton, and 5-Ton Truck Fleets (U), Sep 1961.

b. T-406, Material Handling Equipment--A Study of Economic Life, Vol. I, May 1962; Vol. II, Feb 1962.

c. T-409, Operation, Maintenance, and Cost Experience of the Tank (M48A), Armored Personnel Carrier (M59), and Self-Propelled Howitzer (M52) Vehicle Fleets (U), Sep 1962.

d. T-413, Allocation of Maintenance and Support Resources for Tactical Communications (U), Aug 1963.

e. T-428, Operation and Maintenance Experience of the Heavy and Medium Tractors (crawler), 20-Ton Crane, Road Grader, 1.5 kw Generator and 45 kw 400-cps Generator (U), Aug 1964.

f. T-460, Operation, Maintenance, and Lifetime of M60 Tanks, M113 Armored Personnel Carriers, and M88 Recovery Vehicles (U), Vol. I, Feb 1965; Vol. II, May 1965.

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LOGISTICS DEPARTMENT
TECHNICAL MEMORANDUM RAC-T-479
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Aging and Lifetime of the M151 ¼-ton Truck

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FOREWORD

This memorandum was prepared under the sponsorship of the Deputy Chief of Staff for Logistics, Department of the Army. This study, dealing with the M151 ¼-ton truck, was preceded by a study of the M38-series vehicle several years ago* and a number of studies dealing with other classes of equipment. The purpose of all these studies was to assist the Army in the management of its fleets, and they have directly and indirectly had marked influence on equipment policies.

L. S. Stoneback
Head, Logistics Department

*Operations Research Office, "Operation Maintenance, and Cost Experience of ¼ ¼-Ton Truck Fleet (U)," ORO-T-382, May 61. CONFIDENTIAL

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Further acknowledgment must be made of the guidance, assistance, and cooperation the study received from Col W. W. Smith and Lt Col H. C. Richardson, Materiel Readiness Branch, Deputy Chief of Staff for Logistics; M. D. Finn, Deputy Director Materiel Readiness, US Army Materiel Command, (USAMC); Lt Col M. F. Hoffay, USAMC; L. M. Hoover, Engineering Branch, US Army Supply and Maintenance Command; Lt Col E. H. Kleist and B. Levine, Office, Chief of Engineers; and Maj C. K. Heiden, Office, Chief of Research and Development.

Recognition is also given to RAC military advisors Lt Col D. H. Richardson and Lt Col E. B. Junge, who provided much able assistance.

CONTENTS

Appendixes

Figures

Tables

SUMMARY

Problem

To determine the lifetime of the M151 ¼-ton truck.

Facts

The M151 is the most recent and most preferred model of ¼-ton truck; it is a lightweight personnel and cargo carrier designed to accomplish basic transport on roads and cross-country. M151's were first introduced to field use in large numbers in late 1961.

Current active Army utilization of the ¼-ton truck fleet amounts to approximately 200 million miles annually.

The predecessor models, i.e., the M38 series, were the subject of an earlier ORO(RAC) investigation.[1] In that study it was determined that they have an average "least-cost" lifetime of 5 years. From this study the Army adopted an average "useful life expectancy" for ¼-ton trucks of 6 years.[2]

The Deputy Chief of Staff for Logistics (DCSLOG) requested RAC to investigate the performance of the M151 to determine its lifetime.

Discussion

General experience, confirmed by past RAC studies,[1, 3–5] indicates that as vehicles age they perform less well and consume more resources. The study reported on in this memorandum was directed at determining how performance and resource consumption change as the M151 ¼-ton truck ages. On the basis of this analysis an optimum age for replacement is recommended.

The data base of the study was the operational and maintenance history of 772 M151's observed in Europe from their times of issue as new vehicles to an average accumulation of 13,600 miles over an average period of 18 months. A few vehicles were seen at ages beyond 25,000 miles and 24 months. Maintenance histories for each vehicle were compiled from Army maintenance records. These histories identified maintenance actions by date and vehicle mileage and also showed the nature of the maintenance action, man-hour consumption, parts and components involved, and echelon at which the maintenance was performed.

SUMMARY

Performance and its variation with vehicle age were examined in terms of vehicle-breakdown rate, mean miles per breakdown, availability, and reliability. Two measures of vehicle-breakdown rate were used. One was the rate of replacement of 21 selected parts; failure of any of these parts was assumed to result in a significantly impaired vehicle. The other rate represented replacement of the 10 most important parts from the list of 21; failure of any of these 10 parts was assumed to result in actual vehicle disability. These two breakdown rates represented upper and lower bounds within which to analyze M151 breakdown propensity. The breakdown rates were derived from individually computed age-dependent replacement rates for each of the 21 significant parts. Availability and reliability were then computed on the basis of each of the two breakdown rates; mean miles per breakdown and a measure of performance called the "mission-success index" (the product of availability and reliability) were also computed on both bases.

Maintenance costs as a function of M151 age were derived, including costs of parts; the procurement, storage, and distribution of parts [referred to as stock, store, and issue (SSI)]; and maintenance labor.

The trends of M151 performance and maintenance costs with age found in the data were used to project performance and costs beyond the data into ages presumed to include M151 lifetimes. The lifetime finally derived is based on these projections.

The lifetime derived is that vehicle age at which replacement by a new vehicle with the same initial cost, age-dependent unscheduled maintenance cost, and age-dependent breakdown rate as the old vehicle, in a support environment with the same average response characteristics as that experienced by the old vehicle, will minimize the long-run average cost per unit of effectiveness rendered. Effectiveness is measured in terms of availability, reliability, and nonobsolescence. An obsolescence rate of 2 percent/year was used.

To facilitate conversion of the lifetime to an annual vehicle replacement requirement considering that some vehicles are lost before their lifetimes expire, a graph was prepared from which, for any combination of a lifetime between 4 and 14 years and a premature loss rate between 0 and 20 percent/year, an annual procurement quantity as a percentage of the fleet size may be read.

Engines and transmissions were treated in special detail because of their importance as assemblies, and to demonstrate the idea of equilibrium performance, which was employed in making the projections of vehicle performance and costs.

The response of the support system to M151 demands for maintenance was characterized in terms of the average man-hour consumption and the average response time per maintenance response. The average costs of parts, labor, and SSI consumed per maintenance response were also computed.

Conclusions

1. The lifetime of the M151 is 50,000 miles or 7½ years at the current Army-wide use rate of 550 miles/month. The calendar lifetimes corresponding to 50,000 miles at other rates of use are shown in the accompanying tabulation.

Use rate, miles per month	Lifetime, years
300	14
750	5½
1000	4

2. To maintain a constant fleet size with equal annual procurements when the lifetime is 7½ years and the accidental loss rate is 1.3 percent/month[2] (15.6 percent/year), the annual procurement required is 22 percent of the fleet size.

3. Unless significant reduction in costs of overhaul and increase in quality of product relative to M38-series overhaul can be brought about, overhauled M151's will cost more and perform less well than new M151's in the long run.

4. M151 breakdown rate and unscheduled maintenance costs double by 20,000 miles and quadruple by 50,000 miles.

5. The cost of unscheduled maintenance per 100 miles for the M151 increases with vehicle age (see the accompanying tabulation).

Age, miles	Cost, dollars
New	2.00
10,000	3.20
25,000	5.80
40,000	7.00
60,000	7.70

Of these costs, 61 percent represents SSI, 26 percent is for parts costed to account for the recoverable value of reparables, and the remaining 13 percent is maintenance labor.

6. For the M151 the average per-mile cost of acquisition and unscheduled maintenance is $0.16 for a 25,000-mile replacement cycle, $0.13 for a 40,000-mile cycle, and $0.115 for a 60,000-mile cycle.

7. M151 nonavailability—the time out of service while the vehicle is broken down—does not rise above 5 percent during the first 50,000 miles of life.

8. The average miles traveled per replacement of any of 10 major parts decreases as M151's age (see the accompanying tabulation).

Age, miles	Miles traveled per replacement action
New	16,000
10,000	9,000
25,000	5,500
40,000	4,000
60,000	3,500

9. As M151's age there is an increase in the average number of vehicles available to start but unable to complete a 500-mile movement without needing the replacement of at least 1 of 10 major parts (see the accompanying tabulation).

Age, miles	Vehicles per 100
New	4
10,000	7
25,000	11
40,000	14
60,000	16

10. The average response times required by the support system to make significant parts replacements on M151's were as follows:

a. 2.3 days for any of 21 parts causing significant vehicle impairment when defective

b. 3.9 days for any of 10 major parts causing vehicle immobilization when defective

c. 6.5 days for major assemblies replaced at third echelon

11. The average cost of a maintenance response to an unscheduled M151 demand for support was $27.33.

12. Replacement engines and transmissions give significantly less reliable performance than the original assemblies in early life.

Recommendations

1. M151's should be replaced at 50,000 miles. When performance is especially important earlier replacement should be considered.
2. The current Army policy not to rebuild ¼-ton trucks should be extended to the M151 fleet.
3. The Army should further investigate the performance of replacement engines and transmissions.
4. Rates of vehicle use should be monitored at theater or Army area level as measures of the rate at which vehicle lifetimes are being consumed.

Aging and Lifetime of the M151 ¼-ton Truck

GLOSSARY

adjustment. Bringing into proper relation.
age. Accumulated time or miles in service.
availability. Probability that a vehicle is operable.
availability potential. Probability that a vehicle will be operable after it has been experiencing its current breakdown rate and support-system response time for an indefinitely long period.
breakdown. Transition from operability to inoperability.
degraded. Having lower performance and higher maintenance cost as a function of vehicle age than the like-original.
detail sample. Portion of M151 sample for which all maintenance actions and all repair-parts requisitions made at organizational level were included in the study data; for the rest of the sample fewer organizational data were collected.
downtime. Time between breakdown and return to operability.
equilibrium. A stage of vehicle life characterized by constant vehicle breakdown rate and maintenance costs even though the vehicle is getting older.
hard-core part. Any one of 10 prime mobility parts usually representing a vehicle disability as distinguished from a significant vehicle impairment.
lifetime. The period between issue and replacement; also, the duration of the period.
like original. Having the same performance and costs as a function of vehicle age as the part on the vehicle when issued new.
mission-success index. The product of availability potential and reliability; hence, the probability that a vehicle having been experiencing its current breakdown rate and support-system response time for an indefinitely long time is able both to start a mission of specified duration and content and to complete it with specified success.
performance. Breakdown rate, reliability, availability, mission-success index.
prime mobility. Very important to mobility; represents a significantly impaired vehicle when defective.
reliability. Probability that a vehicle able to start a mission of specified duration and content can complete it with specified success.
replacement. Substitution of one part for another.
replacement action. Simultaneous replacement of parts of the same name (e.g., three spark plugs).
replacement job. Replacement action.
response time. The time required by the support system to satisfactorily fill a demand placed on it.
support system. The supply and maintenance organization and resources.

ABBREVIATIONS

APC	armored personnel carrier
DCSLOG	Deputy Chief of Staff for Logistics
DX	direct exchange
FSN	Federal stock number
FY	fiscal year
MOS	military occupational specialty
QMR	qualitative materiel requirement
ROAD	Reorganization Objective Army Divisions
SSI	stock, store, and issue
TAERS	The Army Equipment Records System
USAREUR	US Army, Europe
USCONARC	US Continental Army Command

Chapter 1

INTRODUCTION

BACKGROUND

Past ORO/RAC studies[1, 3–5] have shown that vehicles perform less reliably and cost more to maintain as they age. Furthermore, this aging occurs in a dynamic technological environment, which seems almost continuously able to produce a vehicle today superior to the one it produced yesterday.

Such circumstances have inspired interest among vehicle fleet managers in determining optimum lifetimes for vehicles. Lifetime in this instance has a different meaning from the common one, which applies to biological organisms and refers to their period of life. Biological life ends irrevocably. Probably no motor vehicle built has naturally experienced the end of a lifetime in the sense that it could not be restored to an operable state by the investment of finite effort. The question of vehicle lifetime is whether there is a point in vehicle life when the fleet role might be better filled by replacing a current fleet member with another vehicle, possibly a new model. ("Better" usually implies less cost, more performance, or an improved combination of cost and performance.)

In industry such a lifetime may be determined by comparing the monetary cost and return of keeping a current vehicle with the cost and return of replacing it, and doing what gives the greatest net return. If a point is reached at which replacement is preferred, a lifetime has been determined.

In the Army the situation is complicated in two ways: (a) the "return" of having a vehicle is not measurable in monetary terms and (b) even if it were, the goal may not be to maximize the net monetary return. The net return to be maximized may be national security, which may be best accomplished by managing the military vehicle sector in a way that does not maximize monetary value. Although this subject is not covered in this study, the findings of the study should be helpful to decision makers concerned with this type of problem.

The first complication results in the necessity to define a nonmonetary measure of return. Furthermore, different types of military activity may require different units for measuring return, and these may have to be compared with each other. In such comparisons, judgments that assign military values to various levels of return and then weigh military values of return against monetary values of costs must eventually be made. These value judgments are discussed in the last chapter of this memorandum.

All the other chapters consist of analyses of M151 performance and cost data and their implications in the determination of effective lifetime.

THE M151 TRUCK

Description and Role

The subject of this study is the M151 ¼-ton utility 4 × 4 truck [Federal stock number (FSN) 2520-542-4783]. According to the operator's manual[6] the M151 was ". . .designed as a general-purpose personnel or cargo carrier, for use over all types of roads as well as cross-country terrain, and in all weather conditions." According to "Principles of Automotive Vehicles,"[7] "General-purpose vehicles are motor vehicles designed to be used interchangeably for movement of personnel, supplies, ammunition, or equipment. . . and used without modification to body or chassis to satisfy general automotive transport needs."

The M151 is the most recent in a series of similar vehicles all designed to fill the same role. The predecessor of the M151 was the M38A1 ¼-ton truck. According to the project card kept in control of the development of the M151,[8] a requirement existed ". . . for a ¼-ton 4 × 4 utility truck of improved design, reduced weight, and better performance." The object of the development was "to provide a vehicle in the ¼-ton utility class of improved design, light weight, and low cost to replace the present standard ¼-ton truck (the M38A1)." In the May 1964 Army Materiel Plan[2] the M151 is described as having ". . . less weight and improved performance over the M38-series trucks." The successor to the M151 is only in the planning stage, but in its proposed qualitative materiel requirement (QMR)[9] it is described as "an austere and low-cost personnel and weapons carrier with a rated payload of ¼ ton." Under the heading "Reasons for Requirement" it is stated that ". . . [the] DA [Department of the Army] directed that a QMR be developed for a new ¼-ton truck with sheer useful functionalism. In this QMR the focus should be on simplicity, durability, ease of operation and maintenance, and reduced cost in relation to the M151."[9]

In a recent RAC study[9] of the proposed QMR for the vehicle scheduled to replace the M151, the third conclusion is: "The vehicle determined to be most suitable by this study does not differ greatly from the present M151."

Fleet Size

The current active Army inventory of ¼-ton trucks is about 30,000. As of the end of September 1964 about 16,000 of these were M151's and none of them were more than 4 years old.

APPROACH

The aging rates and lifetime derived in this study apply to vehicles issued new and maintained at support echelon and lower. Thus rebuild is not a part of the maintenance accounted for. The desirability of rebuild is considered from a cost point of view in App C and more generally in Chap. 6, but in both cases rebuild is treated as the end of the new life and the beginning of a rebuilt life. The major results of the study apply to vehicles issued new and subjected to maintenance short of rebuild.

The unit of return of M151's was established as a mile of movement. The quality of a mile was described by the probability that it could be begun when it was needed (availability) and the probability that once begun it could be completed without breakdown (reliability).

Costs considered were initial price and costs of unscheduled maintenance. Costs of scheduled maintenance and fuel were assumed to be constant throughout vehicle life, and therefore not influencing life. (Of course this assumption is valid only if replacement vehicles have the same scheduled maintenance and fuel costs as M151's, but the lifetime analysis was confined to such a situation, primarily for reasons set forth in App C in the discussion of "role life.")

The study gathered data that described M151 ¼-ton truck field performance in terms of reliability, availability, and resource consumption for a range of truck ages sufficient to indicate the effects of aging on performance. Because resource consumption and availability directly involve the maintenance support environment, data on support-system response to M151 truck maintenance demands were also collected. Since accumulated usage was regarded as the most sensitive single measure of vehicle age, usage data were of particular interest to the study.

The basic data elements from which reliability, availability, and resource consumption of vehicles may be derived are vehicle-breakdown rate, time required by the support system to restore the broken-down vehicle to operability, and resources expended in the restoration effort. The basic data contributing to each vehicle characteristic are shown in Table 1. As can be seen, breakdown rate is of fundamental importance. It is both the rate at which the vehicle falls out of operability and the rate at which it demands expenditures of skilled man-hours, tool-hours, and parts; it is the tempo of vehicle troublemaking.

TABLE 1

Relations between Data Elements and Vehicle Characteristics

Basic data	Vehicle characteristic		
	Reliability	Availability	Resource consumption
Breakdown rate	X	X	X
Restoration time	—	X	—
Restoration resource expenditure	—	—	X

Because the cost of maintenance and vehicle availability depend not only on the vehicle itself but also on the efficiency and quickness of response of the support system, costs and downtimes characteristic of M151 maintenance were made the subject of a separate chapter, Chap. 2.

In Chap. 3 the performance of engines and transmissions is given special attention because of their importance to the quality and cost of vehicle performance, and as examples for introducing and demonstrating the idea of equilibrium performance, used subsequently in projecting vehicle performance and costs beyond the data.

Chapter 4 discusses the effects of vehicle age on vehicle performance in terms of breakdown rate, reliability, availability, and mission-success index (a combination of reliability and availability).

Chapter 5 discusses the influence of vehicle aging on maintenance expenditures in terms of maintenance labor man-hours, maintenance labor costs, parts costs, and SSI.

In Chap. 6 the determination of vehicle lifetime is described in detail, using the analyses and projections contained in Chaps. 2 to 5.

The results derived are averages for the sample observed. The performance and costs of individual vehicles may of course be higher or lower than the averages.

DATA

The basic data collected were records of monthly miles of operation and maintenance performed on 772 M151 ¼-ton trucks in Seventh Army, US Army, Europe (USAREUR), between 1 Sep 61 and 30 Sep 63. These data were collected by study members from existing Army records including vehicle logbooks, the predecessor Organizational Equipment Files (DA Form 478's), and Field Maintenance Job Orders (DA Form 811's). For 617 of these M151's, maintenance actions (excluding lubrication) were recorded only for the group of selected parts shown in Table 2. For the remaining 155 vehicles, more detailed information was obtained. For this subsample, additional supply data were gathered from organizational requisition registers, and maintenance actions were recorded for all parts.

Vehicle Sample

Source. All 772 vehicles observed were observed from time of initial issue, all were observed in USAREUR, and all were manufactured by the Ford Motor Company. Their Army registration numbers range from 2B6566 to 2D2855; they were preponderantly B and C (about evenly divided).

The sample was stratified to represent M151 operations in armored divisions, infantry divisions, and armored cavalry regiments as shown in Table 3. No attempt was made to make the size of the strata proportional to their size in the USAREUR or worldwide fleets.

Size. As shown in Table 3, the sample of vehicle life studied had two dimensions—the number of vehicles and the mileage span covered. The effects on vehicle life of other factors—climate, terrain, mission, driver competence—were not specifically studied, and so were not isolated as the additional dimensions of the sample that they are.

Figure 1 shows how the study sample of M151's compares with the total M151 population of 30 Sep 64 in terms of size, age, and theater. The theater distributions were taken from the Hi-Five Summary of November 1964.[10]

Appendix A discusses the adequacy of the sample. In summary it is believed to be satisfactory to approximately 19,000 miles, where it drops below

100 vehicles. Beyond 25,000 miles the sample size is essentially 0, and therefore furnishes a foreshortened view of M151 aging. As a result there is only a little information about the performance of replacement assemblies and some

TABLE 2

M151 Parts for Which Maintenance Activity Was Recorded for All Vehicles

Nomenclature	FSN
Arm assembly	
Front suspension, upper	2530-678-3122
Front suspension, lower	2530-678-3118
Arm and shaft assembly, rocker	2805-678-3182
Battery	6140-057-2553
Bearing, roller, tapered	3110-678-1863
Belt, V, generator	3030-681-1486
Carburetor	2910-678-1857
Clutch	
Parts kit	2520-887-1353
Bearing, thrust	3110-158-6196
Disk	2520-678-1343
Plate, pressure	2520-678-1346
Coil, ignition	2920-424-0371
Cylinder assembly (brake master cylinder)	2530-678-3077
Differential	2720-678-3123
Distributor	2920-678-1399
Engine	2805-678-1820
Gear, steering	2530-678-1809
Generator	2920-314-0556
Hose, fuel line	2910-770-1543
Prop shaft	
Front	2520-678-3072
Rear	2520-678-3073
Pump	
Fuel	2910-678-1856
Oil	2805-678-1387
Water	2930-678-1849
Radiator	2920-678-3232
Regulator generator	2920-540-9476
Shock absorber	
Rear	2540-678-2978
Front	2540-678-2996
Spark plug	2920-752-4258
Starter	2920-678-1850
Tire	2610-678-1363
Transmission and transfer assembly	2520-678-1808

uncertainty of probable replacement times of the original parts that were still intact at 20,000 miles. Only after the vehicles are operated several more years will these data be available. Since fleet managers must make replacement decisions before the fleet actually is degraded to an unacceptable condition, this study has used data now available as a reasonable basis for analysis and projection.

Vehicle Usage Rate. The average usage rate of the sample was 756 miles/month and was distributed as shown in Fig. 2. Since the rate for the total USAREUR fleet was about 550 miles/month,[11] the sample was an atypically active portion of the M151 USAREUR fleet.

Segmentation. It was necessary for the analysis to consider the data gathered as representing four samples, each having a different degree of data

TABLE 3

Average Months in Service, Miles per Month, and Total Miles Traveled of the M151 Sample

(30 Sep 63)

Organization	Vehicles	Average		
		Months in service	Miles per month	Total miles
3d Armd Div	207	18	781	14,056
3/33 Arm	26	22	655	14,415
3/12 Cav	68	15	755	11,332
2/32 Arm	20	21	803	16,859
1/33 Arm[a]	19	19	779	14,806
1/48 Inf[a]	10	17	886	15,064
2/48 Inf[a]	34	19	853	16,206
4th Armd Div	116	18	687	12,361
2/15 Cav	37	21	592	12,441
2/35 Arm	17	18	798	14,364
1/37 Arm	11	17	734	12,479
2/51 Inf	18	15	732	10,984
4/35 Arm	13	18	738	13,286
2/37 Arm[a]	20	15	739	11,087
24th Inf Div	167	20	718	14,360
3d Brigade HQ	11	17	617	10,497
1/19 Inf	13	23	736	16,933
1/21 Inf	30	23	689	15,850
2/21 Inf	27	23	722	16,606
1/34 Inf	31	17	698	11,866
3/19 Inf[a]	42	18	673	12,116
2/34 Inf	13	24	840	20,[illegible]55
2d Armd Cav Regt	167	17	785	13,345
1/2 Armd Cav	59	19	769	14,610
2/2 Armd Cav	65	18	662	11,913
3/2 Armd Cav	63	16	878	14,041
14th Armd Cav Regt	115	16	832	13,312
1/14 Armd Cav	62	17	793	13,474
2/14 Armd Cav	53	16	820	13,123
Total average USAREUR	772	18	756	13,603

[a]The 155 vehicles of the detail sample.

completeness. In the first place the decision of the study to collect all recorded maintenance data for 155 of the vehicles and only selected data for the remaining 617 vehicles immediately created two samples with different degrees of data completeness. In addition a new and more detailed maintenance reporting system [The Army Equipment Records System (TAERS)] was installed in the

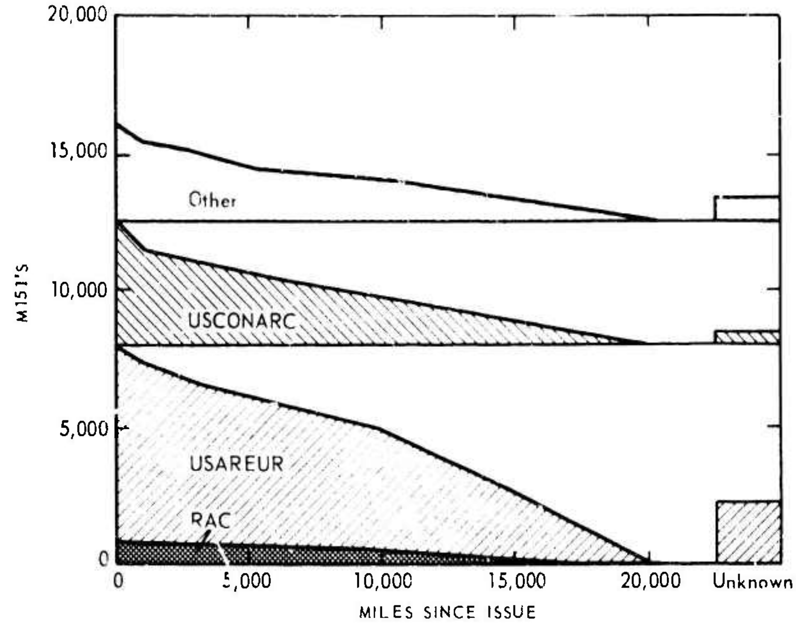


Fig. 1—M151 Sample as of 30 Sep 63 Compared with Total Active Population of Army as of 30 Sep 64

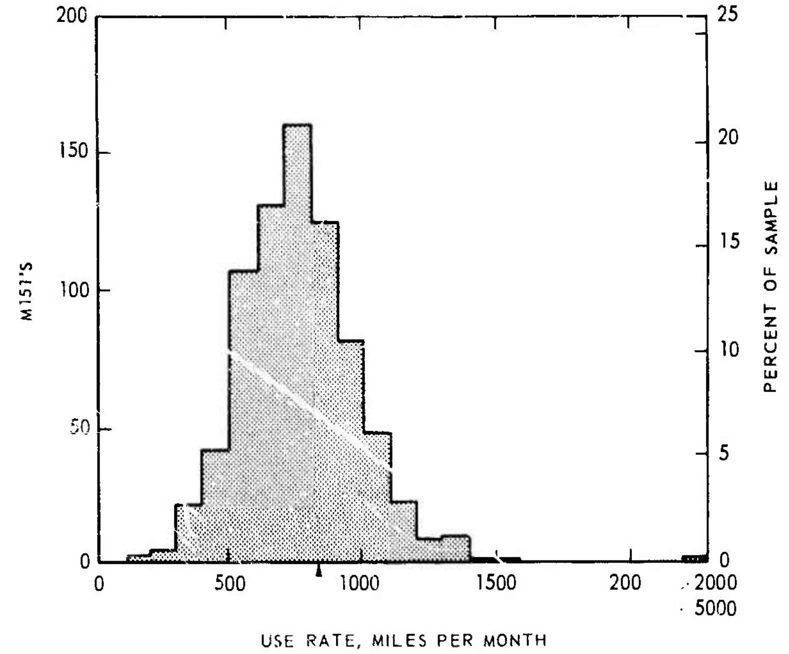


Fig. 2—Use-Rate Distribution of the Vehicle Sample
Sample: 772 vehicles, ▲ Mean: 756 miles/month.

Army while the study was in progress. This innovation meant that each of the RAC-created samples was subdivided into two pieces: a piece for which only those maintenance actions included in the old recording system were recorded, and a subsequent piece for which the more complete records required by the new TAERS system were available. A further complication was that both the M151's and the TAERS system were introduced to different units at different times. Figures 3 and 4 show the mileage and calendar-age distributions of the total sample and the portion of it covered by TAERS. Figure 5 shows a mileage distribution of the smaller intensively studied sample of 155 vehicles and the portion of it covered by TAERS.

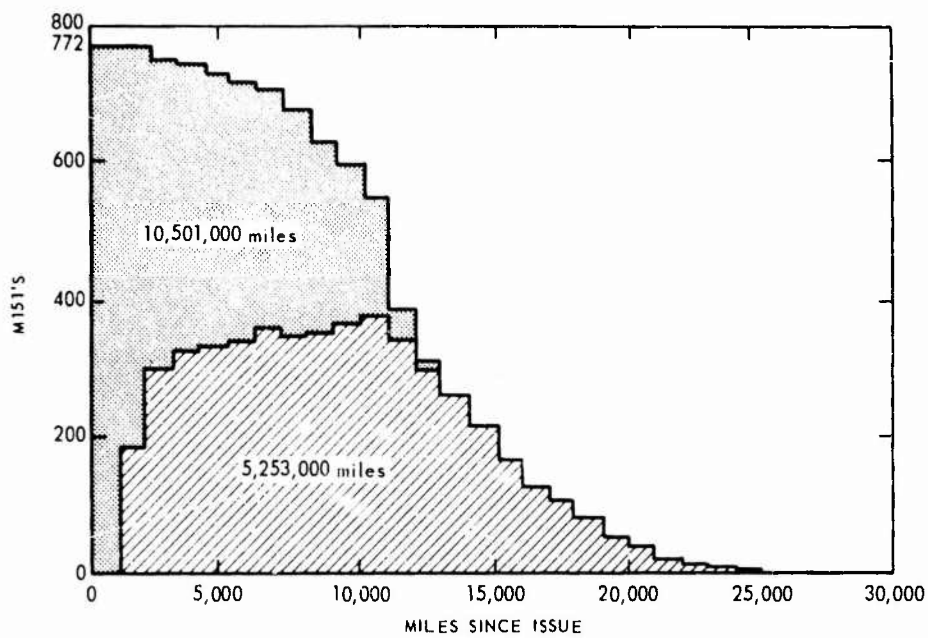


Fig. 3—Observed Sample of M151 Life as Distributed in Vehicle Mileage

Totol somple   Sample covered by TAERS

Vehicle Performance Data

Maintenance Data. Maintenance data took the basic form: maintenance event x was experienced by vehicle number y on date z when the vehicle was s miles old. A maintenance event was the adjustment, repair, or replacement of one or more parts, or a scheduled semiannual maintenance check and lubrication. For maintenance events occurring at third echelon (direct-support field maintenance) three dates concerning the event were available: the date work was requested, the date it began, and the date it was completed. For maintenance events occurring at second or organizational echelon (battalion and company maintenance) the only date available was the date work was finished. At both echelons man-hours expended per maintenance event were available. Data on the skill level or military occupational specialty (MOS) of the man-hours expended and on the numbers and kinds of tool-hours expended per

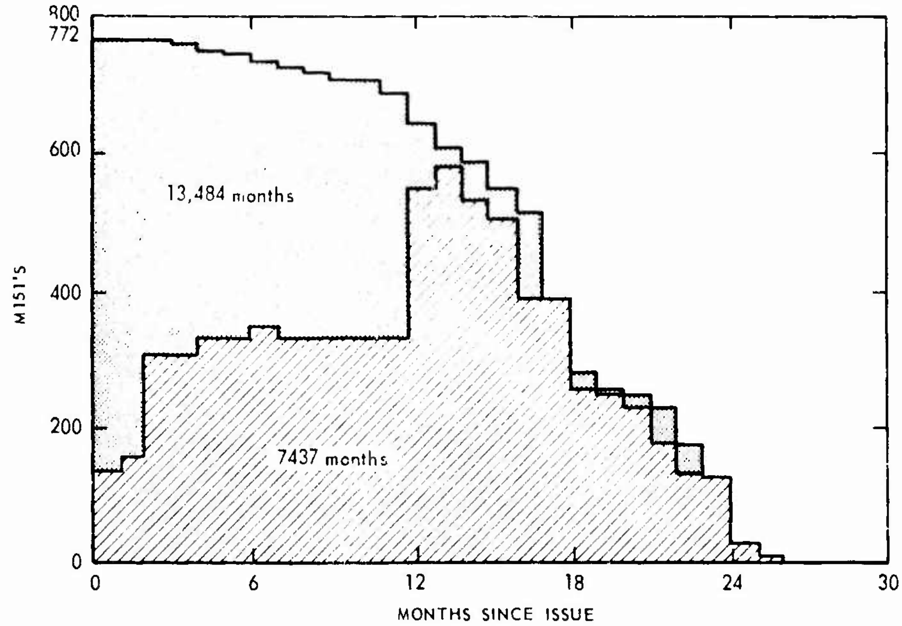


Fig. 4—Observed Sample of M151 Life as Distributed in Vehicle Calendar Age

Total sample   Sample covered by TAERS

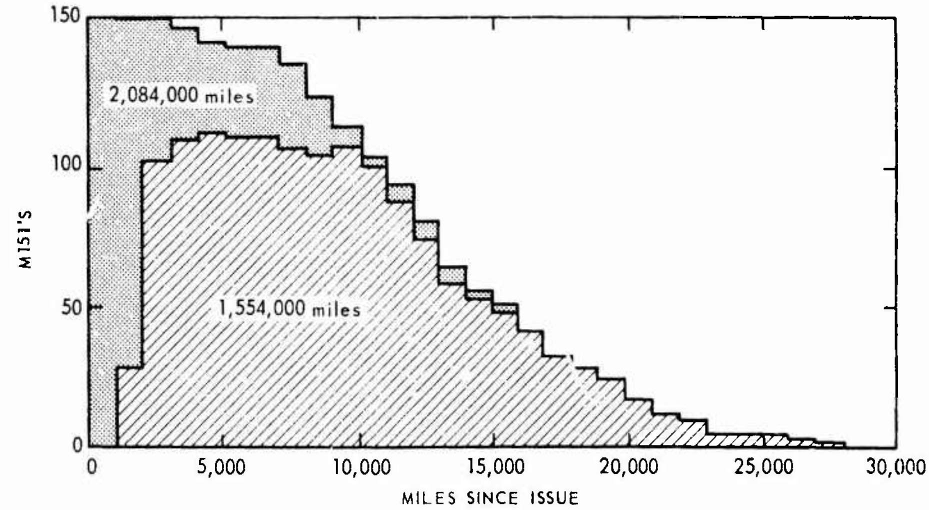


Fig. 5—Sample of 155 M151's Observed in Detail as Distributed in Vehicle Mileage

Total detail sample   Detail sample covered by TAERS maintenance event were not readily available. In general there was no indication whether a maintenance action performed was preventive or restorative although actions performed on specific parts during scheduled checks were probably preponderantly preventive.

Repair-Parts Data. Data on repair-parts usage are recorded on requisition registers at organizational level. Each requisition shows the part requisitioned, the quantity of it requisitioned, the date on which the requisition was made, and the date on which it was filled. Except in cases where large quantities of an item were requisitioned in support of all or many vehicles of the organization, the vehicle for which the part was requisitioned was also identified. These data provided a source of parts-consumption data in addition to that recorded in the vehicle logbooks.

Operational Data. Operational data took the form of end-of-month odometer readings or miles accumulated during the month for each vehicle.

Chapter 2

SUPPORT-SYSTEM RESPONSE TO M151 MAINTENANCE DEMANDS

INTRODUCTION

Support-system response to equipment maintenance demands directly influences equipment lifetime in two ways: (a) the efficiency of the response directly affects the expense of the response and hence the expense of having the equipment and (b) speed of the response directly affects equipment readiness.

This chapter discusses the response of the support system to repair demands placed on it by M151 ¼-ton trucks. The purpose of the chapter is to develop and present only the two factors that directly affect the lifetime of the M151: resources expended per support action and vehicle downtime per support action. The analysis covers only unscheduled demands for maintenance met at second and third echelons and the time required to fill repair-parts requisitions made at second echelon.

RESOURCE CONSUMPTION

Resources accounted for in this discussion include direct and supervisory maintenance man-hours; repair parts; and dollars expended in the procurement, supply, and distribution of parts (SSI). Maintenance tools and plant are not considered, nor are training costs and other support expenses associated with personnel.

Maintenance

Maintenance is the set of actions taken to correct or preclude equipment deficiencies. Only adjustments, repairs, and replacements of vehicle components and parts are discussed; inspections, washings, and lubrications are not included.

The data base for this section of the analysis consists of all known recorded maintenance events for the 155 vehicles covered in detail by TAERS. A total of 2243 maintenance actions were recorded for this sample of M151 vehicles. A breakdown of these actions according to echelon and type of action is shown in Table 4.

Man-hours. Since available data frequently did not show the number of man-hours expended on a given maintenance action, the sample of maintenance

TABLE 4

Sample of Maintenance Actions from which Support-System Maintenance Response to M151 Demands Was Determined

Type of action	Echelon		
	Second	Third	Both
Adjustment	325	10	335
Repair	177	28	205
Replacement	1548	155	1703
Total	2050	193	2243

TABLE 5

Actions Sample for Which Man-Hour Consumption Was Known

Type of action	Echelon		
	Second	Third	Both
Adjustment	79	10	89
Repair	73	20	93
Replacement	467	122	589
Total	619	152	771

TABLE 6

Mean Man-Hour Consumption per Maintenance Action, by Echelon of Maintenance and Type of Action

Type of action	Echelon		
	Second	Third	Both (weighted average)
Adjustment	0.87	2.80	0.93
Repair	1.25	2.80	1.46
Replacement	1.39	4.67	1.69
Total (weighted average)	1.34	4.30	1.55

actions shown in Table 5 is smaller than that in Table 4. The effect of this sample shrinkage on the analysis is presumed small; it is described further in App A.

To compute the average man-hours per maintenance action the number of actions shown in Table 5 was divided into the total number of man-hours consumed for each action type. The results of this calculation are shown in Table 6.

The distributions of man-hours consumption per maintenance action are shown in Figs. 6 and 7. These figures show that most of the actions consumed fewer man-hours than the averages taken from Table 6 and are indicated by

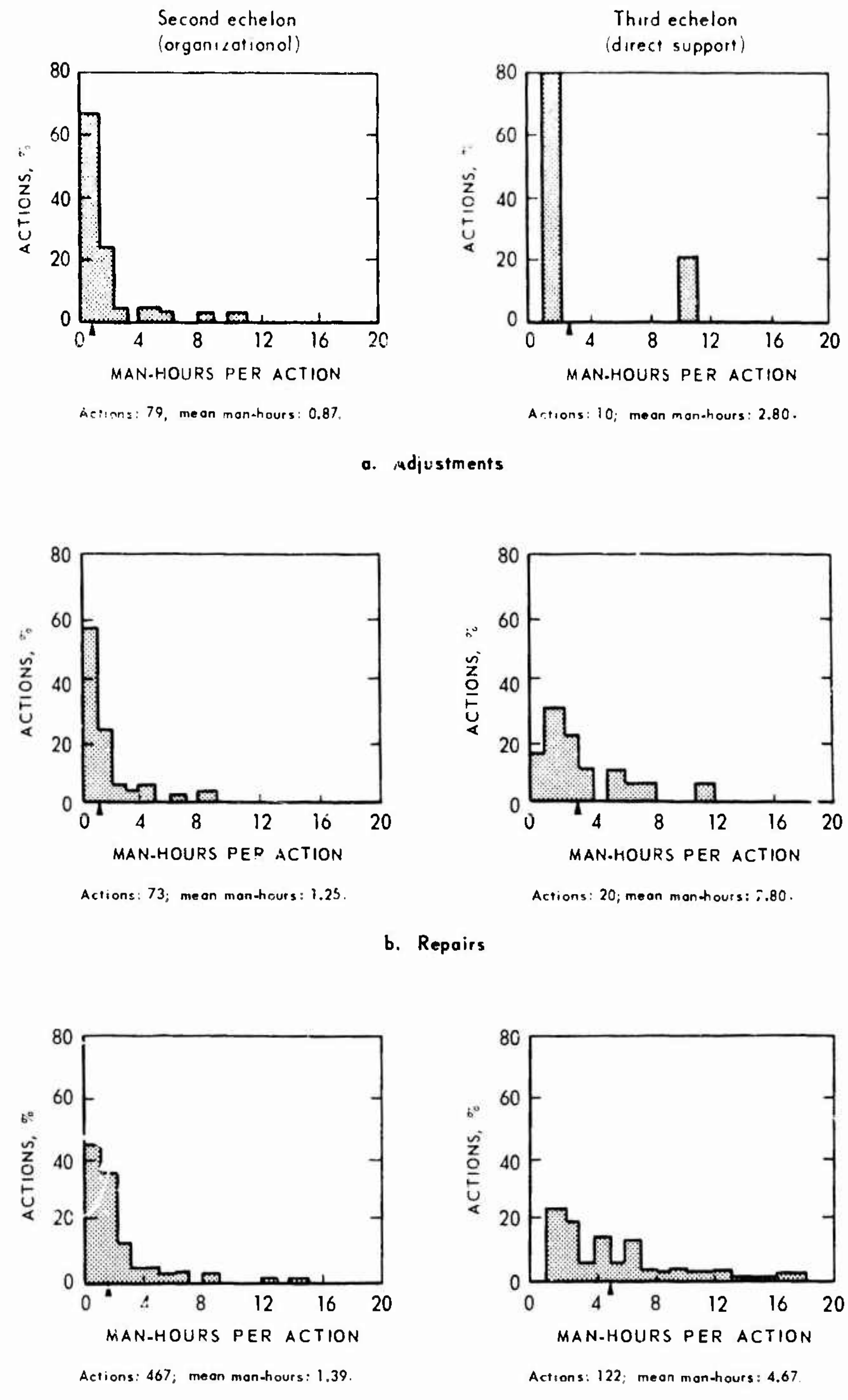
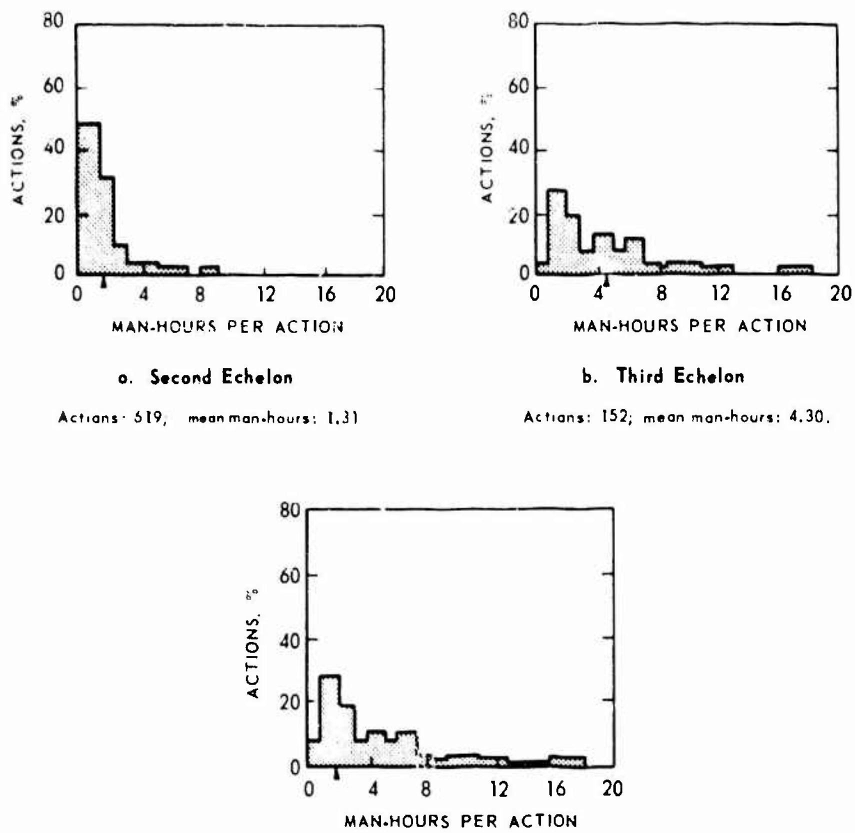


Fig. 6—Distributions of Man-Hours per Maintenance Action Expended on M151 ¼-ton Trucks by Organizational and Direct-Support Maintenance



a. Second Echelon

Actions: 619; mean man-hours: 1.31

b. Third Echelon

Actions: 152; mean man-hours: 4.30.

c. Both Echelons

Actions: 771; mean man-hours: 1.90

Fig. 7—Distributions of Man-Hours per Maintenance Action for All Actions

fiducial marks on Figs. 6 and 7. At second echelon the grouping to the left was marked. Ninety-one percent of unscheduled second-echelon actions consumed less than 4 man-hours, almost 50 percent less than 1 hr. At third echelon the distribution was broader. Fifty-two percent of the actions consumed less than 4 man-hours, only 2 percent less than 1.

Cost of Man-Hours. Man-hour expenditures were costed in two different ways. First, since the man-hours reflected in Table 6 were direct man-hours (man-hours expended by mechanics and mechanics' helpers), they were costed at the rate of \$1.80 per hr in both second and third echelons. The \$1.80 rate is the weighted mean for all maintenance personnel of grade E-5 and lower in the maintenance organizations that support vehicles in armored and mechanized infantry divisions under the Reorganization Objective Army Divisions (ROAD) organization.[12–15] Although each echelon was analyzed separately the rates were \$1.80 in both cases. The hourly rates used in the calculation were taken from AR 35-247.[16] Table 7 contains the hours of Table 6 costed at \$1.80 per hour.

A second costing of this labor was made by incorporating a cost for supervision. This was done by inflating the man-hours of Table 6 by 15 percent, an inflation that assumed an organizational pyramid based on a ratio of 1 supervisor to 7 to 8 supervisees at every level. (This supervisor-to-supervisee ratio was indicated by an analysis of the staffing pattern of two large maintenance battalions. The ratio can be expressed as follows: number of personnel of grade E-6 and up divided by number of personnel of grade E-5 and down. For the maintenance battalion furnishing direct support to the ROAD armored division[14] this ratio is 14.5 percent; for the battalion supporting a mechanized infantry division[12] the ratio is 15.1 percent.)

TABLE 7

Costs of Direct-Maintenance Labor per Maintenance Action

(In dollars)

Type of action	Echelon		
	Second	Third	Both (weighted average)
Adjustment	1.57	5.04	1.67
Repair	2.25	5.04	2.63
Replacement	2.50	8.44	3.04
Total (weighted average)	2.36	7.74	2.59

TABLE 8

Costs of Maintenance Labor, Including Supervision, per Maintenance Action

(In dollars)

Type of action	Echelon		
	Second	Third	Both (weighted average)
Adjustment	1.96	6.44	2.09
Repair	2.81	6.44	3.30
Replacement	3.12	10.74	3.81
Total (weighted average)	2.93	9.89	3.53

Based on the rates shown in AR 35-247,[16] the mean cost per second-echelon man-hour considering all maintenance personnel in second echelon (supervisors as well as mechanics) was found to be $1.95. For third echelon the cost was found to be $2 per man-hour. Table 8 shows the cost of labor per maintenance action when the man-hours shown in Table 6 are inflated by 15 percent and then multiplied by these man-hour labor costs.

Supply

Parts. The cost of parts consumed was determined for each maintenance action in Table 5 by costing parts at their list prices taken from Army manuals.[17] The mean cost of parts replaced per second-echelon replacement action was found to be $9.50. For third-echelon replacement actions a mean cost of $95 was found. The weighted mean for both echelons was about $17 per replacement action. Table 9 summarizes these results.

TABLE 9

List Cost of Parts per Replacement Action

Echelon	List cost, dollars
Second	9.50
Third	95.00
Both (weighted average)	17.00

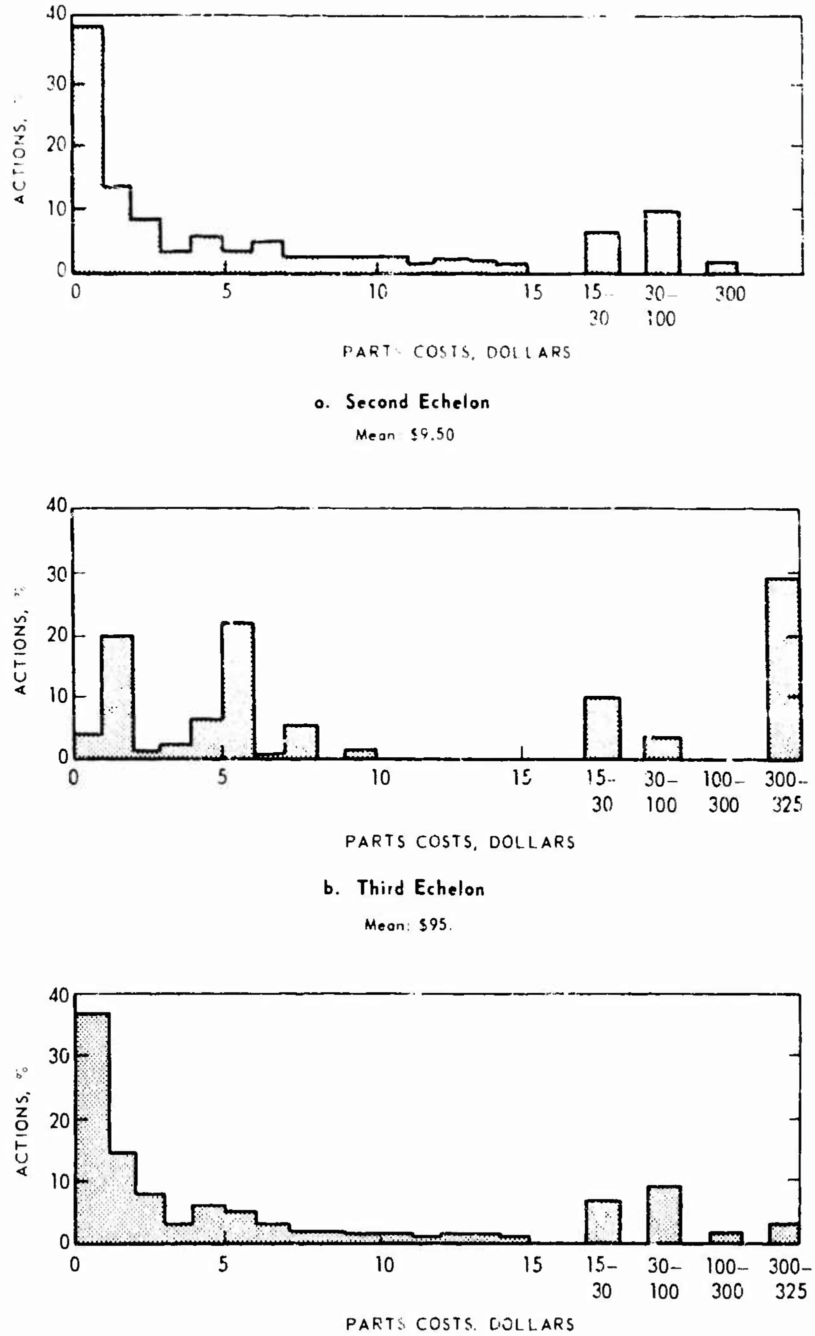
Figure 8 shows the distribution of these costs for each echelon and then for both echelons combined. Sixty-eight percent of second-echelon replacement actions consumed less than $5 of parts, though a few cost more than $100. The very-high-cost second-echelon replacement action usually involved the replacement of tires. At third echelon 30 percent of the replacement actions consumed less than $5 of parts, another 30 percent between $5 and $10, and almost 30 percent between $300 and $325. The latter were all engine or transmission replacements charged at list price. Thirteen percent of third-echelon replacement actions had parts costs scattered between $15 and $100; none fell between $100 and $300.

A second cost of parts was developed in which the following major reparable items were costed at 30 percent of list price:

Engine	Generator
Transmission	Carburetor
Differential	Fuel pump
Distributor	Radiator
Battery	Water pump
Starter	Tire

Thirty percent is the accounting value generally used by the Army to reflect the cost of returning reparable items to serviceable condition. (A previous RAC study[1] showed that rebuild costs of 18 M38 direct-exchange (DX) items averaged 26 percent of their list price.) Since a large number of replacements of the items listed are or will be rebuilt rather than new, the resulting parts costs per replacement action shown in Table 10 are probably a more reasonable measure of parts costs than are the full list costs shown in Table 9.

Indirect Costs. No study of indirect costs of supply was undertaken as part of this study. However, such a study was previously conducted for the support of M38-series ¼-ton trucks at Ft Knox.[1] The analysis accounted for procurement, storage, and distribution costs commonly referred to as SSI.



a. Second Echelon
Mean: $9.50

b. Third Echelon
Mean: $95.

c. At Either Second or Third Echelon
Mean: $17

Fig. 8—Distributions of Costs of Parts Consumed in Replacement Actions Performed on M151 ¼-ton Trucks

Costs are list prices of parts replaced.

The average cost of these activities was found to be 2.6 times the list price of the items supplied.

Another portion of the M38-series ¼-ton truck report dealt with the repair costs of reparable items. When the SSI factor is combined with the repair costs for reparable items, it was found that the average cost of all parts installed was 2.27 times the list price at organizational level and 1.37 times the list price at third echelon.

TABLE 10

Cost of Parts per Replacement Action, Assuming 30 Percent Rebuild Cost for DX Items

Echelon	Cost, dollars	Percent of list cost
Second	6.70	70.5
Third	24.30	36.1
Both (weighted average)	9.00	52.9

TABLE 11

Cost of Parts per Replacement Action Including SSI

Echelon	Cost, dollars
Second	21.50
Third	130.00
Both (weighted average)	31.00

Table 11 summarizes the results of applying these parts cost factors to the list price costs shown in Table 9.

Distribution of Maintenance Activity and Resource Consumption by Echelon

The distribution of maintenance activity and resource consumption between echelons is summarized in Table 12. Of the 2243 maintenance actions shown in Table 4, 91 percent were performed at second echelon and 9 percent at third. However, 24 percent of all the man-hours, 50 percent of the list-price dollar value of parts consumed, and 36 percent of the dollar value of all consumed support-system resources accounted for were consumed at third echelon.

TABLE 12

Distribution of Maintenance Actions and Support-System Resource Consumption between Echelons

Item	Distribution, %: Second echelon	Third echelon
Maintenance actions observed	91	9
Man-hours consumed	76	24
List-price value of parts consumed	50	50
Dollar value of all resources considered	64	36

Second-echelon maintenance accounts for ten times as many actions as third echelon but consumes less than twice as many maintenance dollars.

Summary

The two resources consumed by maintenance of the M151 ¼-ton truck are man-hours and supply resources. Supply resources include parts, supply-system manpower, and overhead. Parts costs used in the effective life calculation were based on list prices adjusted to take account of SSI and costs incurred during repair or rebuild of reparable DX items.

Table 8, which shows labor costs and Table 11, which shows adjusted parts costs, are combined in Table 13 to give the total dollar cost of support-system resources (excluding maintenance tools and plant and personnel support) consumed per maintenance action.

TABLE 13

Dollars Consumed in Parts, SSI, and Direct and Supervisory Labor per Maintenance Action

Type of action	Cost by echelon, dollars		
	Second	Third	Both (weighted average)
Adjustment	1.96	6.44	2.09
Repair	2.81	6.44	3.30
Replacement	21.62	140.74	34.81
Total (weighted average)	19.44	114.30	27.33

RESPONSE TIME

Introduction

"Response time" is the time that elapses between the communication of a demand for maintenance support and the satisfaction of that demand. The longer the time, the lower is the availability of a fleet of equipment.

Response time is affected by the efficiency with which the maintenance organizations allocate and employ their resources and the efficiency of the supply system in anticipating demands for parts and prepositioning the parts where they will be needed.

Downtime

Although 91 percent of all unscheduled maintenance actions studied in the previous section occurred at second echelon, response time was not recorded there. Not all such actions implied an immobilized vehicle, but many of them did, and the absence of data on how much time elapsed in returning the vehicle to operability for these actions constituted a research data gap. Deadline reports were of assistance, but because they are made only at 24-hr intervals many short jobs never appear on them. To fill this gap, an analysis was made

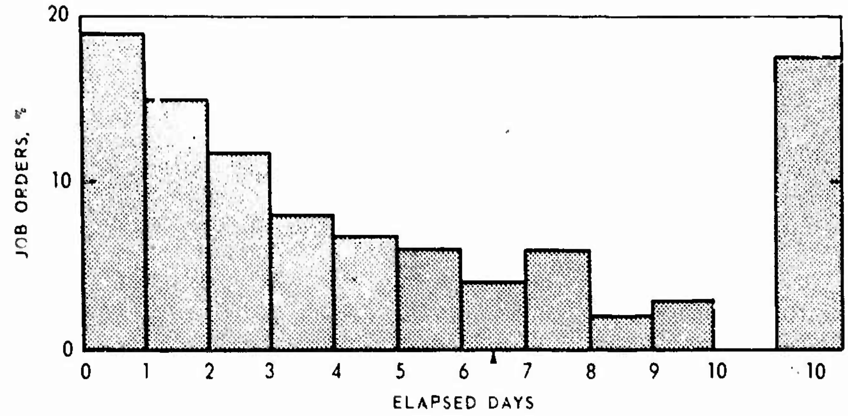
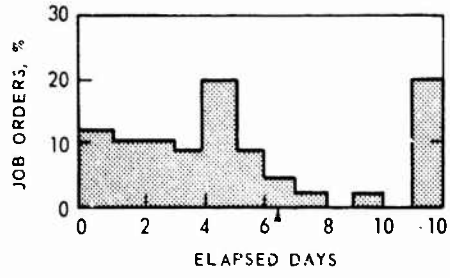


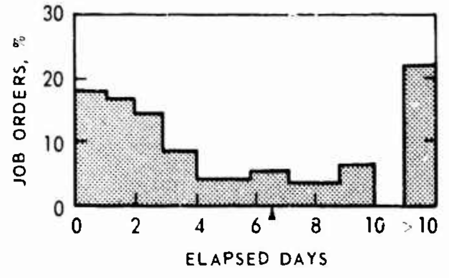
Fig. 9—Distribution of Third-Echelon Response Times to M151 ¼-ton Truck Demands for Maintenance

674 job orders; mean: 6.5 days job order.



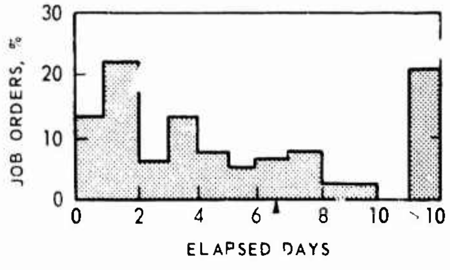
a. **Engine Replacements**

Job orders: 45; mean: 6.5.



b. **Transmission Replacements**

Job orders: 118; mean: 6.5.



c. **Clutch Replacements**

Job orders: 188; mean: 6.5.

Fig. 10—Distributions of Third-Echelon Response Times for Three M151 ¼-ton Truck Repair Job Orders

TABLE 14

Downtime for Replacements of Prime Mobility Parts

System	Part	Average downtime per replacement job, days	Jobs observed	Echelon	Downtime source
Power and propulsion	*Clutch[a]	6.5	101	3	FMJO[b]
	*Differential[a]	6.4	14	3	↓
	*Engine[a]	6.5	66	3	↓
	*Propeller shaft[a,c]	5.0	53	2	FMJO
	*Transmission[a]	6.5	138	3	DR[d]
Electrical	Battery	2.0	31	2	DR,E[e]
	Belt, generator	0.5	18		E
	Coil	0.5	10	2	DR,E
	Distributor	0.5	91	2	E
	Generator	1.2	90	2	DR,E
	Regulator, generator	1.0	96	2	E
	Spark plug	0.5	149	2	E
	Starter	1.5	12	2	DR,E
Suspension	Brake master cylinder	0.5	8	2	E
	*Suspension arm[a]	1.0	10	2	↓
	Tire	0.5	97	2	↓
	*Wheel bearing[a]	1.0	185	2	E
Fuel	Carburetor	1.5	75	2	DR,E
	*Fuel pump[a]	1.0	61	2	DR,E
Cooling	*Radiator[a]	3.2	101	3	FMJO
	*Water pump[a]	0.5	7	2	E
Vehicle weighted average		2.5	1418	—	—

[a]Hard-core parts—their weighted mean downtime is 3.9 days job.
[b]Field maintenance job orders.
[c]Only rear propeller shafts were counted as hard core; 20 of the 53 propeller-shaft replacement jobs observed were rear propeller-shaft jobs.
[d]Deadline report.
[e]Estimate.

by (a) selecting a group of maintenance actions that usually represent a seriously debilitated vehicle (the rationale of this selection is stated at length in Chap. 4) and (b) estimating mean response times for the selected actions performed at second echelon. Deadline reports and third-echelon downtimes were used as guides in making these estimates.

Third-echelon actions were fully documented with beginning date and ending date. For all third-echelon jobs performed on M151's in the total sample, the mean elapsed time between the request for work and the completion of the work was 6.5 days. The distribution about this mean is shown in Fig. 9. The mean response time for engine, transmission, and clutch replacements were all coincidentally 6.5 days; however, the distribution for each of these three jobs differs (see Fig. 10).

The availability and reliability analyses in this study were based on replacements of the prime mobility parts shown in Table 14. The table also shows the mean downtimes associated with each type of action and the source of the downtime information. The parts are grouped by vehicle system.

As is further explained in Chap. 4, some of the parts of Table 14 were designated as "hard-core prime mobility parts" on the basis that replacement of one of these parts would probably represent actual vehicle immobilization rather than mere vehicle impairment. The mean downtime per hard-core job was 3.9 days.

The estimated downtimes are regarded as conservative since they rely on the assumption that the necessary parts and maintenance resources are usually available to perform the jobs soon after they arise. The following discussion of supply-system response to requisitions for parts placed at organizational level suggests this assumption is optimistic with respect to parts.

Supply Performance

The data base of this discussion is about 2300 requisitions for M151 ¼-ton truck parts placed at organizational level in the units studied in detail during calendar year 1963. Times to fill these requisitions are shown in Fig. 11.

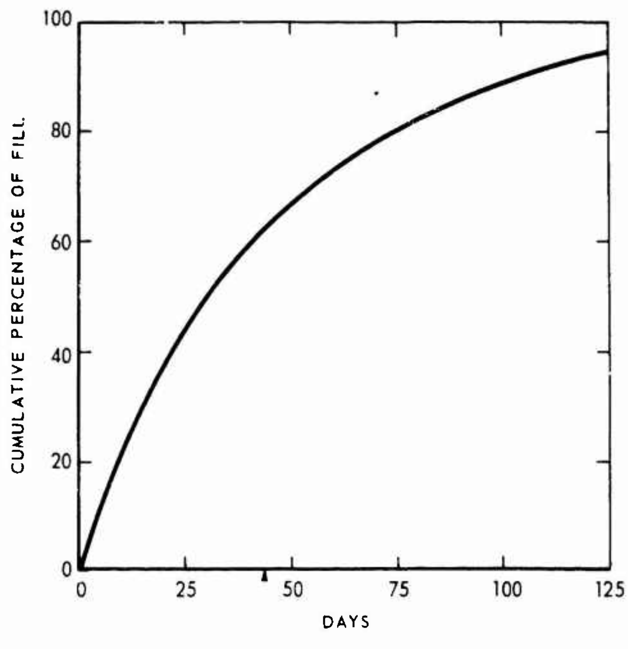


Fig. 11—Time To Fill Organizational Requisitions for M151 ¼-ton Truck Parts

Mean: 44 days.

The mean time to fill was 44 days. The curve shows that after 1 day less than 2 percent of the requisitions were filled, after 6 days less than 15 percent were filled, and a month was required to achieve a 50 percent fill. This curve varies very little among units, and is very similar to that for the tank or the armored personnel carrier (APC). The presence or absence of the requisitioned part on the stockage list seems to have essentially no effect on the curve of Fig. 11.

This problem is well known and is fully documented in RAC-TP-158.[20] The data presented here are intended to portray the problem only as it applies to M151 ¼-ton trucks and to emphasize it as a particularly disturbing aspect of support-system response to M151 demands.

Summary

Downtimes for critical second-echelon maintenance events were estimated with aid from deadline report information. The mean downtime per critical event was determined to be 2.5 days. For the hard-core prime mobility parts the mean downtime per event was 3.9 days. These estimates are presumed conservative because they are based on an assumption that repair parts are usually readily available. The possibly optimistic nature of this assumption is demonstrated by the finding that the supply system required a month to fill half the requisitions for M151 ¼-ton truck parts placed at organizational level.

Chapter 3

PERFORMANCE OF MAJOR ASSEMBLIES

INTRODUCTION

This chapter has two purposes: to discuss the performance of engines and transmissions as important aspects of M151 performance; and, using engines and transmissions as examples, to introduce and demonstrate the idea of performance equilibrium—an idea employed in Chaps. 4 and 5 in projecting M151 performance and maintenance costs.

Engines and transmissions are major assemblies in their cost, complexity, and essentiality to successful vehicle operation. This chapter presents their observed replacement rates as they vary with age, then projects these rates to estimate future rates; assembly mean lives are estimated. Since few data on the performance of replacement assemblies were available, the projections assumed that replacement assemblies perform the same as original assemblies.

In the last section of this chapter the available data on the performance of replacement assemblies are compared with the performance expected when they are assumed to perform the same as the originals.

DESCRIPTION[6]

The engine is a liquid-cooled 4-cylinder-in-line overhead-valve gasoline 71-hp engine. The transmission has four speeds,of which the top three are synchronized,and a torque rating of 120 ft-lb.

LIKE-ORIGINAL PERFORMANCE

Method

For each of the two assemblies the following analysis was conducted:

(a) A statistical distribution was fitted to the observed replacement rate of original assemblies. From this distribution it was possible to project the replacement rate of original assemblies and to estimate the mean and standard deviation of original assembly life.

(b) Assuming that replacement assemblies have the same replacement rate vs age as that projected for original assemblies (i.e., have "like-original" performance), replacement rates of second, third, and for transmissions, fourth assemblies were derived.

(c) A projection of the total replacement rate was derived by adding the projected rates for original assemblies and subsequent assemblies.

Finally, the replacement rate of the two assemblies combined was derived by adding their separate rates.

Engines

Observed Performance. The cumulative replacements of M151 engines observed during the study are shown in Fig. 12. By the end of the first 19,000 miles of vehicle life the total number of engines replaced amounted to just under 16 percent of the number of vehicles. However, this percentage does include some second replacements. The performance of the original engines

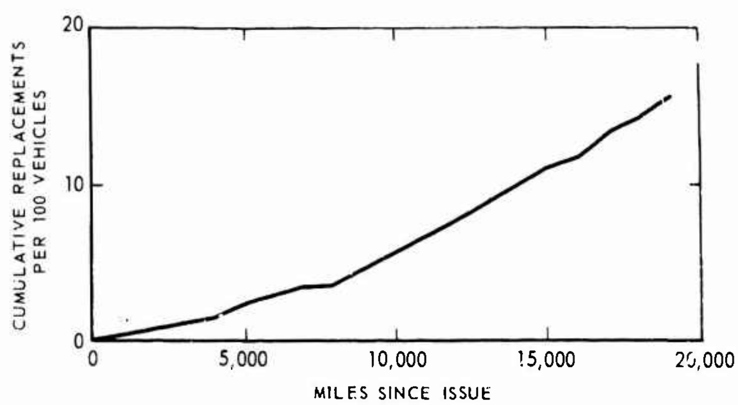


Fig. 12—Observed Cumulative Replacements of Engines

and their replacements is shown in Fig. 13. By the end of the first 19,000 miles of vehicle life 14 percent of the original engines had failed. The increasing slope of the curve indicates that replacements were occurring at an increasing rate. In particular, in the first 10,000 miles about 5.5 percent of the engines were replaced as compared with 8.5 percent in the next 10,000 miles—an increase of more than 50 percent.

Analysis. To project the replacement rate of original engines a statistical curve was fitted to the data. Figure 14 shows the portion of the curve corresponding to the age range covered by the data.

Figure 15 shows the statistical curve ("Original") extended to 80,000 miles. This constitutes a projection of the replacement rate of original engines. Engines replaced according to such a curve have a mean life of 51,400 miles with a standard deviation of 28,000 miles.

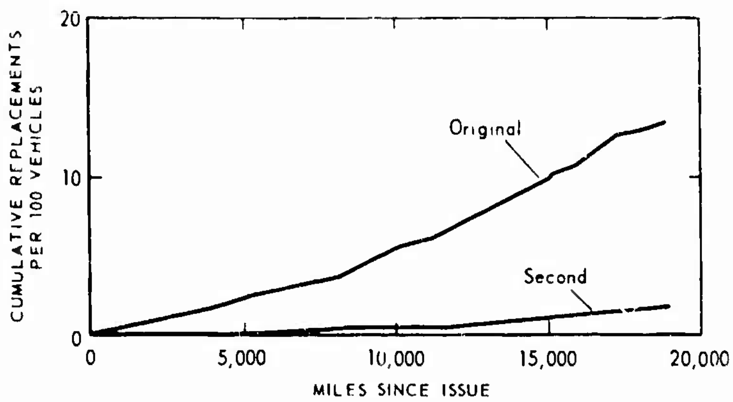


Fig. 13—Observed Cumulative Replacements of Original and Second Engines

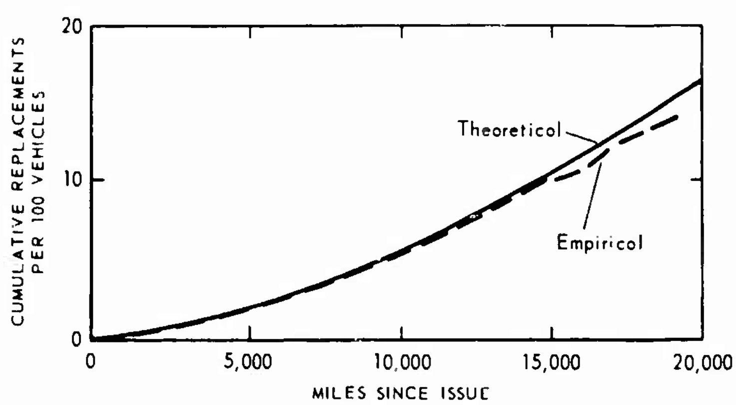


Fig. 14—Theoretical and Empirical Cumulative Replacements of Original Engines

Also shown in Fig. 15 are the expected replacement rates of second and third engines if they perform like the originals. Under the like-original assumption, rates of fourth and higher-order engines are negligible in the 0-to-80,000-mile range.

Of special interest is the rate at which these replacements occur at particular vehicle ages (see Fig. 16). The total rate levels off at about 55,000 miles at a value of 9.4 percent per 5000 miles—4.7 times the rate of 2 percent when the vehicle was new. The constant rate is called "equilibrium" and is expected to continue indefinitely, provided only that all engines have a replacement rate the same as that of the original engines.

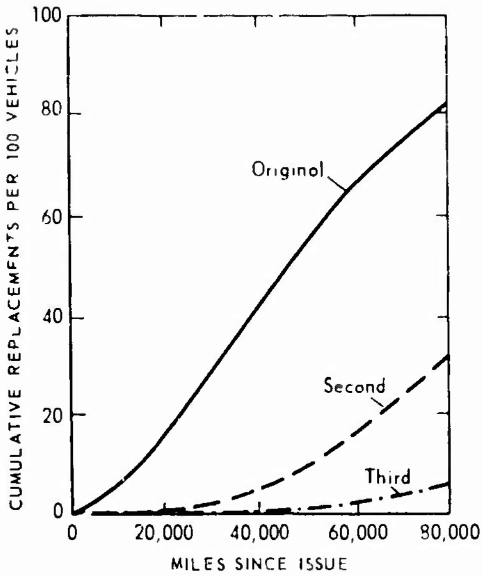


Fig. 15—Projected Cumulative Replacements of Engines

Assuming like-original performance of replacement engines.

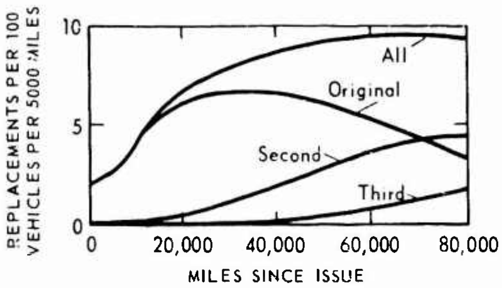


Fig. 16—Projected Engine Replacement Rates

Assuming like-original performance of replacement engines.

Transmissions

Observed Performance. The cumulative replacements of M151 transmissions observed during the study are shown in Fig. 17. By the end of the first 19,000 miles of vehicle life the total number of transmissions replaced amounted to 33 percent of the number of vehicles, of which 25 percent were original transmissions, 6 percent were replaced for the second time, and 2 percent for the third time. As was the case for engines, the replacement rate of the original assemblies increased. Eight percent were replaced in the first 10,000 miles and 17 percent in the second 10,000 miles.

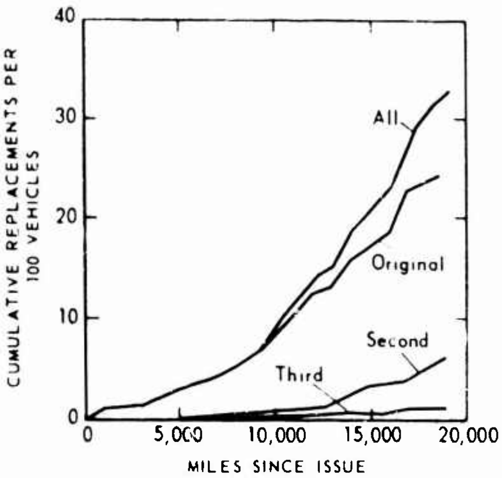


Fig. 17—Empirical Cumulative Replacements of Transmissions

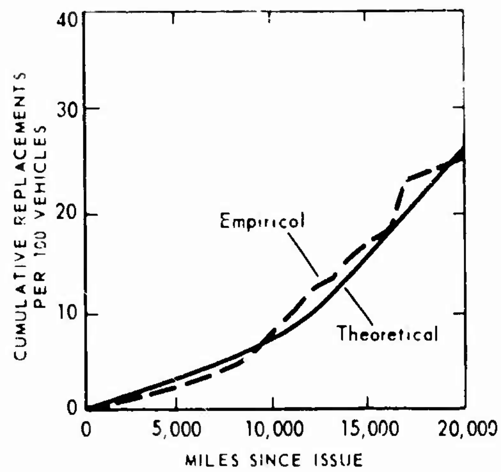


Fig. 18—Theoretical and Empirical Cumulative Replacements of Original Transmissions

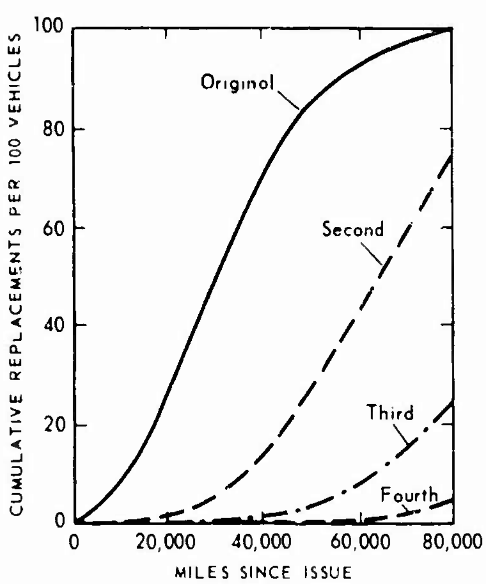


Fig. 19—Projected Cumulative Replacements of Transmissions

Assuming like-original performance of replacement transmissions.

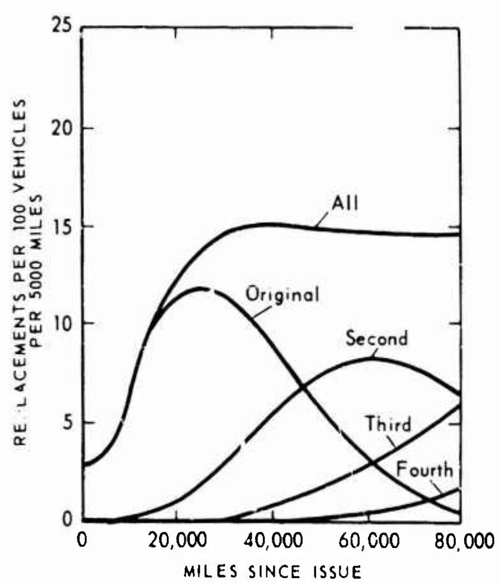


Fig. 20—Projected Transmission Replacement Rates

Assuming like-original performance of replacement transmissions.

Analysis. The statistical curve fitted to the transmission data is shown compared with the data in Fig. 18. The curve "Original" in Fig. 19 shows the statistical curve essentially in its entirety; it constitutes a projection of the replacement rate of original transmissions. Transmissions replaced according to such a curve have a mean replacement age of 32,000 miles and a standard deviation of 18,000 miles.

The other curves in Fig. 19 are the expected replacement rates of second, third, and fourth transmissions if all replacement transmissions have the same performance as that projected for the original transmissions. Fifth and higher-order transmission replacements are negligible in the 0-to-80,000-mile age range under the assumption of like-original performance.

In Fig. 20 the projected replacement rates are shown noncumulatively. As with the engine, an equilibrium in the total rate eventually occurs. The equilibrium value of 14.5 percent per 5000 miles is first attained at about 30,000 miles, is then exceeded slightly, and is returned to at about 50,000 miles; from there it will exist indefinitely provided only that each order of transmissions has like-original performance. The equilibrium rate is about five times the initial rate of 3 percent/5000 miles.

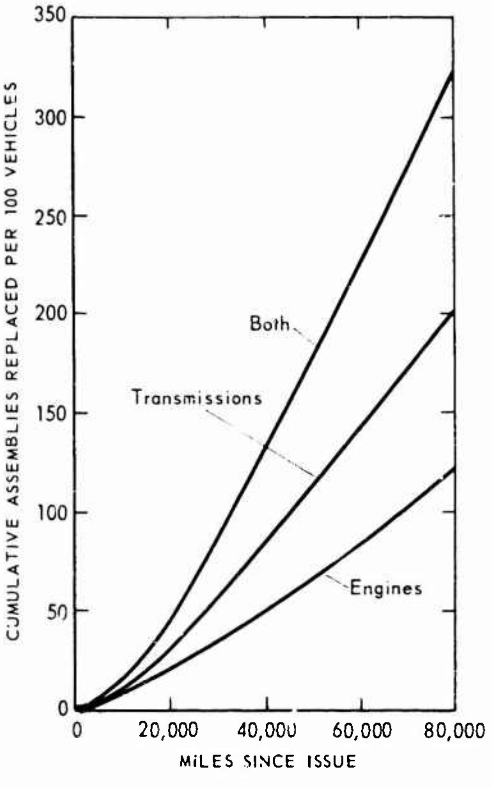


Fig. 21—Projected Cumulative Replacements of Engines and Transmissions

Assuming like-original performance of replacement assemblies.

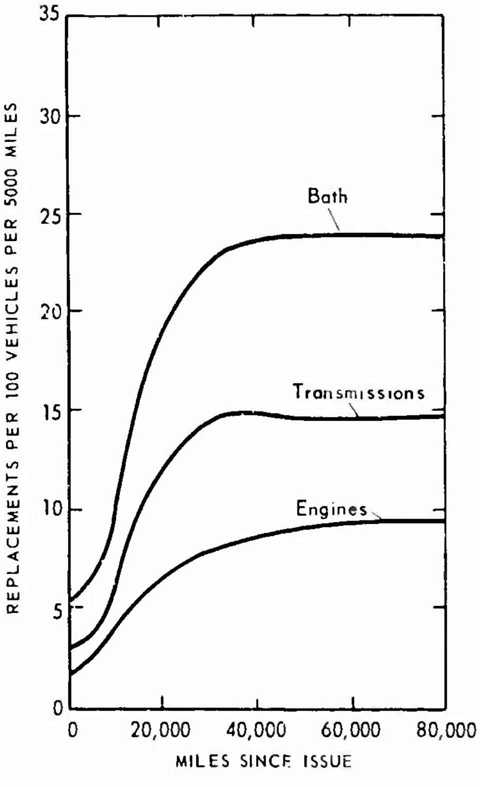


Fig. 22—Projected Replacement Rates for Engines and Transmissions

Assuming like-original performance of replacement assemblies.

Engines and Transmissions Combined

To show the accumulation of major assembly replacements according to the projections previously presented, Fig. 21 has been prepared. After an early slow rate of accumulation, there is a strong upturn between 10,000 and 20,000 miles. After 20,000 miles the accumulation is quite steady. By 55,000 miles the average M151 will have experienced two major assembly replacements if replacement assemblies give like-original performance.

Figure 22 shows the rates noncumulatively. The curve for the assemblies combined exhibits the same behavior as the individual curves: after an early rise the replacement rate becomes constant. The combined rate curve flattens at about 39,000 miles at a level of 23.9 percent per 5000 miles and will remain there as long as each replacement order of each assembly has like-original performance.

ACTUAL PERFORMANCE OF REPLACEMENT ASSEMBLIES

In this section the actual performance of replacement assemblies is discussed. It was not possible from the available data to determine precisely how many replacement assemblies were new and how many were repaired. However, the early replacement engines observed were probably preponderantly new because most of the sample vehicles were among the earliest issued and the assembly repair pipeline was not sufficiently established during much of the study period to furnish a significant number of rebuilt engines. Rebuilt transmissions were probably available more frequently than rebuilt engines because (a) more transmissions were replaced and the repair pipeline could therefore be filled more quickly, (b) transmissions are simpler assemblies and hence are more easily repaired, and (c) the heavier demand for replacement transmissions probably made repair more urgent.

Method

Investigation of the actual performance of M151 replacement assemblies consisted of comparing the actual performance to the performance predicted by two different techniques. The two prediction techniques are described in the following paragraphs.

(a) The replacement rate of assemblies was assumed to depend only on the miles of usage accumulated on the assembly, and the rate for original assemblies was assumed to apply identically to subsequent "new" or unused assemblies. This technique is the like-original technique of the previous section; it was expected to give optimistic predictions because it assumes that assembly performance is not influenced by the aging of its mechanical operating environment.

(b) The replacement rate of assemblies was assumed to depend only on vehicle age regardless of assembly age or order of replacement; the rate was assumed to be just the total rate observed for each assembly. This technique assumes that when a vehicle has gone 10,000 miles the probability of replacement of a given major assembly will be the same regardless of whether the assembly then in the vehicle is the original one, is a "new" replacement that has just been installed, or is a rebuilt third replacement that has been used during 1000 miles of vehicle operation. This technique was expected to give pessimistic predictions because it assumes that the probability of assembly replacement is not related to the age of the assembly itself. The prediction technique based on this assumption will be called the "vehicle-age" technique.

The rates predicted by the two techniques were then compared with the observed rates of replacement assemblies shown on the empirical curves of Figs. 13 and 17.

Engines

Two predictions of second-engine replacement rates are shown in Fig. 23: one based on the application of the like-original technique and the other on the vehicle-age technique. As expected the vehicle-age technique is the more pessimistic predictor, forecasting a rate about double that predicted for like-original performance.

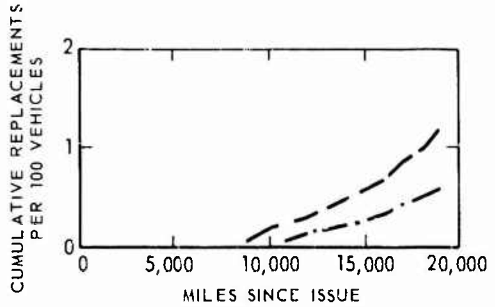


Fig. 23—Two Predictions of Cumulative Replacements of Second Engines

—·— Like-original technique
——— Vehicle-age technique

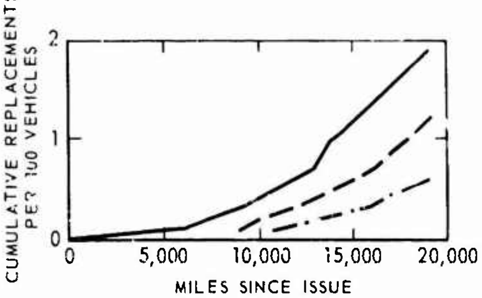


Fig. 24—Actual Cumulative Replacements of Second Engines Compared with Two Predictions

Number of second engines observed, 66 and replaced, 7.

——— Actual performance
—·— Like-original technique
——— Vehicle-age technique

The actual performance is compared with the two predictions in Fig. 24. The actual replacement rate was about three times as high as that predicted for engines giving like-original performance and 50 percent higher than engines assumed to fail according only to vehicle age.

Transmissions

Two predictions of replacement transmission performance are presented in Fig. 25. Assuming like-original performance, cumulative second replacements will number 1.5 percent of the fleet by vehicle age 19,000 miles; cumulative thirds will be essentially zero. The vehicle-age technique predicts 4.5 percent second and 0.5 percent third replacements.

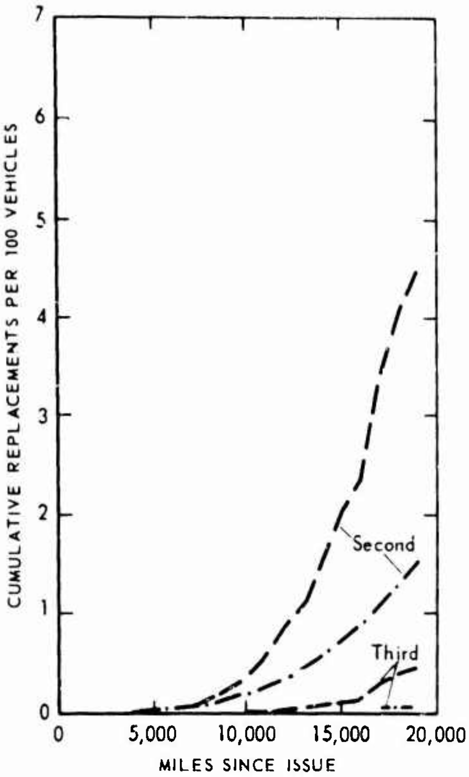


Fig. 25—Two Predictions of Cumulative Replacements of Second and Third Transmissions

—·— Like-original technique
— — — Vehicle-age technique

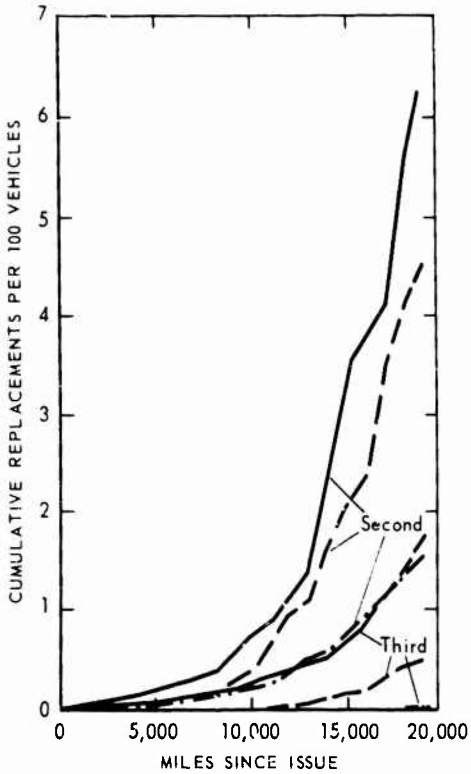


Fig. 26—Actual Cumulative Replacements of Second and Third Transmissions Compared with Two Predictions

Number of transmissions: seconds observed, 116, replaced, 20; thirds observed, 20, replaced, 3.

——— Actual performance
—·— Like-original technique
— — — Vehicle-age technique

Figure 26 shows the actual performance of second and third transmissions compared with the predictions. For second transmissions the actual replacement rate (6.4 percent) is more than four times the rate predicted if replacements give like-original performance and nearly one and one-half times the rate based on the vehicle-age prediction technique. In the case of third-transmission replacements the like-original technique predicted essentially zero replacement but the actual cumulative rate of replacement at 19,000 miles was 1.6 percent. This actual third-transmission rate is three times as high as that predicted by the vehicle-age technique.

Discussion

The significance of these results depends in part on the proportion of assemblies that was new. As was explained earlier in this chapter a number of factors indicate that nearly all engine replacements were new or nonrebuilt but that a larger proportion of transmission replacements might have been rebuilt during this period. If most of the replacement assemblies were new, possible causes for their less-than-original performance would be the inferior quality of installation and the effects of the aging vehicle on the functioning of a new assembly. Whatever the cause, the result was lower reliability and increased support requirements.

It should be noted that these results are based on scant data: the number of replacement assemblies and the number of replacements were small. Hence, although the results are phrased strongly and in precise numerical terms, they are best viewed simply as early indications of replacement-assembly performance inferior to original-assembly performance. Further observation would be needed to determine how inferior it will be over 20,000 or 30,000 miles of replacement-assembly life.

CONCLUSIONS

Original engines have a mean life of 51,400 miles; original transmissions have a mean life of 32,000 miles. The standard deviation of each is about one-half the mean life: for the engine 28,000 miles, for the transmission 14,000 miles.

For each assembly, if replacement assemblies perform the same as the projected performance of original assemblies, an equilibrium replacement rate about five times the replacement rate on brand-new vehicles will occur by about the mean life of the assembly. This equilibrium rate is just the reciprocal of the mean life. For engines the initial rate is 2 percent/5000 miles; the equilibrium is 9.4 percent. For transmissions the initial rate is 3 percent; the equilibrium is 14.5 percent/5000 miles.

Equilibrium for the combined rates occurs at about 39,000 miles, a vehicle age approximately the weighted average of the vehicle ages at which the individual equilibriums occur, taking as weights the equilibrium proportion of three transmission replacements to two engine replacements.

From the predictive point of view the influence of equilibrium is striking. The ascent of the replacement rate for the combined assemblies in the first 20,000 miles of M151 life is expected to stop abruptly by 40,000 miles if replacement assemblies perform like the originals.

Transmissions failed at about twice the rate of engines over the period of life observed.

Replacement assemblies gave early performance markedly inferior to original assemblies. Second-engine replacements accumulated to 2 percent of the fleet size at about three times the rate they would have had they performed as well as the originals did. Second-transmission replacements accumulated to 6.5 percent of fleet size at four times the rate they would if they had performed as well as the originals. Third-transmission replacements accumulated to 1.6 percent of fleet size over a period during which they would have accumulated to less than $\frac{1}{10}$ of one percent had they and second assemblies performed as well as original assemblies. Because of the small data base of the replacement-assembly analysis, these results should be taken only as early indicators and not as strong measures of replacement-assembly performance.

Chapter 4

M151 PERFORMANCE

INTRODUCTION

In this chapter M151 performance as it varies with vehicle accumulated mileage is developed from the data and then is projected beyond the data into mileages of relevance for determining vehicle lifetimes.

MEASURES OF PERFORMANCE

The measures of performance used in this analysis were vehicle-breakdown rate, mean miles per breakdown, reliability (the probability that a vehicle can negotiate some amount of movement without breakdown), availability (the probability that when called on to perform a mission the vehicle will not be out of service because of a breakdown), and mission-success index (a combination of reliability and availability). The rate of all unscheduled maintenance actions is also presented as a gross measure of performance.

The basic data here are the breakdown rate and time out of service per breakdown; given these, all the primary measures can be derived. However, these two basic data are not explicitly contained in supply and maintenance data such as the study had, since the degree of disability corrected by a maintenance action and, if the action was taken at organizational level, the time out of service incurred are not recorded. Times out of service at organizational level were estimated in Chap. 2. The purpose of this section is to define "breakdown" in terms of the available data and to define precisely the other measures of performance employed. Mathematical statements of the measures are in App A.

Unscheduled Maintenance Event Rate

A fundamental measure of vehicle performance is the "unscheduled maintenance event rate." A maintenance event is a response of the support system to a vehicle demand for maintenance. The events considered were adjustments, repairs, and replacements; all such actions known to have been performed on the M151's studied were regarded as unscheduled (i.e., they were taken in response to the condition of the equipment, not the date or the mileage). Such events represent incidents of actual or anticipated vehicle deficiency.

TABLE 15

M151 Prime Mobility Parts

System and nomenclature	FSN
Power and propulsion	
Clutch	
Parts kit	2520-887-1353
Disc	2520-678-1313
Plate	2520-678-1316
Thrust bearing	3110-144-3998
Thrust bearing	3110-158-6196
Differential	2720-678-3123
Engine	2805-678-1820
Prop shaft	
Front	2520-678-3072
Rear	2520-678-3073
Transmission	2520-678-1808
Electrical	
Battery	6140-057-2553
Belt, generator	3030-684-1486
Coil	2920-324-0374
Distributor	2920-678-1399
Generator	2920-314-0556
	2920-735-5736
	2920-737-4750
Regulator, generator	2920-335-4677
	2920-335-4678
	2920-540-9476
	2920-695-6315
Spark plug	2920-632-1088
	2920-752-4258
	5935-835-7724
Starter	2920-678-1850
Fuel	
Carburetor	2320-678-1359
	2910-678-1857
Fuel pump	2910-678-1856
Suspension	
Bearing, wheel	2530-887-1341
	3110-678-1863
Brake cylinder	2530-678-3077
Suspension arm	2530-678-3118
Tire	2610-678-1363
Cooling	
Radiator	2920-678-3232
Water pump	2930-678-1849

Prime Mobility Parts

A measure of vehicle breakdown was developed by counting as a breakdown the replacement of any of the several prime mobility parts listed in Table 15. More precisely, the replacement of any prime mobility part was considered to represent a significant vehicle impairment. The meaning of the list and the rationale behind its construction are more fully explained in the following paragraphs.

(a) Only replacement actions were considered because they were regarded as representing vehicle disabilities that were usually more serious than those corrected by adjustments and repairs.

(b) Nomenclature of a part was taken as the basic identifier because many parts were represented by more than one FSN. Further, although the FSN of the replacement part was usually known, the FSN of the one replaced usually was not. The latter condition prevented the computation of separate replacement rates for individual FSNs.

(c) To be included on the list, a part had both to be deemed important to reliability and availability and to have experienced a number of replacements in the vehicle sample observed.

(d) Although some of the observed replacements of these parts were undoubtedly made in anticipation rather than in correction of failure, all replacements were included in the determination of reliability and availability. This was done on the assumption that the parts thus replaced probably would have failed soon had they not been replaced.

(e) Although a number of occasions are known in which replacements of more than one part occurred simultaneously on the same vehicle, the replacements on such occasions were counted as separate events. This was done on the assumption that some parts were replaced preventively because the vehicle was already in the shop for a failed part and it was convenient to do both at once. In such cases the replaced part would probably have failed soon and generated a replacement event on its own account. Counting these replacements as separate events probably understates the actual vehicle reliability; however, this effect was at least partially offset by doing the opposite for the replacement of several of the same parts in a single action. For example, the simultaneous replacement of two tires was counted as one replacement event even though two disabilities were probably corrected—a present one and a potential near-future one. An exception to the procedures described here was made in the case of clutch parts. Simultaneous replacement of clutch disc, plate, and thrust bearing was regarded as a single event. In this chapter the terms "replacement job" and "replacement action" are used to refer to the replacement of several parts of the same kind; the term "replacement" refers to the replacement of an individual part.

Hard-Core Prime Mobility Parts

To lend perspective to the definition of breakdown just given, a second list, called the hard-core prime mobility parts, was formed by eliminating certain parts from Table 15. Included were parts that (a) usually do not have to be replaced to permit the vehicle to complete its movement (e.g., spark plugs, battery, and starter); (b) usually can be replaced in a short time (e.g., tire and fan belt); and (c) are usually replaced anticipatively when partial deterioration is evident (e.g., battery, spark plugs, distributors, carburetor, coil, and master cylinder).

This hard core consists of 10 items which were found to account for 46 percent of the prime-mobility-parts replacement jobs observed. As the name suggests, "breakdowns" defined by this list of parts were considered "harder," i.e., more serious, more literally breakdowns in vehicle operability. This hard-core prime mobility parts list includes the following:

- Engine
- Transmission
- Clutch
- Differential
- Rear prop shaft
- Fuel pump
- Radiator
- Water pump
- Suspension arm
- Wheel bearing

Vehicle-Breakdown Rate

A meaningful measure of vehicle-breakdown rate was regarded as being somewhere between the sum of the replacement action rates of all the prime mobility parts and the sum of the replacement action rates of the hard-core parts. In the remainder of this memorandum, whenever breakdown rate and measures based on it are portrayed, they are shown as bands rather than lines; the upper and lower boundaries of the bands are determined by the full list and hard-core list.

The hard-core list was regarded as the truer measure of incidents of actual inoperability and the full list as the truer measure of incidents of significant impairments, including incidents of inoperability.

Mean Mileage per Vehicle Breakdown

This measure is the reciprocal of the vehicle-breakdown rate. It is the mean vehicle usage that generates one vehicle breakdown.

Availability

Availability is the probability that a vehicle is not broken down. It is a measure of vehicle and support-system performance combined. Vehicle availability depends on (a) how frequently vehicles fail and (b) how long the support system requires to restore a failed vehicle to serviceability.

The availability measure used in this study is called "availability potential" for reasons set forth in App A. The full list and the hard-core replacement rates were used to determine the lower and upper boundaries of a band of availability potential.

Reliability

The term "reliability" is used in this study to mean the probability that some mission will be accomplished successfully. "Mission" was defined to be 500 miles of operation and "success" was defined in two ways: (a) without requiring the replacement of a prime mobility part and (b) without requiring the replacement of a hard-core prime mobility part. Reliability based on the hard-core parts is the upper boundary and that based on the full list is the lower boundary of the band of reliability derived.

Mission-Success Index

The mission-success index is a measure of availability and reliability combined and is calculated as the product of availability potential and reliability. It is the probability that a vehicle will be able both to start and to successfully finish a randomly demanded 500-mile movement.

OBSERVED PERFORMANCE

All Unscheduled Maintenance Actions

Figure 27a shows the upward trend of the rate of occurrence of all unscheduled maintenance actions as accumulated vehicle mileage increases. The curves for each type of action show clearly that this upward trend is attributable to replacement actions only; the rates of adjustment and repair are relatively constant. The adjustment rate averages 0.2 adjustments per 1000 vehicle miles, about double the repair rate. The replacement rate begins at 0.5 replacement actions per 1000 vehicle miles (about 63 percent of the rate for all actions) and increases to 1.6 replacement actions per 1000 vehicle miles at 18,000 miles (about 80 percent of the rate for all actions and about triple its initial value of 0.5). The peak around 10,000 miles was caused by coincidental replacement of various electrical, suspension, and cooling-system components.

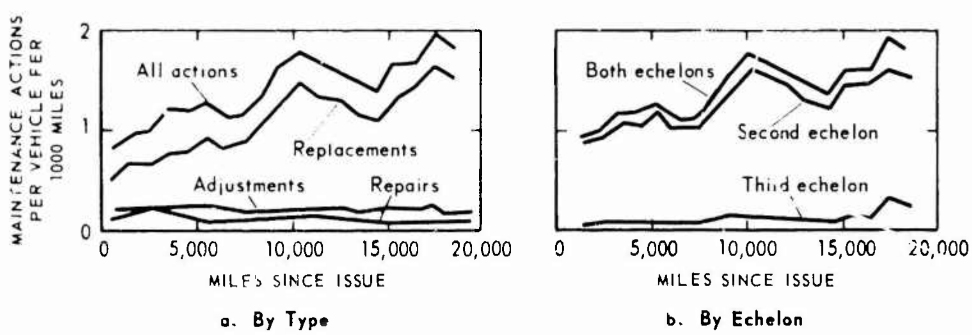


Fig. 27—Rate of Occurrence of Unscheduled Maintenance Actions

About 91 percent of the maintenance actions occurred at second echelon and the remainder at third (see Fig. 27b). This ratio remains fairly constant in vehicle age.

The analysis of action types for third and second echelon shown in Figs. 28 and 29 demonstrates that in both echelons increases in the total action rate are due primarily to increases in replacement actions and that the rates of repair and adjustment were relatively constant. The proportion of replacement actions to the total number of actions was slightly larger at third echelon than at second, averaging 80 percent compared with 75 percent. Also the ratio of repairs to adjustments differed: at second echelon there were two adjustments for each repair, at third echelon there were three.

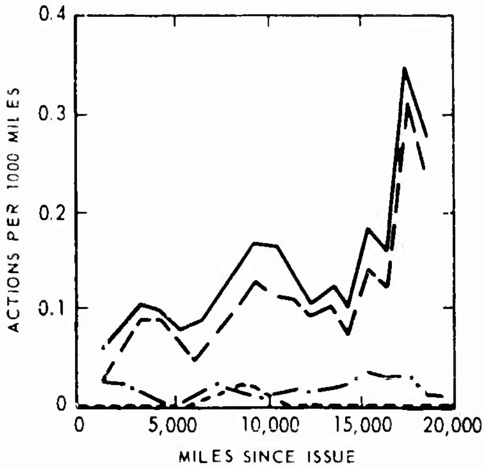


Fig. 28—Rate of Occurrence of Third-Echelon Unscheduled Maintenance Actions, by Type

——— All ‒ ‒ ‒ Replacements
—·— Repairs ------ Adjustments

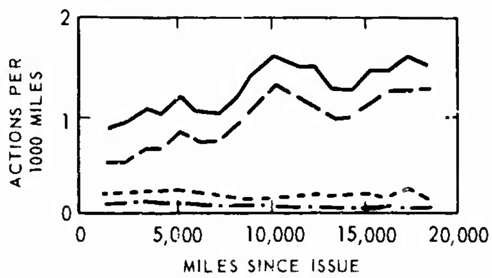


Fig. 29—Rate of Occurrence of Second-Echelon Unscheduled Maintenance Actions, by Type

——— All ‒ ‒ ‒ Replacements
—·— Repairs ------ Adjustments

Vehicle-Breakdown Rate

The vehicle-breakdown rate is shown as a band in Fig. 30. The upper boundary of the band is the sum of replacement-job rates for prime mobility parts. The lower boundary is the sum of replacement-job rates for the hard-core prime mobility parts. The band slopes upward with increasing vehicle age. The relatively constant width of the band indicates that the tendency to increase comes primarily from the hard core; the remainder of the prime mobility parts apparently have a relatively constant replacement job rate over the first 20,000 miles of vehicle life.

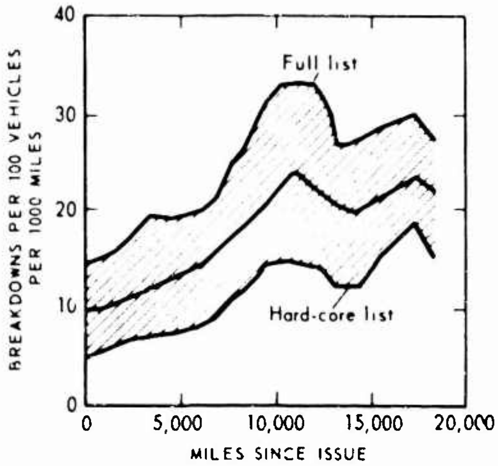


Fig. 30—Observed Breakdown Rate: Replacement Rate of Prime Mobility Parts

Hard-core replacement jobs begin at a rate of about 5 per 100 vehicles during the first 1000 miles. By age 20,000 miles this number has increased to about 18 per 100, or 3.6 times the earlier rate.

The full-list rate starts at about 15 jobs per 100 vehicles during the first 1000 miles of movement. By age 20,000 miles it has reached a level of about 32, a little more than double its initial value.

A line through the middle of the band would start at 10 jobs per 100 vehicles and reach 25 by 20,000 miles, indicating a growth of $2\frac{1}{2}$ times in the M151 breakdown rate.

Mean Mileage per Vehicle Breakdown

As shown by the band in Fig. 31, the mean miles per vehicle breakdown decline rapidly in the first 10,000 miles of vehicle life, then decline more slowly. The sharp dip at 10,000 miles exaggerates this appearance. The initial range is between 8000 and 16,000 miles per breakdown; by 20,000 miles this has dropped to between 3500 and 6000 miles per breakdown.

Availability Potential

The "observed availability potential" shown in Fig. 32 was formed from the empirical replacement rates shown in Fig. 30 and the mean downtimes per replacement presented in Chap. 2. The band bounded by availability potentials

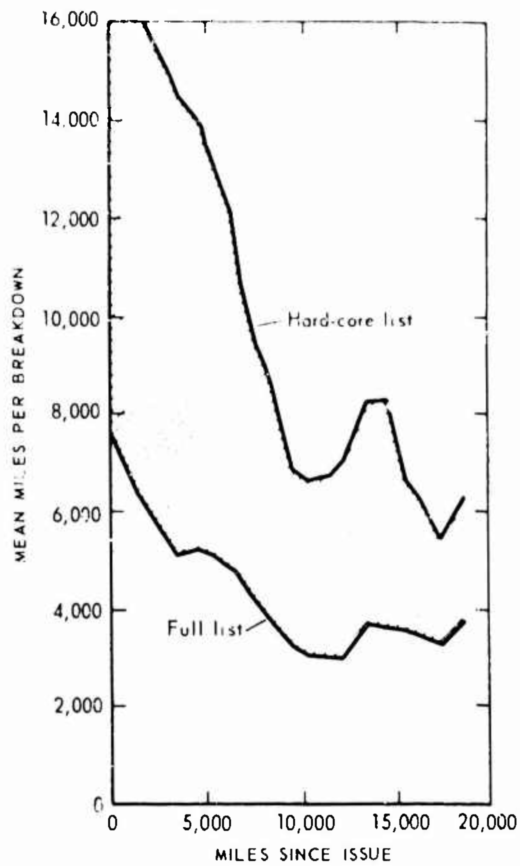


Fig. 31—Observed Mean Miles per Vehicle Breakdown

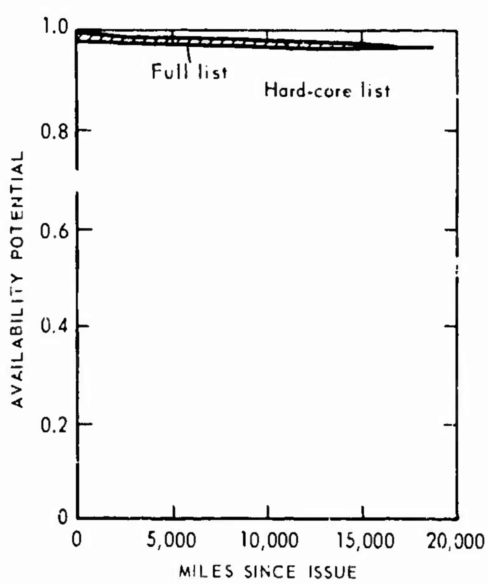


Fig. 32—Observed Availability Potential as a Function of Vehicle Age

based on the hard-core and full lists of the prime mobility parts is very narrow and diminishes to a line beyond 16,000 miles.

The availability potential declines slightly over the first 20,000 miles of M151 life from an initial value of between 0.98 and 0.99 to about 0.97, about a 1-percent change.

Reliability

The observed reliability is shown as a band in Fig. 33; it was derived directly from the empirical breakdown rates of Fig. 30. The hard-core reliability was about 0.97 when the vehicles were new and dropped to about 0.92 during their first 20,000 miles of life (a drop of about 5 percent); the full-list reliability fell from about 0.93 to about 0.86 (a decrease of about 8 percent) over the same period. Using the midline to summarize, reliability is regarded as having been about 0.95 when the vehicles were issued new and having dropped 6 to 7 percent to 0.89 during the first 20,000 miles of life.

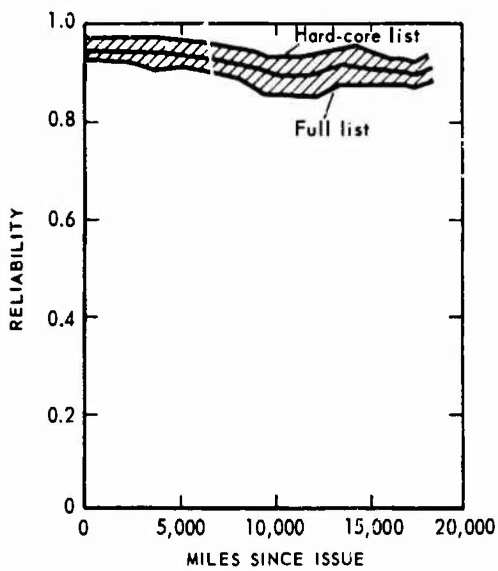


Fig. 33—Observed Reliability as a Function of Vehicle Age

(Mission: 500 miles)

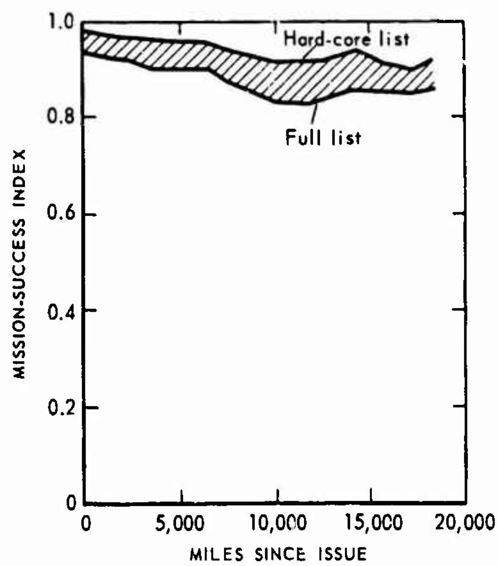


Fig. 34—Observed Mission-Success Index as a Function of Vehicle Age

(Use rate: 550 miles/month; Mission: 500 miles)

These figures mean that when the M151's are new, an average of 3 percent will be unable to complete a 500-mile movement because of a major failure and 7 percent are expected to experience at least a significant impairment. M151's of age 20,000 miles are expected to experience more than twice as many difficulties, i.e., 8 percent would be disabled and a total of 14 percent would experience at least significant impairment.

Mission-Success Index

The observed mission-success index is simply the product of the observed availability potential and the observed reliability (see Fig. 34). This success index is 0.97 for a new M151 if only hard-core parts are considered; the index has decreased to approximately 0.90 by 20,000 miles. If the full list of prime mobility parts is considered, the probability is 0.93 at new issue and about 0.84 at 20,000 miles.

In other words, for new vehicles the percent unable to start and complete a 500-mile march ranged between 3 and 7; this incapacity more than doubled during the first 20,000 miles of M151 life to between 10 and 16 percent.

Conclusions

Most of the results reported in this section were derived from two sets of basic information: the rate of occurrence of maintenance events and the time out of service per event. The implications of these two were expressed as measures of reliability, availability, and mission success. Vehicle failure, unavailability, and unreliability double in the first 20,000 miles of life.

PROJECTED PERFORMANCE

Critical to the determination of M151 lifetimes was the projection of M151 performance into ages considerably beyond the greatest age at which any vehicles were observed during the course of the study.

Two sets of projections were made. One was based on the assumption that replacement parts would have the same life as that indicated by the data for the parts in the vehicle at time of issue. This set of projections was termed "like-original." A second set of "degraded" projections was also made because (a) it has long been Army practice to repair parts that have considerable residual value, (b) there is evidence[3,4,21] that such repaired and rebuilt parts do not perform as well as the original parts, and (c) there are also indications[5] including findings in Chap. 3 of this memorandum that even unused or "new" replacement parts do not perform as well as original parts. The conclusions of the study are based on the degraded projections and so they are presented in this chapter. An exception is the breakdown rate, of which both the like-original and the degraded projections are shown to indicate how much they differ. For reference, the like-original projections of the other measures of performance are presented in App A.

Equilibrium

The projections made in this study relied heavily on the idea that the vehicle-breakdown rate eventually achieves something close to an equilibrium, i.e., that it eventually levels off at a constant rate, with a resultant leveling off of vehicle reliability and availability.

A formal mathematical discussion of the concept of equilibrium as it applies to failure of complex equipment is contained in "The Failure Law of

Complex Equipment."[22] Appendix A contains a detailed discussion of the determination of equilibrium for the M151 and the significance of this equilibrium in the projection of vehicle-breakdown rates. The figures and discussion included in this chapter are based on this long-range analysis, but attention is concentrated on the portion of vehicle life that is pertinent to the determination of effective lifetime.

Projections of Vehicle-Breakdown Rate

Vehicle-breakdown rate is used here synonymously with the prime-mobility-parts replacement rate, as discussed earlier in this chapter. Figure 35 shows projections of replacement rates for the full list of prime mobility parts and also for the hard-core parts alone. Figure 36 shows these same two projections adjusted to reflect the expected degraded performance of replacement parts as shown in the shaded portion of the figure. The figure shows that the breakdown rate increases steadily between 0 and 50,000 miles to a level approximately quadruple the rate at vehicle issue.

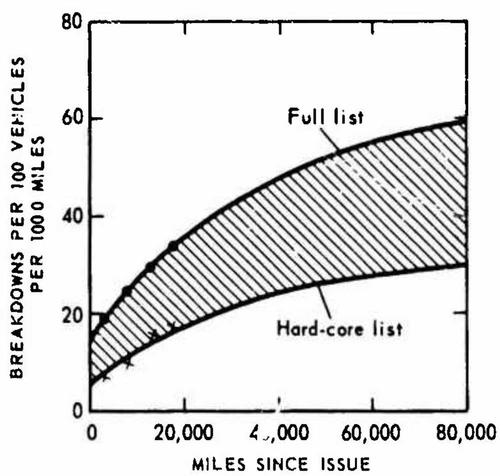


Fig. 35—Projection of Breakdown Rate: Replacement-Job Rate of Prime Mobility Parts

• Observed rate for all prime mobility parts
× Observed rate for hard-core prime mobility parts

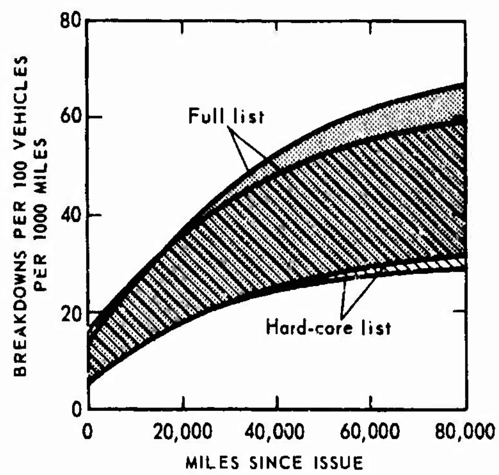


Fig. 36—Two Projections of Breakdown Rate Comparing Like-Original and Degraded Performance

Degraded
Like original

Mean Miles per Breakdown

The degraded projection of this performance measure is presented in Fig. 37. In early life this measure declines rapidly. For new vehicles more than 14,000 vehicle-miles are required on the average to generate one hard-core part breakdown; approximately 7000 vehicle-miles on the average are required to generate one breakdown based on the full list of prime mobility parts. For vehicles 20,000 miles old, these figures are more than halved. By 50,000 miles the descent has slowed considerably; at that point the projection lies between 1800 and 3600 miles per breakdown.

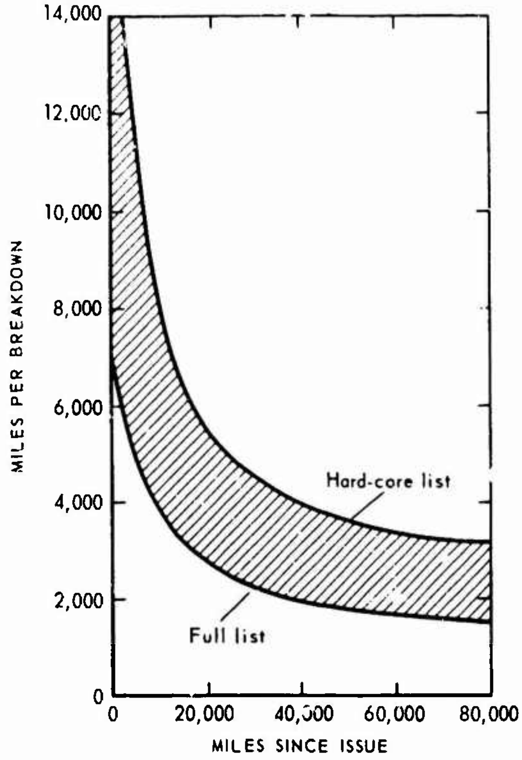


Fig. 37—Projected Mean Miles per Vehicle Breakdown

Availability Potential

Figure 38 shows the degraded projection of availability potential. The breakdown rates were obtained from Fig. 36 and the downtimes per breakdown from Table 14.

The availability potential declines from an initial value of about 0.99 to about 0.96 at 50,000 miles.

Considering unavailability, the number of downed vehicles is 1 percent when the fleet is new, about $2\frac{1}{2}$ to 3 percent at 20,000 miles, and 4 percent at 50,000 miles. As noted earlier, the availability potential bands are narrow because the hard-core parts account for most of the downtime and because the availability rate is generally high.

Reliability

The projected breakdown rates in Fig. 36 were used to determine the projections of the reliability shown in Fig. 39. The reliability changes are similar to those in the other performance measures shown, deteriorating rapidly for 50,000 miles and then more slowly. The reliability of new vehicles lies between 0.92 and 0.98. By 50,000 miles it has declined to between 0.75 and 0.87.

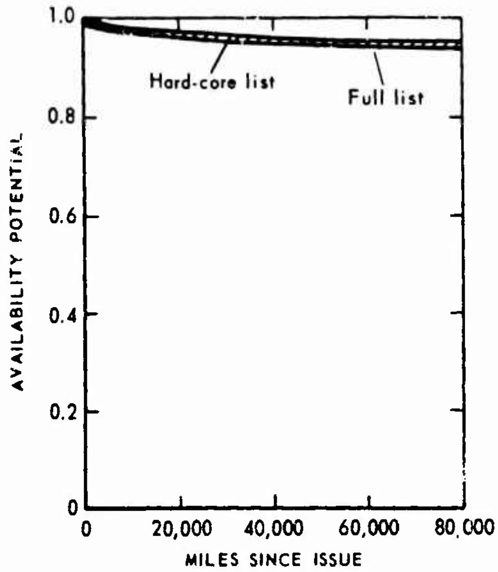


Fig. 38—Projection of Availability Potential

Use rate: 550 miles/month.

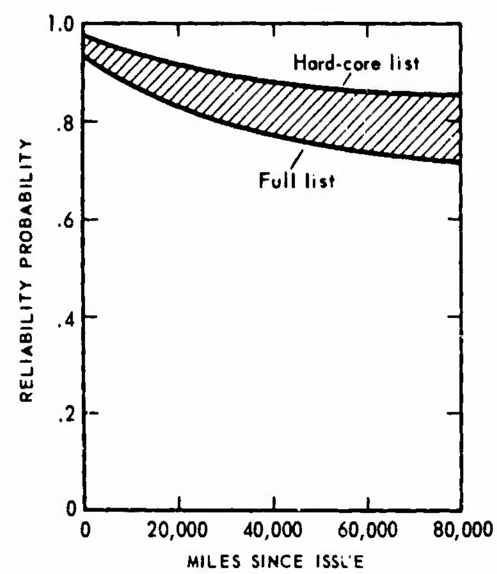


Fig. 39—Projection of Reliability

Mission: 500 miles.

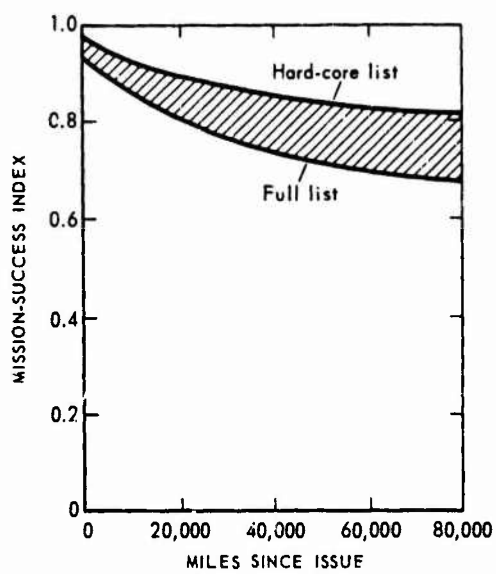


Fig. 40—Projection of Mission-Success Index

Use rate: 550 miles/month; mission: 500 miles.

These changes mean that an average of 2 percent of new vehicles will not be able to complete a 500-mile march without a breakdown of one of the hard-core parts and 8 percent will experience a breakdown of one of the parts in the full list. By 20,000 miles these figures have increased to 9 percent and 16 percent and by 50,000 miles to 13 and 25 percent. These represent a doubling of failure by 20,000 miles and a quadrupling by 50,000 miles.

Mission-Success Index

Projections of availability potential and reliability are combined to yield the projections of the mission-success index shown in Fig. 40. Changes in the mission-success index are dominated by and closely resemble the changes in reliability. The mission-success index declines 18 percent by 50,000 miles.

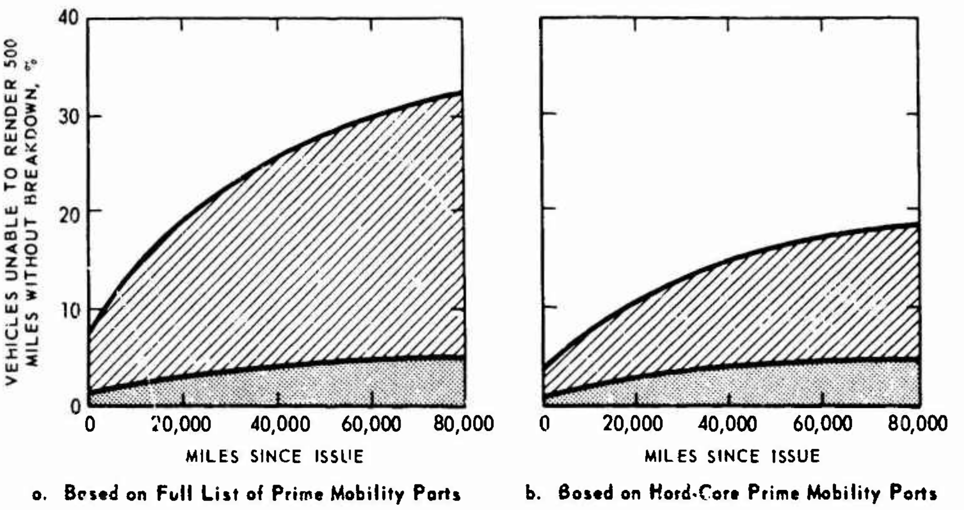


Fig. 41—Projection of Mission Failure

Dropouts Nonstarters

Figure 41 shows the percentage of vehicles unable to furnish 5000 miles of movement either because they would be unable to start or because they could start but would be unable to finish because of need to replace prime mobility parts.

The full-list performance shown in Fig. 41a is characterized by a nonstarter rate of $1\frac{1}{2}$ percent for new vehicles and a dropout rate of 8 percent for a total of $9\frac{1}{2}$ percent. The total has more than doubled by 20,000 miles and nearly triples to 28 percent at 50,000 miles. Throughout the projection the nonstarters account for approximately one-sixth of those unable to complete the mission.

Figure 41b shows that the percentage of nonstarters and dropouts caused by replacement of hard-core mobility parts begins at 4 percent, a percentage that doubles by 10,000 miles, triples by 25,000 miles, and quadruples by 50,000

TABLE 16

Degraded Projection of Performance Deterioration with Age

Age, miles	Breakdowns per 1000 miles		Mean miles per breakdown		Availability potential[a]		Reliability[b]		Mission-success index[a,b]	
	Hard-core list	Full list	Hard-core list	Full list	Hard-core list	Full list	Hard-core list	Full list	Hard-core list	Full list
0	0.055	0.140	18,000	7000	0.999	0.991	0.975	0.935	0.974	0.926
20,000	0.180	0.375	5,500	2700	0.979	0.969	0.912	0.825	0.894	0.800
50,000	0.275	0.595	3,600	1750	0.962	0.952	0.872	0.749	0.840	0.712
75,000	0.312	0.660	3,220	1530	0.957	0.946	0.856	0.719	0.820	0.680

[a]Use rate: 500 miles/month.
[b]Mission: 500 miles.

miles. Of the total vehicles unable to complete a mission owing to hard-core breakdowns, about one-fourth are unavailable at the beginning of the mission and three-fourths break down after a successful start.

CONCLUSIONS

Various measures of vehicle performance at several mileage points are summarized in Tables 16 and 17. Table 16 shows that the rate of breakdown of the full list of prime mobility parts more than doubles between 0 and 20,000 miles and quadruples by 50,000 miles. The mission-success index declines from 0.926 at issue to 0.712 at 50,000 miles, a reduction of 23 percent. These measures mean that for a fleet of 100 vehicles, breakdowns per 1000 miles increase from 14 at issue to 60 at 50,000 miles, and that the total number of nonfinishers on 500-mile missions increases from 7 at issue to 29 at 50,000 miles.

TABLE 17

Degraded Projection of Performance Deterioration with Age in Number of Vehicles Affected

Age, miles	Breakdowns per 100 vehicles[a]		Vehicles per hundred unable to successfully provide a 500-mile movement[b]					
			Nonstarters		Dropouts		Total nonfinishers[c]	
	Hard-core list	Full list	Hard-core list	Full list	Hard-core list	Full list	Hard-core list	Full list
0	6	14	0	1	3	7	4	7
20,000	18	38	2	3	9	17	11	20
50,000	28	60	4	5	13	25	16	29
75,000	31	66	4	5	14	28	18	32

[a] Per 1000 miles of fleet movement.
[b] Use rate: 500 miles/month; mission: 500 miles.
[c] Equals nonstarters + dropouts ± 1; discrepancies are due to rounding.

Chapter 5

M151 MAINTENANCE COSTS

INTRODUCTION

Maintenance cost is the price of keeping equipment operable; it is incurred when the support system corrects or prevents vehicle deficiencies. The magnitude depends on inherent characteristics of both the vehicle and the support system. Thus the results of this chapter represent a synthesis of the results of Chaps. 2 and 4.

A main purpose of this chapter is to present the effects of age on M151 maintenance costs and to project such costs to ages relevant to the determination of M151 effective lifetime. Both maintenance man-hours consumption and dollar costs are discussed. As in Chap. 2, only unscheduled maintenance actions are treated.

OBSERVED COSTS

Method

Maintenance costs as a function of M151 age were derived in terms of man-hours, cost of man-hours, cost of parts replaced, and a summary cost including cost of man-hours, parts, and SSI. Each of these costs was derived by multiplying the appropriate cost per maintenance action presented in Chap. 2 by the maintenance event rates presented as a function of vehicle age in Chap. 4. Costs for organizational and direct-support echelons were obtained by summing up for each echelon the costs of the three types of maintenance actions (i.e., adjustment, repair, and replacement for each echelon). Costs of prime mobility parts were derived by multiplying the replacement rate for each item (presented in App B) by the price of the item and summing the costs of the parts for each age interval. Separate costs of engines, transmissions, and tires were derived in the same way.

Parts

The costs of parts replaced averaged $1.06 per 100 vehicle-miles of operation in the first 19,000 miles of vehicle life. Parts replaced were costed at list price[17–19] except DX items, which were costed at 30 percent of list price.

Transmissions, tires, and engines accounted for 28 percent of the total parts costs. Table 18 shows average parts costs for the first 19,000 miles.

TABLE 18

Average Cost of Parts Replaced for the First 19,000 Miles of M151 Life[a]

Part	Cost, dollars per 100 miles	Percent of total
Engine	0.07	7
Transmission	0.18	17
Tires	0.04	4
Other	0.77	72
Total	1.06	100

[a]DX items costed at 30 percent of list price.

As shown in Fig. 42, the cost of parts increased with age; the cost of $1.54 per 100 miles in the age interval 15,000 to 20,000 miles is 2½ times that of $0.59 per 100 miles during the first 5000 miles of life. This figure also shows that the cost of the individual parts also increased as the vehicle aged, another evidence of their increasing failure frequencies during early vehicle aging.

Cost of parts replaced are shown by echelon in Fig. 43. Over the first 19,000 miles parts installed at third echelon accounted for 33 percent of the cost of all parts replaced. For the first 15,000 miles this proportion was constant at about 30 percent but increased to 40 percent in the 15,000- to 20,000-mile interval.

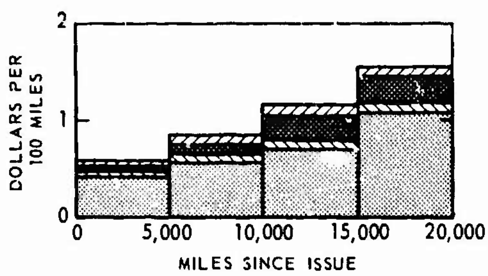


Fig. 42—Cost of Parts Replaced as a Function of Vehicle Age

DX items costed at 30% of list price.

Engine, Tires, Transmission, Other

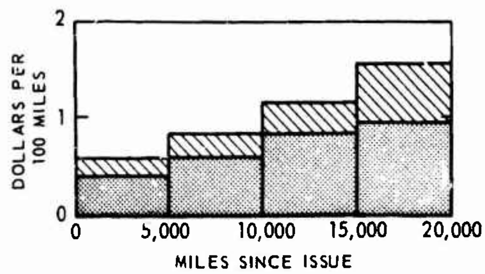


Fig. 43—Cost of Parts Replaced, by Echelon, as a Function of Vehicle Age

DX items costed at 30% of list price.

3d echelon (direct support)

2d echelon (organizational)

Labor

Man-Hours. Over the first 19,000 miles of M151 life direct-maintenance man-hours for unscheduled adjustments, repairs, and replacements were consumed at the rate of 0.23 man-hours/100 vehicle-miles—0.17 of them at second echelon and 0.06 at third echelon (see Fig. 44a). Thus, an average of 1 second-echelon man-hour was being consumed every 588 miles, 1 third-echelon man-hour every 1670 miles. Man-hour consumption changed as the vehicle aged, increasing steadily from 0.16 man-hours per 100 miles in the first 5000 miles of life to 0.31- about double its early value—in the 15,000- to 20,000-mile age interval.

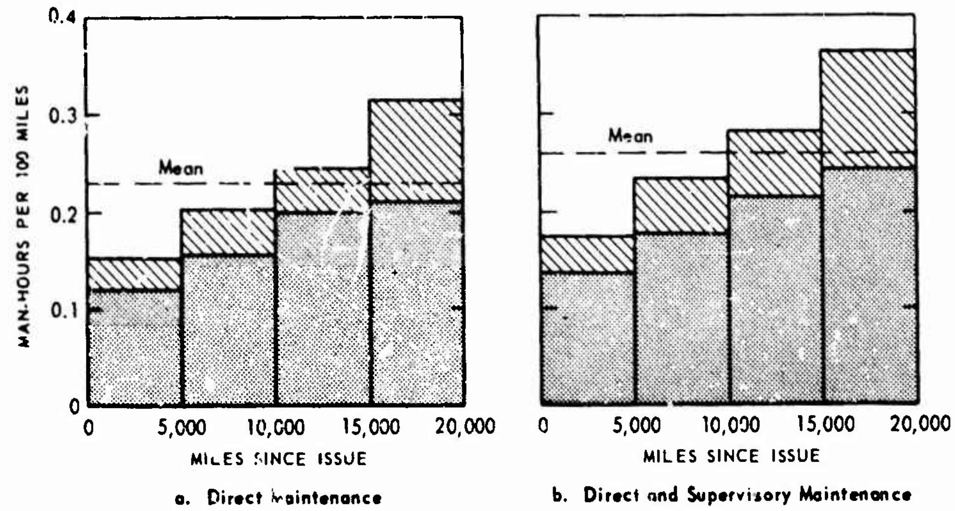


Fig. 44—Labor Consumed as a Function of Vehicle Age

3d echelon (direct support) 2d echelon (organizational)

Figure 44b shows maintenance man-hour consumption when the values plotted in Fig. 44a are inflated by 15 percent to account for supervisory maintenance man-hours (see Chap. 2). During the first 19,000 miles of M151 life direct- and supervisory-maintenance man-hours for unscheduled adjustments, repairs, and replacements were consumed at the mean rate of 0.26 man-hours per 100 vehicle-miles—0.20 of them at second echelon and 0.07 at third. An average of 1 second-echelon man-hour was being consumed every 500 miles and 1 third-echelon man-hour every 1430 miles. Man-hour consumption changed as the vehicle aged, increasing steadily from 0.18 man-hours per 100 miles in the first 5000 miles of life to 0.36—double its early value—in the 15,000- to 20,000-mile age interval.

The hours were distributed between second and third echelons in the approximate ratio of 3 to 1. The ratio was constant at about 3½ to 1 in the first 15,000 miles, then dipped to 2 to 1 in the last 5000 miles observed.

Costs. Costs of direct and supervisory labor are shown in Fig. 45. They double from \$0.36 per 100 miles in the first 5000 miles of life to \$0.72 per 100 miles between 15,000 and 20,000 miles. Their mean for the first 19,000 miles was \$0.51 per 100 miles, of which \$0.37 (73 percent) was second-echelon labor.

All Maintenance Costs

The costs of unscheduled maintenance performed during the first 19,000 miles of M151 life are shown in Fig. 46 in four categories: prime mobility

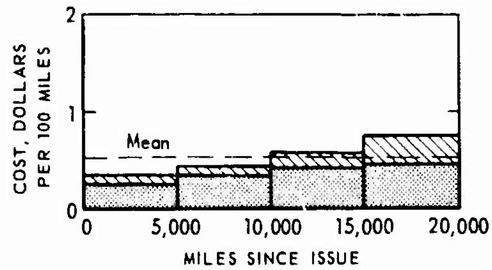


Fig. 45—Cost of Direct- and Supervisory-Maintenance Labor as a Function of Vehicle Age

3d echelon (direct support)

2d echelon (organizational)

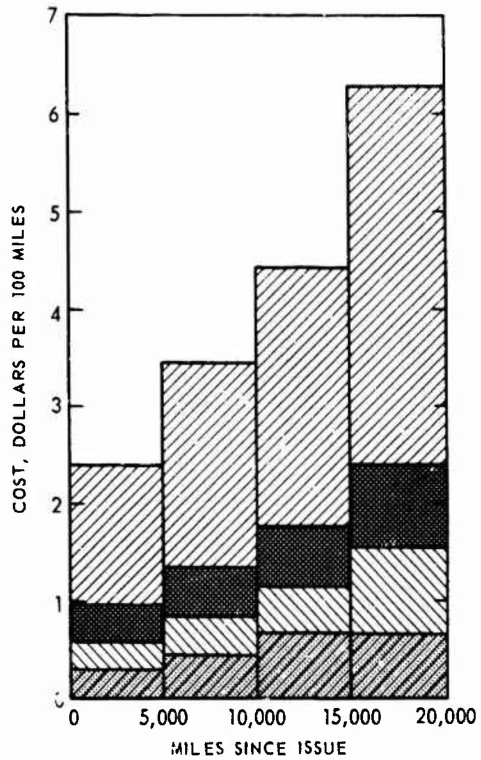


Fig. 46—Observed Costs of Unscheduled Maintenance as a Function of Vehicle Age

SSI

Directional supervisory labor

Parts (DX items at 30 percent of list price)

Prime mobility parts (DX items at 30 percent of list price)

TABLE 19

Mean Cost of Parts, Labor, and SSI Observed over the First 20,000 Miles of M151 Life

Category	Mean cost, dollars per 100 miles	Percent of total
Prime mobility parts[a]	0.58	14
All parts[a]	1.06	26
Direct and supervisory labor	0.51	13
SSI	2.51	61
Total	4.08	100

[a]DX items costed at 30 percent of list price.

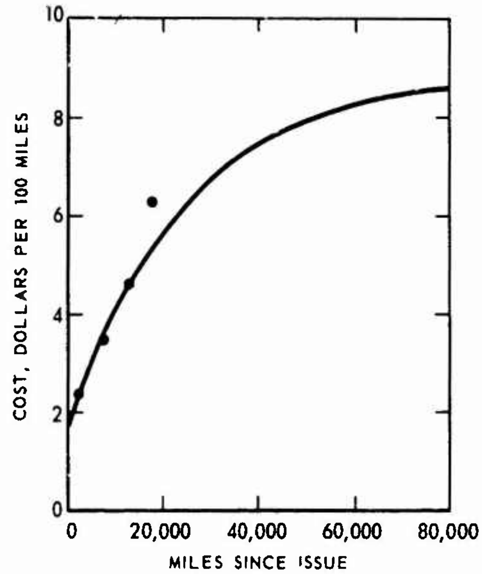


Fig. 47—Projected Maintenance Costs

• Observed costs

parts, other parts, labor (direct and supervisory), and SSI. Table 19 shows for each category the mean over the first 20,000 miles of M151 life and the percentage of the total represented by each category. Parts and labor accounted for 39 percent of the total costs; the remainder was SSI. The total cost changed from about $2.40 per 100 miles in the first 5000 miles of life to $6.25 in the 15,000- to 20,000-mile period, an increase of more than 150 percent.

PROJECTED COSTS

Method

Maintenance costs were projected by a method similar to that used in projecting vehicle-breakdown rate. Fundamental to the projection was the idea that a maintenance cost equilibrium would eventually be obtained. The details of the estimation of equilibrium and projections are contained in App A.

Costs

Figure 47 shows the projected maintenance costs for the M151 through 80,000 miles assuming degraded performance of replacement parts. By 60,000 miles it is predicted that maintenance costs will reach $8.27 per 100 miles, almost five times the corresponding cost at issue of $1.68 per 100 miles.

Chapter 6

M151 LIFETIME

INTRODUCTION

The earlier chapters of this paper have shown that as M151's age their performance deteriorates and their maintenance costs increase. The purpose of this chapter is to develop an effective lifetime for the M151 based on these factors and the concurrent influence of obsolescence.

The lifetime technique employed was that used in previous ORO/RAC studies;[3-5] it is described in the next section of this chapter in general terms. The last section of the chapter contains a discussion of the effective lifetime obtained for the M151. More technical lifetime discussion is presented in App C.

METHOD

The lifetime technique used in this study is based on four principal vehicle characteristics: acquisition cost, maintenance cost as it varies with age, vehicle performance as it varies with age, and technological obsolescence. Costs are amortized evenly over the portion of vehicle life remaining at the time they are incurred. The performance measure used is the mission-success index discussed in Chap. 4. Obsolescence is assumed to occur continuously at the rate of 2 percent/year compounded, which is the rate used in an earlier study[3] of wheeled vehicles. The combination of mission-success index and technological competitiveness (the obverse of obsolescence) is called effectiveness.

The portions of acquisition and maintenance costs amortized in a given interval are charged to the vehicle effectiveness attained during that same age interval. The effective lifetime is the vehicle age at which the average cost per effectiveness unit since vehicle issue is minimized. This technique is stated in mathematical terms in App C.

RESULTS

Computed Lifetimes

Based on the measured performance of only the hard-core parts and components, the effective lifetime of the M151 was determined to be 46,500 miles;

if the performance of the full-list parts and assemblies is considered, the lifetime decreases to 37,600 miles. At a use rate of 550 miles/month these mileages correspond to 7 and 5½ years, respectively. These results are summarized in Table 20.

TABLE 20

Computed M151 Lifetimes at a Usage Rate of 550 Miles/Month

Performance measure basis	Lifetime	
	Miles	Years
Hard-core parts	46,500	7
Full list of prime mobility parts	37,600	5½

Discussion

Sensitivity. The lifetimes derived are the minimum points on the cost-effectiveness curves shown in Fig. 48. Both curves are relatively flat on both sides of these lifetime points. On the full-list curve the variation in cost-effectiveness from the 37,600-mile lifetime is less than 5 percent in the 28,000- to 49,000-mile range. For the hard-core curve the range of mileage representing less than 5 percent deviation extends from 32,000 to 64,000 miles.

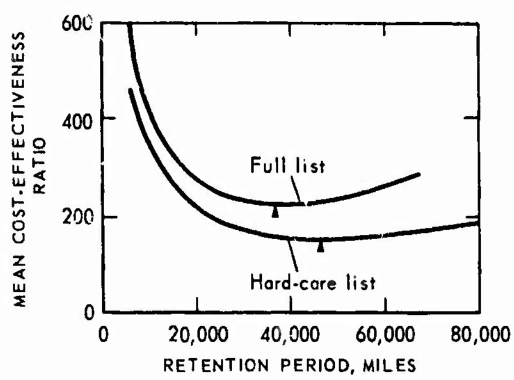


Fig. 48—Cost-Effectiveness Retention Curves

▲ Lifetimes: full list, 37,600 miles; hard-core list, 46,500 miles.

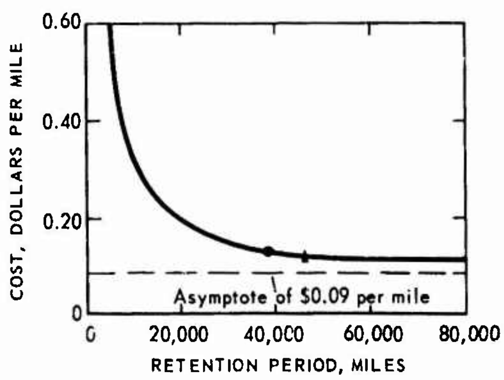


Fig. 49—Average Cost per Mile of M151's Considering Acquisition Cost ($2900) and Unscheduled Maintenance Costs (Degraded)

● Full-list lifetime ▲ Hard-core lifetime

Because of the degradation of vehicle performance at higher mileage, it is useful to look at costs and performance separately.

Costs. In Fig. 49 the mean cost per mile of M151 life is shown for various replacement ages. This curve is obtained by dividing the sum of the acquisition cost and the accumulated maintenance costs (derived from the degraded projection discussed in Chap. 5) by the accumulated miles of life. It differs from the cost-effectiveness retention curves of Fig. 48 in that it does not take account of performance or obsolescence. Figure 49 shows that on the basis of cost alone it is always less expensive to continue operating M151's than it is to replace them.

However, it is also evident from the slope of the curve in Fig. 49 that the major part of the total cost has already been recovered by the time a vehicle reaches the 37,000- to 47,000-mile age range. Of the total per-mile saving available in extending M151 life beyond 5000 miles, 94 percent has been realized by 50,000 miles (an average of about 2 percent saved per 1000-mile extension). To realize the next 2 percent requires an extension of 30,000 miles.

In the lifetime calculation the cost of a vehicle is assumed to remain constant. App C investigates the effect on mean cost per mile when the original vehicle has current M151 costs but successively purchased vehicles have different acquisition and maintenance costs.

TABLE 21

Cost of Various Replacement Cycles

Retention period, miles	Average cost of maintenance, dollars/mile	Average cost of acquisition and maintenance, dollars/mile	Percent of 25,000-mile cost of acquisition and maintenance	Annual fleet cost,[a] dollars	Annual fleet saving over previous cycle, dollars
25,000	0.058	0.161	100	32,200,000	—
35,000	0.064	0.136	84	27,200,000	5,000,000
50,000	0.069	0.119	74	23,800,000	3,400,000
75,000	0.077	0.110	68	22,000,000	1,800,000

[a]30,000 vehicles for 200 million miles/year.

Table 21 presents a comparison of fleet costs for four representative vehicle-replacement cycles. The savings which result from choosing a 50,000-mile life instead of a 35,000-mile life are $3,400,000 per year—about 13 percent of the total annual acquisition and maintenance costs. To save another $1,800,000 per year would require retaining vehicles until 75,000 miles.

Performance and obsolescence. The change in mission-success index from 0 to 80,000 miles is presented in Fig. 50. The trend is of course downward as the vehicles age. At 37,600 miles (the lifetime based on the full list of prime mobility parts) the full-list mission-success index is 0.75; the hard-core mission success-index is 0.86. At 46,500 miles (the lifetime based on the hard-core parts) the full-list mission-success index is 0.73; the hard-core index is 0.85. Performance levels at the 47,000-mile life are 2 to 3 percent lower than at the 37,000-mile life.

Figure 51 shows decay in vehicle competitiveness resulting from a 2 percent/year obsolescence rate. Table 22 shows lifetimes, which incorporate the 2 percent obsolescence rate compared with those derived when no obsolescence is considered. The introduction of a 2 percent/year rate of obsolescence reduces lifetimes by 10 percent in the full-list case and 14 percent in the hard-core case. The reduction is larger for the hard-core case because the lifetimes themselves are longer and hence the obsolescence has become greater.

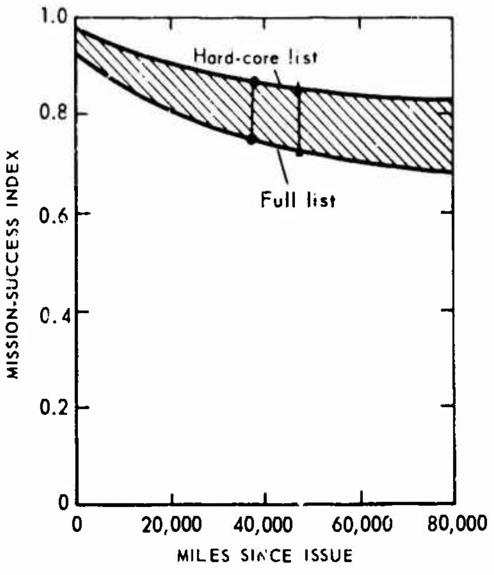


Fig. 50—Degraded Mission-Success Index

● Full-list lifetime

▲ Hard-core lifetime

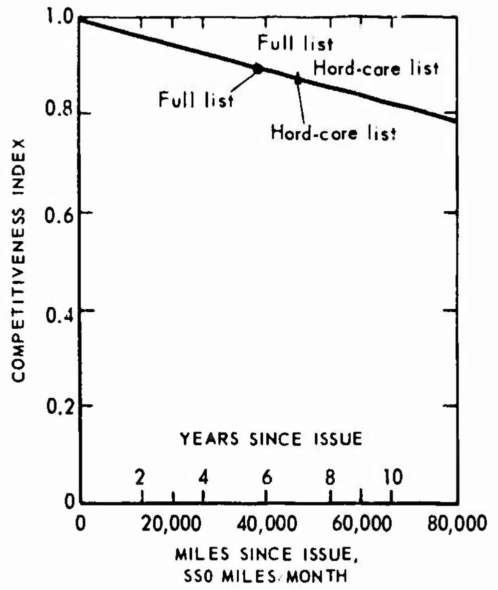


Fig. 51—Relative Decline of M151 Technological Competitiveness When Obsolescence Rate Is 2 Percent/Year Compounded

TABLE 22

M151 Lifetimes for Obsolescence Rates of 0 and 2 Percent/Year Compared

Performance measure	Lifetime				Reduction in lifetime owing to obsolescence, %
	Miles		Years		
	Obsolescence rate, %				
	0	2	0	2	
Hard-core parts	54,200	46,500	8.2	7.0	14
Full list of prime mobility parts	42,000	37,600	6.4	5.5	10

In Table 23 both mission success and technological competitiveness are shown for four representative retention periods. Not only are the values at the end of the period shown in Figs. 50 and 51, but averages for each period are also shown. By comparing the change shown in the percentage columns with that shown similarly for costs in Table 21, the meaning of lifetimes chosen between 35,000 and 50,000 miles becomes clearer. For example, a life of 50,000 miles costs 25 percent less per mile than a life of 25,000 miles, while the average hard-core mission-success index is 3 percent lower.

TABLE 23

Performance and Competitiveness for Various Replacement Cycles

Retention period, miles	End-of-period value			Average during period					
	Mission success		Competitiveness	Mission success				Competitiveness	Percent of 25,000 mile value
	Hard-core list	Full list		Hard-core list	Percent of 25,000 mile value	Full list	Percent of 25,000 mile value		
25,000	88	79	0.877	92	100	84	100	0.940	100
35,000	86	76	0.832	90	98	82	98	0.916	98
50,000	84	72	0.769	89	97	80	95	0.882	94
75,000	82	68	0.675	87	95	76	90	0.828	88

Since the ¼-ton truck role is not one of combat offense or defense, the outcome of military actions will probably not directly depend on the modernity of the ¼-ton trucks in the vehicle fleet. For this reason the primary cause of ¼-ton truck deterioration will be utilization rather than obsolescence, and the most effective restorative act will be the substitution of a new vehicle, which is not necessarily of a new model.

Summary. Although the cost-effectiveness ratios are relatively constant over a range within 10,000 to 15,000 miles on either side of the calculated effective lifetimes, earlier vehicle ages were found to represent improved levels of performance and technological competitiveness. Table 24 summarizes quantitatively a comparison of the 37,000- and 47,000-mile lifetimes.

TABLE 24

Comparison of 37,000-Mile Life with 47,000-Mile Life

Characteristic	Life		Change from 37,000 to 47,000, %
	37,000 miles	47,000 miles	
Mean cost per mile of acquisition and maintenance, dollars per mile	12.5	11.5	8
Mission-success index, hard core	0.86	0.85	-1
500-mile march, non-starters and dropouts per 100 vehicles	14	15	+7
Technological competitiveness	0.89	0.85	-4

If obsolescence is ignored in the analysis, the 37,000-mile full-list lifetime increases to 42,000 miles and the 47,000-mile hard-core lifetime is extended to 54,000 miles, increases of 11 and 16 percent respectively.

Recommended Lifetime

On the basis of these considerations, this study recommends an M151 lifetime of 50,000 miles. In Table 25 this mileage is translated into lifetime years for four different rates of utilization.

This is a "liberal" lifetime: it is based on the performance of only the hard-core parts although failure of other parts may disable a vehicle; the influence of obsolescence on effectiveness is partially discounted; and the performance of replaced engines and transmissions was assumed to be considerably better than the performance actually indicated in replacement assembly failure data. For these reasons shorter lifetimes and earlier vehicle replacement should be considered for units in which the quality of M151 performance is important to successful combat-mission accomplishment.

Two suggested guidelines governing replacement are the following:

(a) Early-life replacement is significantly more costly than replacement at the 50,000-mile effective life. The performance gains to be realized from such early replacement should therefore be carefully weighed against the need for them and the costs they will entail.

(b) Replacement later than 60,000 miles reduces the average performance level of the fleet and furnishes only a slight cost advantage. As a general rule lifetimes should therefore not be extended beyond 60,000 miles.

TABLE 25

Recommended M151 Lifetime for Various Use Rates

Use rate, miles per month	Lifetime, years
300	14
550	$7\frac{1}{2}$
750	$5\frac{1}{2}$
1000	4

OVERHAUL

Primarily as a result of the findings of ORO-T-381,[21] overhaul of ¼-ton trucks is not currently an Army practice.

In that study of M38-series ¼-ton trucks, overhaul was found to cost an average of approximately $1850 per vehicle. Direct parts and labor accounted for about half this amount, overhead and transportation for the other half. If M151 overhaul should cost approximately the same amount, the least-cost-lifetime analysis contained in App C shows that overhaul of M151's is not economical. According to this analysis, it is unlikely that the M151 model will dominate the ¼-ton truck inventory long enough to make this $1850 rebuild cost economical. It is important to note that the analysis is based on the assumption that reissued overhauled vehicles will experience maintenance costs that are no greater than those of a new vehicle. Since ORO-T-381[21] and ORO-T-401[3] both showed that maintenance costs of overhauled vehicles are higher than those of newly issued vehicles and that their performance is worse, the case against M151 overhaul becomes even stronger. Only a significant improvement in the overhauled product and/or reduction in overhaul costs could modify this conclusion.

PROCUREMENT AND PREMATURE LOSSES

The lifetime may be simply used to determine annual procurement quantities if it is desired to maintain a fleet of constant size with a constant annual procurement of new vehicles. Thus a lifetime of $7\frac{1}{2}$ years implies a complete fleet turnover every 7½ years, which in turn implies an annual procurement of 13.3 percent (100 ÷ 7½) of the fleet.

However, in reality some vehicles are lost (usually owing to accidents) before their natural lifetime expires. The annual procurement must provide replacements for these vehicles as well. Thus if the premature loss rate is 15.6 percent/year (that currently attributed to ¼-ton trucks[2]) and the lifetime is 7½ years, the constant annual procurement required to maintain a fleet of constant size should be 22.2 percent of the fleet size as compared with 13.3 percent if the premature-loss rate is zero.

To permit inclusion of the premature-loss rate in estimating the constant annual procurement required to maintain a constant fleet size for vehicles of a given lifetime, Fig. 52 is presented for lifetimes from 4 to 14 years and for washout rates 0, 5, 10, 15, and 20 percent/year. To read the figure, find the lifetime on the vertical axis (e.g., 7½ years), and extend a horizontal line to the curve of the appropriate loss rate (e.g., 15.6 percent/year); from this point drop a vertical line to the horizontal axis and read the annual procurement expressed as a percent of the fleet size (which would be 22.2 percent in the example used). The derivation of Fig. 52 is described in App A.

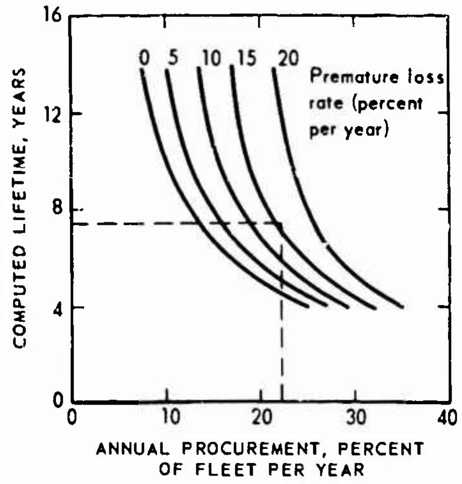


Fig. 52—Annual Procurement Required To Replace Vehicles Whose Ages Will Become Equal to the Computed Lifetime and/or Lost before the Computed Lifetime

Of course the general question of how much to procure when it is desired to increase or reduce the fleet size, or when past procurements have not been approximately equal so that vehicles tend to be grouped around certain ages leaving relatively few at other ages, is more complex than the simple conditions treated above. Nevertheless the foregoing analysis and graph can be of use for even these more complex analyses as a source of first indications, reference points, and goals.

Appendix A

TECHNICAL NOTES

Tables

INTRODUCTION

In this appendix calculations and findings treated only summarily in the body of the report receive fuller, more technical description.

SAMPLE SIZE

Total Sample

The sample shown in Table 3 is considered satisfactory to about 19,000 miles, where it drops below 100 vehicles. Up to that mileage the probability that at least one prime-mobility replacement job (the measure of vehicle breakdown used—see Chap. 4) will occur per 1000 miles is greater than the minimum probability observable with 80 percent confidence of an error 5 percent or smaller as shown in Table A1. In the first mileage increment (1000 to 2000 miles) at least 200 vehicles were observed, in the second increment (2000 to 13,000 miles) at least 300, etc.

TABLE A1

Minimum Probabilities Observable and Observed that at Least One Prime-Mobility-Part Replacement Job Will Occur in 1000 M151 Miles

(With 80 percent confidence that the error ≤ 5 percent)

M151		Probabilities	
Sample size	Age increment, accumulated miles	Minimum observable per 1000 miles	Observed per 1000 miles
200	1,000– 2,000	0.14	0.16
300	2,000–13,000	0.10	0.20
200	13,000–15,000	0.14	0.27
100	15,000–19,000	0.25	0.29
75	19,000–20,000	0.30	0.31
50	20,000–21,000	0.40	0.31
25	21,000–23,000	0.60	0.32

Although the sample does not strictly meet the conditions under which a confidence limit of the kind stated can be derived, i.e., that each 1000-mile interval of a vehicle's life is independent of all the others of its life, the table is believed to give an indication that the sample size is reasonable for the mileages covered.

The fact that the sample size is essentially zero beyond 25,000 miles is viewed as representing a somewhat short look into M151 aging. This view derives from the relation between part-replacement distributions and mean lives and vehicle performance as it varies with vehicle age (discussed in Chaps. 3 and 4), the observed failure rates of major M151 components which indicate mean lives of 30,000 to 80,000 miles, and the observation in a number of studies[1,3–5,21] that replacement parts—new as well as repaired—do not perform as well as the original ones. Thus, although to get a measure of vehicle performance with a solid empirical base for vehicles older than say 75,000 miles, and especially in the steady state, it would have been good to have seen most original parts fail and a good number of seconds and thirds as well, no more than 30 percent of the originals and almost none of the replacements of any prime mobility part were seen replaced by 19,000 miles. It appears in greater detail in Chaps. 3 and 4, where projections beyond the data are made, that the look to 19,000 miles is a somewhat foreshortened view of M151 aging. The main effect is probably that the performance of replacement assemblies is unknown, and only to a considerably lesser degree is there uncertainty in the probable replacement times of the original parts still intact at 20,000 miles.

However, the sample is viewed as a reasonable base from which to project performance at the present time. USAREUR was one of the first to receive M151's and only after they are operated for several more years will there exist data of the kind suggested to be desirable. Fleet managers must make replacement decisions before the fleet actually arrives at an unacceptable state.

Sample Used in Analysis of Man-Hour Consumption

In Chap. 2 the analysis of man-hours consumed by maintenance actions is based on a limited sample because many records did not show the man-hours expended.

The extent to which the subsample of actions for which man-hours were recorded (Table 5) was a biased sample of the total sample (Table 1) and is thought to be small and to vary with the type of action and the echelon. Some indications may be described.

For second-echelon actions, a known large source of actions without man-hours recorded resulted from the practice of recording for a scheduled semiannual maintenance check the total number of man-hours expended in the check and not the number expended on each of the single actions performed. All except 5 percent of second-echelon adjustments and repairs can be accounted for by the mutually exclusive categories "occurred during scheduled semiannual maintenance checks" and "had man-hours recorded." The extent to which second-echelon adjustments and repairs made during scheduled maintenance tend to be a group different from such actions not made during scheduled semiannual maintenance is not known. For replacement actions taken at second echelon, 48 percent may be accounted as having "occurred during scheduled semiannual maintenance" or "had man-hours recorded." Some of the remaining blank man-hour fields are the result of recording total man-hours for maintenance incidents in which more than one maintenance action was taken. But another significant part of the blank man-hour fields in second-echelon replacement records must be attributed to simple omission.

Essentially all third-echelon blank man-hour data can be attributed to the occasional practice of recording man-hours expended for groups of actions instead of the individual actions. Omissions of man-hour records at third echelon were rare.

In summary, known data inadequacies leave possible room for bias and distortion in the distributions of maintenance-action man-hour consumption shown in Fig. 6. Nevertheless the distributions are regarded as giving good indications of the magnitude and range of man-hour consumption. Man-hour data for second-echelon adjustments and repairs are regarded as most accurately represented. Second-echelon part replacements and third-echelon adjustments are regarded as least well represented—the former because of the tendency of replacement actions to occur in numbers greater than one and the tendency of such groups of actions to be reported as a total man-hour figure, and the latter because the sample is small. The sample of third-echelon repairs is also regarded as small. Third-echelon parts replacements are regarded as well represented.

REQUISITION FILL TIMES

The curve representing the fill rate of M151 requisitions shown in Fig. 11 was not directly observed but was derived as follows.

Requisitions made for M60 tanks, M113 APCs, and M88 recovery vehicles as well as M151 ¼-ton trucks were analyzed together and separately. The separate analysis treated only those requisitions filled during the period of observation. The combined analysis treated both those that were filled and all requisitions observed (filled or not).

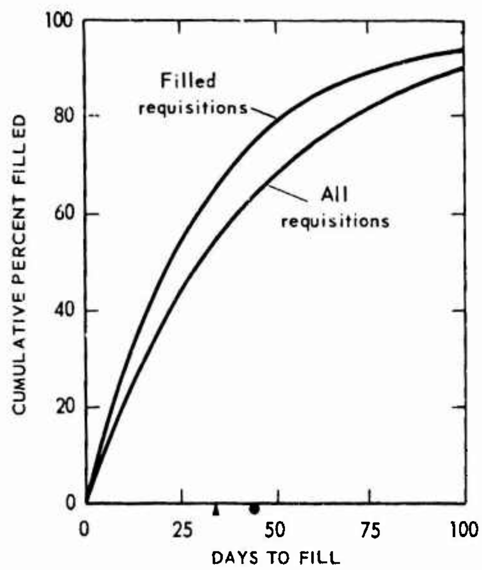


Fig. A1—Fill Rates for o Sompte of Requisitions Mode on M60 Tanks, M113 APCs, ond M151 ¼-ton Trucks in USAREUR in 1963

▲ Meon time to fill fil'ed requisitions
● Meon time to fill oll requisitions

In the analysis of only those requisitions that were filled, it was found that the fill rate for one type of vehicle differed little from that of the others or of the vehicles combined. In particular the fill rate of filled requisitions for the M151 was found to be essentially identical to that for the vehicles combined. This curve is the upper of the two shown in Fig. A1. The fill rate of all requisitions for the vehicles combined is shown as the lower curve in Fig. A1.

Because the fill rates of filled requisitions for no vehicle were observed to deviate much from that of the combined rates and because the M151 in particular was observed not to deviate at all, the fill rate for all M151 requisitions was taken to be the same as that observed for the vehicles combined. Thus the curve of Fig. 11 is identical to the lower curve of Fig. A1.

The upper and lower curves are well represented by $e^{-0.735t}$ and $e^{-0.570t}$ (where t is in units of 25 days) so that their respective mean fill times are 34 and 44 days.

MEASURES OF PERFORMANCE

Breakdown Rate

The breakdown rate per 1000 miles h was defined to be the sum of the replacement rates of the appropriate set (full list or hard-core list) of prime mobility parts.

Mean Miles per Breakdown

The mean miles per breakdown was defined as 1000 times the reciprocal of the breakdown rate, or $1000/h$.

Availability Potential

Availability potential B is defined by

$$B = \frac{1}{1 + h\lambda u},$$

where h = the breakdown rate per 1000 miles
λ = the mean downtime (in months) per breakdown
u = the mean use rate in thousands of miles per month

The availability potential is the steady-state probability that a vehicle will not be down if it goes down at the constant rate h and is restored in the constant mean time λ when the use rate is constant at u. Thus availability potential is the availability that would eventually obtain under conditions of constant h, λ, and u. For the M151, of course, h is slowly changing with age, and as a result the actual availability at some age differs from the availability potential at that age. But because h changes slowly, availability and availability potential differ very little. Indeed, stochastic fluctuations in h are likely to lead to greater variability in availability than the difference between availability and availability potential due to h-growth with vehicle age.

Reliability

Reliability R for a 500-mile mission was defined by

$$R = e^{-h/2},$$

where h is the breakdown rate per 1000 miles. R is the probability that a vehicle able to begin a mission can complete it without breakdown.

Mission-Success Index

Mission-success index S was defined by

$$S = BR \frac{e^{-h/2}}{1 + h\lambda u},$$

where the symbols are as previously defined. Mission-success index is the probability that a vehicle is neither out of commission with a breakdown when a 500-mile mission is demanded of it nor will suffer a breakdown while executing the mission.

EQUILIBRIUM BREAKDOWN RATE

Equilibrium of M151 breakdown rate exerted an important influence in the projections of performance and maintenance costs made in Chaps. 4 and 5. Eventual equilibrium of M151 breakdown rate may be expected for a number of reasons.

M151 breakdown rate was defined to be the replacement rate of a set of important parts. Thus, equilibrium breakdown rate represented a constant replacement rate. By replacement rate of the set of parts was meant the sum of the individual replacement rates.

The replacement of a defective item by a workable one has acquired the name "renewal," and a sequence of such replacements in one functional position is called a "renewal process."[23] Thus the breakdown rate defined was a superposition of 21 renewal processes. Three properties of renewal process—two of individual processes and one of superposed processes—have major relevance for equilibrium. One is that a renewal process allowed to continue indefinitely eventually achieves equilibrium.[23] The second is that if the replacement rate is constant, equilibrium exists immediately.[23] The third is that as the number of superposed processes becomes increasingly large, the total replacement rate tends increasingly toward constancy.[22]

The equilibrium predicted for the M151 breakdown rate was attributed to all three influences. First, it was assumed to exist not immediately but only after some time. Second, the rapidity with which it would attain equilibrium was assumed enhanced by the number of individual renewal processes (i.e., 21) being superposed. Third, the rapidity was considered further enhanced by the constant replacement rates of many of the individual parts.

DERIVATION OF EQUILIBRIUM PERFORMANCE AND COSTS

Vehicle-failure rate had been defined as the combined failure rates of a set of prime mobility parts (see Chap. 4). The equilibrium vehicle-failure rate would be $\Sigma_i \frac{1}{\mu_i}$, where μ_i was the steady-state mean life of prime mobility part i. The approach indicated then was to estimate the mean life of each prime mobility part.

Estimates of mean lives of prime mobility parts were made as follows. Replacement rates as a function of vehicle age were computed for each prime mobility part. These rates are described, tabulated, and plotted in App B. The rates of first replacements were plotted on log-log paper on which they usually lay linearly. They were assumed representable by Weibull distributions,[24] the cumulative form of which is

$$F(x) = 1 - e^{-(x-\gamma)^{\beta}/\alpha}.$$

The mean of a Weibull distribution is[25]

$$\mu = \gamma + \alpha^{1/\beta}\Gamma(1/\beta + 1).$$

Cumulative fractions of replacement, which should have occurred by the mean, were computed by

$$F(\mu) = 1 - e^{-\Gamma(1/\beta+1)}.$$

Since $F(\mu)$ is a function of only β and β was represented by the slope of the log-log graph, a table of $F(\mu)$ for various β was formed. Means were then determined graphically by extrapolating the linear graph of each part to the cumulative fraction replaced $F(\mu)$ appropriate for its slope β and reading off the corresponding age. For all but six of the prime mobility parts it is believed that the mean lives indicated by the data were determined to within ±7 percent by this technique. For the six, widely different interpretations of the data were possible because it was somewhat scattered as it lay on log-log paper. The study merely made what seemed reasonable interpretations.

The mean lives estimated and the numbers of observed replacements on which they were based are shown in Table A2. Also shown in Table A2 are the price per item, the estimated equilibrium replacement job rate, and the resultant equilibrium parts cost incurred per mile.

The column labeled "$\overline{P}$" contains ratios $(n \times j)/q$ where n is the quantity of the item in an M151, j is the number of replacement jobs observed, and q is the number of items observed replaced. $\overline{P}$ is the ratio of the number of parts that would have been replaced if an entire set of items were replaced with each replacement job to the number of items that actually were replaced. Jobs were regarded as the relevant action for reliability considerations and quantity replaced the relevant parameter for supply and parts costs considerations.

The equilibrium replacement job rate for a part was derived according to the expression

$$h_e = \overline{P}/\mu,$$

where h_e is the equilibrium replacement job rate and μ is the mean life of the item. The equilibrium costs were derived by

$$c_e = nc_i/\mu,$$

where c_e is the equilibrium cost, n is the number of items in an M151, and c_i is the cost of one item as shown in Table A2.

The estimates of mean lives and equilibriums contained in Table A2 are labeled "like-original" because they are based on the behavior of the parts original with the vehicles; in deriving the equilibriums the assumption was made that parts in the vehicles subsequent to the original parts would have mean lives the same as the originals.

TABLE A2

Like-Original Equilibrium Replacement Job Rates and Costs of Prime Mobility Parts

System and part	Quantity in M151	Replacement observed		$\overline{P}$	Mean life, thousands of miles	Cost, dollars per item	Equilibrium replacement jobs per mile	Equilibrium parts cost, dollars per mile
		Jobs	Quantity					
Power and propulsion								
Clutch	1	89	89	1	35	15.00	$28.6 \cdot 10^{-6}$	$0.429 \cdot 10^{-3}$
Clutch bearing alone	1	12	12	1	17	5.00	$58.8 \cdot 10^{-6}$	$0.294 \cdot 10^{-3}$
Differential	1	14	14	1	475	80.00[a]	$2.1 \cdot 10^{-6}$	$0.168 \cdot 10^{-3}$
Engine	1	68	68	1	51	92.40[b]	$19.1 \cdot 10^{-6}$	$1.793 \cdot 10^{-3}$
Prop shaft								
Front	2	30	30	2	60	10.20	$33.4 \cdot 10^{-6}$	$0.341 \cdot 10^{-3}$
Rear	2	19	21	1.810	50	12.10	$36.2 \cdot 10^{-6}$	$0.481 \cdot 10^{-3}$
Transmission	1	138	138	1	32	97.50[b]	$31.2 \cdot 10^{-6}$	$3.012 \cdot 10^{-3}$
Electrical								
Battery	2	34	52	1.231	60	9.95	$20.6 \cdot 10^{-6}$	$0.332 \cdot 10^{-3}$
Belt, generator	2	18	26	1.386	60	2.00	$23.1 \cdot 10^{-6}$	$0.067 \cdot 10^{-3}$
Coil	1	10	10	1	80	5.29	$12.5 \cdot 10^{-6}$	$0.066 \cdot 10^{-3}$
Distributor	1	91	91	1	32	30.10	$31.2 \cdot 10^{-6}$	$0.939 \cdot 10^{-3}$
Generator	1	90	90	1	34	83.90	$29.1 \cdot 10^{-6}$	$2.465 \cdot 10^{-3}$
Generator regulator	1	96	96	1	37	32.90	$27.0 \cdot 10^{-6}$	$0.888 \cdot 10^{-3}$
Spark plug	4	136	174	1.396	27	0.50	$55.9 \cdot 10^{-6}$	$0.056 \cdot 10^{-3}$
Fuel								
Carburetor	1	75	75	1	35	20.00	$28.6 \cdot 10^{-6}$	$0.572 \cdot 10^{-3}$
Fuel pump	1	61	61	1	44	27.00	$22.7 \cdot 10^{-6}$	$0.613 \cdot 10^{-3}$
Cooling								
Radiator	1	101	101	1	33	25.00	$30.3 \cdot 10^{-6}$	$0.759 \cdot 10^{-3}$
Water pump	1	7	7	1	1000	12.90	$1.0 \cdot 10^{-6}$	$0.013 \cdot 10^{-3}$
Suspension								
Brake master cylinder	1	8	8	1	60	5.00	$16.7 \cdot 10^{-6}$	$0.084 \cdot 10^{-3}$
Suspension arm	2	10	10	2	70	12.50	$28.6 \cdot 10^{-6}$	$0.358 \cdot 10^{-3}$
Wheel bearing	4	97	117	2	35	30.00	$57.2 \cdot 10^{-6}$	$3.432 \cdot 10^{-3}$
Tire	4	37	194	1.267	25	1.02	$50.6 \cdot 10^{-6}$	$0.163 \cdot 10^{-3}$
Total	37	1253	1796	—	—	—	$655.1 \cdot 10^{-6}$	$17.438 \cdot 10^{-3}$

[a]Estimated.
[b]Thirty percent of list price.

TABLE A3

Degraded Equilibrium Replacement Job Rates and Costs of Prime Mobility Parts

System and part	Like-original mean life, thousands of miles	Adjusted mean life, thousands of miles	Percent of like new	Rationale of adjustment	Equilibrium replacement jobs per mile	Equilibrium parts cost, dollars per mile
Power and propulsion						
Clutch	35	35	100	a	28.6×10^{-6}	0.429×10^{-3}
Clutch bearing alone	17	17	100	a	58.8×10^{-6}	0.294×10^{-3}
Differential	475	70	15	b	14.3×10^{-6}	1.144×10^{-3}
Engine	51	36	70	c	27.8×10^{-6}	2.567×10^{-3}
Prop shaft						
Front	60	60	100	d	33.4×10^{-6}	0.341×10^{-3}
Rear	50	50	100	d	36.2×10^{-6}	0.484×10^{-3}
Transmission	32	32	100	d	31.2×10^{-6}	3.042×10^{-3}
Electrical						
Battery	60	60	100	d	20.6×10^{-6}	0.332×10^{-3}
Belt, generator	60	42	70	b	33.0×10^{-6}	0.095×10^{-3}
Coil	80	80	100	d	12.5×10^{-6}	0.066×10^{-3}
Distributor	32	32	100	d	31.2×10^{-6}	0.939×10^{-3}
Generator	34	34	100	a	29.4×10^{-6}	2.465×10^{-3}
Generator regulator	37	37	100	d	27.0×10^{-6}	0.888×10^{-3}
Spark plug	25	15	60		93.1×10^{-6}	0.133×10^{-3}
Starter	100	80	80	e	12.5×10^{-6}	0.070×10^{-3}
Fuel						
Carburetor	35	35	100	a	28.6×10^{-6}	0.572×10^{-3}
Fuel pump	44	44	100	d	22.7×10^{-6}	0.613×10^{-3}
Cooling						
Radiator	33	33	100	a	30.3×10^{-6}	0.759×10^{-3}
Water pump	1000	80	8	b	12.5×10^{-6}	0.161×10^{-3}
Suspension						
Brake master cylinder	60	60	100	d	16.7×10^{-6}	0.084×10^{-3}
Suspension arm	70	63	90	e	31.8×10^{-6}	0.397×10^{-3}
Tire	35	21	60	e	95.4×10^{-6}	2.340×10^{-3}
Wheel bearing	25	25	100	a	50.6×10^{-6}	0.163×10^{-3}
Total	—	—	—	—	778.2×10^{-6}	18.379×10^{-3}

[a]Seemed unusually bad at the beginning; when improved, age deteriorated; seems likely to end up where it was.

[b]Wear expected to set in.

[c]Anticipated rebuild quality.

[d]Its quality and that of its environment seem unlikely to deteriorate.

[e]Environmental deterioration expected.

The limited information that exists on this matter indicates that lives for repaired parts and even new parts installed subsequent to failure of the originals are less than those of the original parts. A further consideration is that the mean lives presented in Table A2 are based on only the first 19,000 miles of vehicle life; parts that have large mean lives (e.g., over 50,000 miles) and may show signs of wearout (increased failure frequency) as they approach their mean lives may have shown only small, random failure frequencies in the sample of life observed. For example, the differential and the water pump show failure frequencies in their first 19,000 miles of life indicative of mean lives of 475,000 miles and 1,000,000 miles respectively. These are regarded as unrealistic estimates on the basis of common experience with mechanical parts of such a nature. The expectation is that these parts will eventually wear out at ages considerably short of the lives listed in Table A2.

To account for these probable unrealities in Table A2, Table A3 was prepared in which mean lives were adjusted as seemed appropriate. The equilibriums in Table A3 are presented in the body of the study as "degraded" and "realistic." They are degraded in the sense that they are derived by degrading the like-original estimates.

The equilibrium total maintenance cost was derived by multiplying equilibrium parts costs derived for prime mobility parts shown in Tables A2 and A3 by a number of factors. Each prime-mobility-part cost was multiplied by the factor 2.27 or 1.37 depending on whether the part was usually replaced at second or third echelon (see Table 13 for identification of echelon at which each prime mobility part was usually replaced) to account for its SSI and repair costs and its residual value.

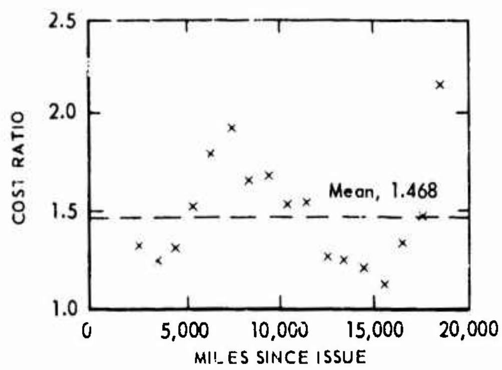


Fig. A2—Ratio of Costs: All Parts to Prime Mobility Parts

Engines and transmissions at 30 percent of list price.

Costs of other than prime mobility parts at equilibrium were derived by assuming that the total parts costs at equilibrium were divided between prime mobility and other parts in the same proportion as they were during the first 19,000 miles of life. This assumption was justified by the failure to detect any tendency of the proportion to systematically depart from its mean as a function of age. Figure A2 shows the ratio of the cost of all parts to the cost of prime mobility parts replaced in the first 19,000 miles of vehicle life in the detail sample. The SSI and repair costs and residual value of these parts were accounted for by assuming all the parts were replaced at second echelon and applying the factor 2.27 to their estimated price.

Costs of labor at equilibrium were derived in a manner similar to that in which costs of other than prime mobility parts were derived. Figure A3 shows the ratio of labor costs for replacement actions to the direct cost of parts replaced for the detail sample of M151's. The cost of labor for performing adjustments and repairs was observed to remain essentially constant with age at approximately $1 per 1000 vehicle-miles and so was left out of consideration in consonance with considering here only costs that evidence change with vehicle age.

A summary of these computations and the resulting equilibrium total maintenance costs is contained in Table A4.

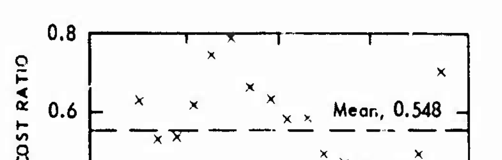


Fig. A3—Ratio of Costs: Maintenance Labor Expended on Replacements to Parts Cost of Prime Mobility Parts

Engines and transmissions at 30 percent of list price.

TABLE A4

Total Maintenance Costs

(100,000 miles)

Item	Fraction of direct prime-mobility-parts costs	Direct cost, dollars per 1000 miles	SSI, repair costs, and residual value factor	Total cost, dollars per 1000 miles
		At Like-Original Equilibrium		
Prime mobility parts	1.0	17.97[a]	{1.37[b], 2.27}	48.20[a]
Other parts	0.168	8.41	2.27	19.09
Labor	0.548	9.85	NA	9.35
Total	—	—	—	77.14[a]
		At Degraded Equilibrium		
Prime mobility parts	1.0	18.38[a]	{1.37[b], 2.27}	53.38[a]
Other parts	0.168	10.47	2.27	23.77
Labor	0.548	12.26	NA	12.26
Total	—	—	—	89.42[a]

[a]Engines and transmissions at 30 percent of list price.
[b]Used as appropriate for each prime mobility part.

PROJECTIONS OF PERFORMANCE

The projection of vehicle-breakdown rate (replacement job rate of prime mobility parts) consisted of determining at what age to expect the equilibrium to be reached and how the performance would proceed from the end of the data to equilibrium.

Equilibrium

Age of Occurrence. A number of reasons exist for expecting equilibrium by 100,000 miles. In Chap. 3 individual equilibriums for engines and transmissions are attained by approximately their mean lives, i.e., by the time only half their first replacement cycle is finished. Although these assemblies have relatively broad replacement distributions, essentially all prime mobility parts have replacement distributions as broad and broader. Of course the broader they are the more nearly constant they are and the sooner they attain their equilibrium. Many exhibit constant replacement rates and are in equilibrium from the beginning. But at any rate none should have to go beyond its mean life to attain equilibrium. This, coupled with the fact that most of the mean lives lie below 80,000 miles and in the degraded model all lie below 100,000 miles, seemed ample justification for assuming approximate equilibrium to obtain around 100,000 miles.

Manner of Approach. Equilibrium was assumed to be approached smoothly and steadily from the end of the data at 19,000 miles of vehicle life. This assumption was based on the smooth approach of engines and transmissions to their individual equilibriums observed in Chap. 3, the expected smoother approach by other individual assemblies with distributions broader than those of engines and transmissions, the smooth approach of the combined engines and transmissions observed in Chap. 3, and the smoothing effects of the broad distribution of prime-mobility-part lives shown in Fig. A4.

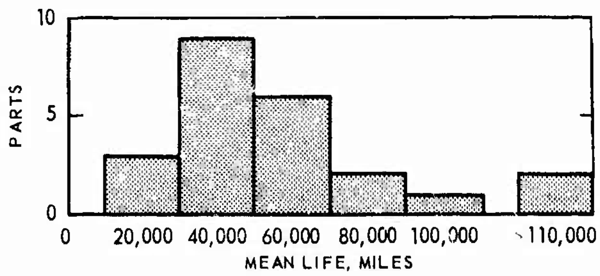


Fig. A4—Distribution of Like-Original Mean Lives of Prime Mobility Parts

Curve Form. By inspection of the data and the equilibrium (e.g., as plotted in Fig. A5) it was assumed curves of the form

$$P(t) = P(\infty) - [P(\infty) - P(0)]e^{-\rho t},$$

where P = the parameter to be projected
t = the age parameter
$P(\infty)$ = the equilibrium value of P
$P(0)$ = the initial value of P
ρ = a constant controlling the rate at which equilibrium is approached

could suitably fit the data and connect them smoothly and asymptotically with the equilibrium. By treating the equilibrium as an asymptote the question of when equilibrium will occur is relegated to the data, the equilibrium level, and the curve form. The fact that this answer was also about 100,000 miles was regarded as evidence that the curve form chosen was appropriate.

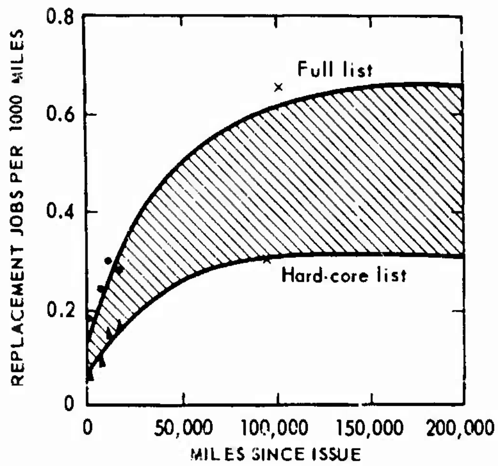


Fig. A5—Projection of Replacement Job Rate of Prime Mobility Parts

- • Prime mobility part replacement jobs per 1000 miles
- ▲ Hard-core jobs per 1000 miles
- × Estimated equilibrium

Projections of Vehicle-Breakdown Rate

Like Original. An estimate of the equilibrium breakdown rate was made by estimating from the replacement experience the mean life of each of the original parts and forming the sum of the reciprocals. The estimated equilibrium was 0.655 replacement jobs per 1000 miles of vehicle use for the full list, and 0.310 for the hard-core list.

The data to be fitted were reduced to five points for each fit to be obtained (one for each of the first four 5000-mile intervals of vehicle life and the equilibrium) as illustrated for the full list and hard-core list of mobility parts in Table A5.

From a sketch of the curve the initial values P(0) were estimated. Given P(0), a ρ for each data point could be computed from the assumed equation. If the ρ seemed consistent the P(0) was assumed appropriate and a useful fit was found. The equation parameters and the "fit" points corresponding to the data points are shown in Tables A6 and A7. The curves fit the asymptotes identically; the full-list curves fit the data at a χ^2 level of about 0.50; the hard-core curves with a χ^2 level of about 0.80. Thus all four curves fit well if a χ^2 level of 0.95 or higher is taken as the rejection criterion. Figure A5 shows the resulting curve and observed data points. This analysis treats the estimated

TABLE A5

Data Points on Which Projections of Vehicle Failure Rate Were Based

Age interval, in units of 5000 miles	Failures per 1000 miles	
	Like original	Degraded
Full List of Mobility Parts		
1	0.183	0.183
2	0.240	0.240
3	0.295	0.295
4	0.330	0.330
.		
.		
.		
Equilibrium	0.655	0.778
Hard-Core Prime Mobility Parts		
1	0.068	0.068
2	0.100	0.100
3	0.155	0.155
4	0.170	0.170
.		
.		
.		
Equilibrium	0.310	0.345

TABLE A6

Equation Parameters and Derived Points Corresponding to Data Points for Projected Vehicle-Failure Rate

Age interval, in units of 5000 miles	Derived rate, failures per 1000 miles	
	Like original[a]	Degraded[b]
1	0.182	0.173
2	0.242	0.239
3	0.294	0.298
4	0.341	0.350
.		
.		
.		
10	0.653	0.771
.		
.		
.		
Equilibrium	0.655	0.778

[a] P(0) 0.112, ρ 0.137.
[b] P(0) 0.100, ρ 0.115.

equilibrium as an asymptote that was never quite actually attained but was essentially attained at what seemed a reasonable time in life—about 100,000 miles—consistent with the expectation developed in the subsection, "Equilibrium."

A number of limitations of the projection, which deserve careful consideration during interpretation of it, are now noted. They are generally attributable to the shortness of the sample in the age dimension.

TABLE A7

Equation Parameters and Derived Points Corresponding to Data Points for Projecting Hard-Core Vehicle-Breakdown Rate

Age interval, in units of 5000 miles	Derived rate, breakdowns per 1000 miles	
	Like-original[a]	Degraded[b]
1	0.074	0.073
2	0.111	0.110
3	0.143	0.142
4	0.169	0.170
.		
.		
.		
40	0.310	0.344
.		
.		
.		
Equilibrium	0.310	0.345

[a]r(0) 0.030, ρ 0.171.
[b]r(0) 0.030, ρ 0.147.

(a) At observed usage rates—about 7000 miles/year—the range of the projection in time is about 29 years. However, no accounting for the effects of time was made beyond those "built into" the accumulation of the 19,000 miles of data over a 2-year period. It seems quite possible that deleterious effects resulting from exposure to the elements may set in sometime during the range of the projection, which had not yet set in during the period of life observed.

(b) The mean lives of prime mobility parts on which the equilibrium breakdown rate was based were derived from replacement data for the original parts of the vehicle; thus they are the lives of new parts operating in a new environment. However, it is expected that after a time many replacement parts will not be new but will be repaired or rebuilt, and experiences of past studies[3,4,21] are that rebuilt assemblies do not have the same life as the original ones. Furthermore the operating environment of the parts will generally be deteriorated from what it was when the vehicle was new, further accelerating wear-out.

(c) As shown in Tables A2 and A3, a few prime mobility parts, which are expected eventually to exhibit increasing replacement rates as they begin to wear out, were not observed to have done so during the first 19,000 miles of M151 life. The random rate they did show was often low and led to intuitively unrealistic mean lives. The inclusion of "realistic" mean lives for these parts would have the effect of raising the estimated equilibrium breakdown rate.

(d) The estimated equilibrium is low to the extent that there are a number of other parts not included in the analysis that could eventually fail with significant frequency to affect mobility.

(e) The usage rate is assumed to remain at about 7000 miles/year. The replacement probability of a part is no doubt influenced by the mileage accumulation rate. The evidence of some past studies[3] indicates that lower probabilities of failure per mile and hence larger mean mileage lives are associable with higher rates of use.

Each of the points raised was examined in some detail. It was generally felt that only points b and c might significantly influence the equilibrium estimate. Data on which to estimate the influence of point e did not exist—the indications of past studies[3] are that deviations from the observed use rate of up to ±25 percent are likely to have small influence. The effects of long exposure to the elements and to the user environment, which were not observable in the first 20,000 miles of life (3 years or less), raised as point b are unknown.

Degraded. Based on a performance degraded to account for the influences of points b and c, an equilibrium of 0.778 replacement jobs per 1000 miles of operation was estimated for the full list (19 percent greater than that estimated directly from the data); the degraded hard-core equilibrium was 0.345 jobs per 1000 miles (11 percent higher than the like original). The projections based on this equilibrium are shown in Fig. A6 along with the original projection. The degraded is probably the more realistic estimate.

For lack of more information or a better estimate the degraded estimate presented in Fig. A6 is the one on which lifetime calculations are based and is viewed as the best prediction of vehicle performance that can be made from the data and general knowledge of the study.

The projections are generally characterized by relatively steep ascents to 50,000 miles, then a gradual further ascent to equilibrium, which is pretty well attained by 100,000 miles. The range of breakdown rates encompassed by the full list of prime mobility parts and the hard-core list is represented pretty well by the magnitude of the hard-core rate itself, indicating that the hard core accounts for a fairly constant 40 to 50 percent of the total breakdowns. By interpolating a value through the center of these projections, new vehicles have a breakdown rate on the order of 10 breakdowns per 100 vehicles in moving 1000 miles. This rate increases steadily to about four times that value by 50,000 miles; equilibrium is about five times the initial value. Thus of the total five-fold increase from initial breakdown rate out to about 100,000 miles of vehicle life, 80 percent of it occurs in the first half of the period.

Projections of Other Performance Measures

Having projected the breakdown rate h, projections of mean miles per breakdown, availability potential, reliability, and mission-success index could be straightforwardly derived by the formulas describing their dependence on h presented earlier. These projections are shown in Figs. A7 to A11.

Projections are shown to 200,000 miles to illustrate plainly the asymptotic nature of the projections and the relative flatness after 100,000 miles. As has been noted earlier, the purpose has been not to predict the performance of

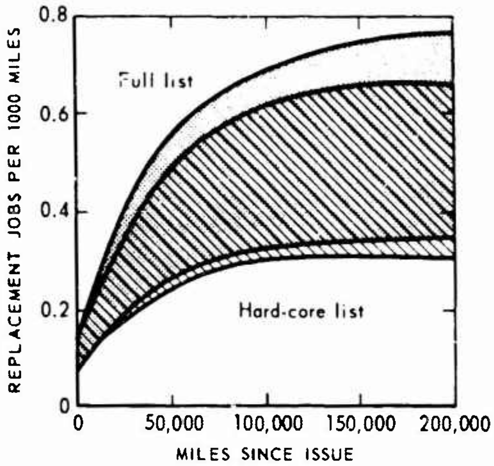
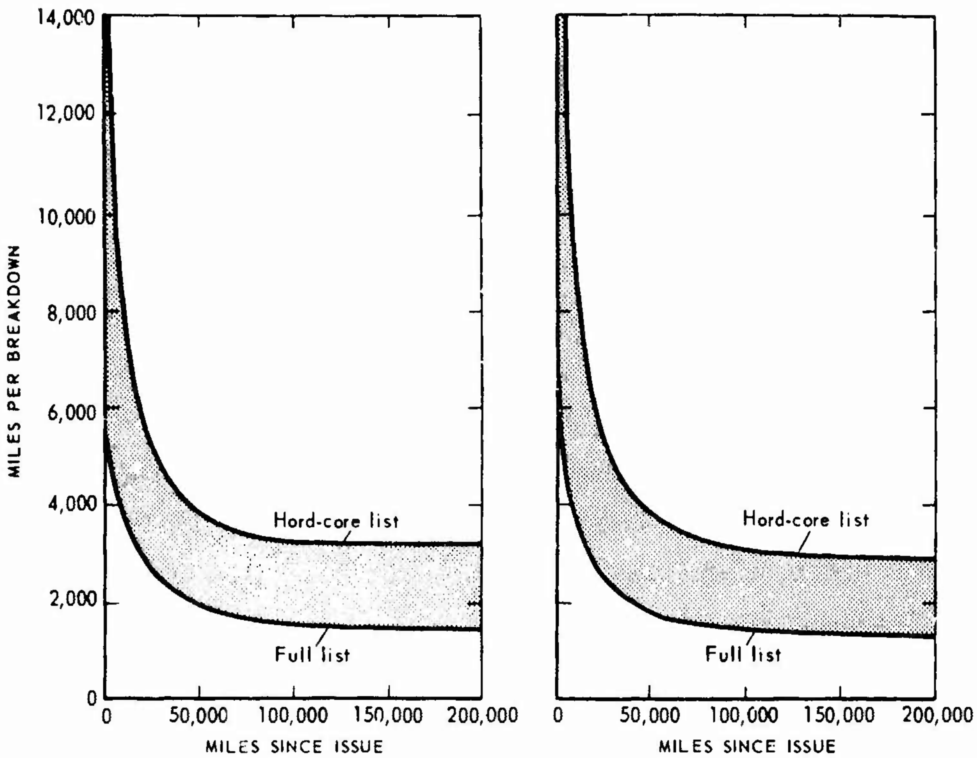


Fig. A6—Two Projections of the Replacement Job Rate of Prime Mobility Parts Compared

One assuming parts always perform as did originals, the other a degraded performance for some parts.

Degraded   Like original



a. Like-Original Projection

b. Degraded Projection

Fig. A7—Mean Miles per Vehicle Breakdown as a Function of Vehicle Age

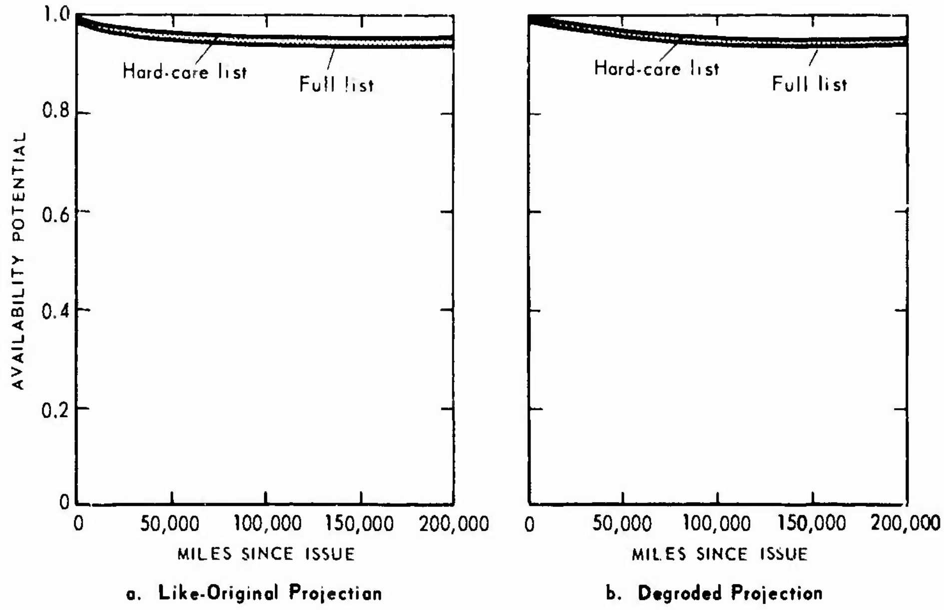


Fig. A8—Availability Potential

Use rate: 550 miles/month.

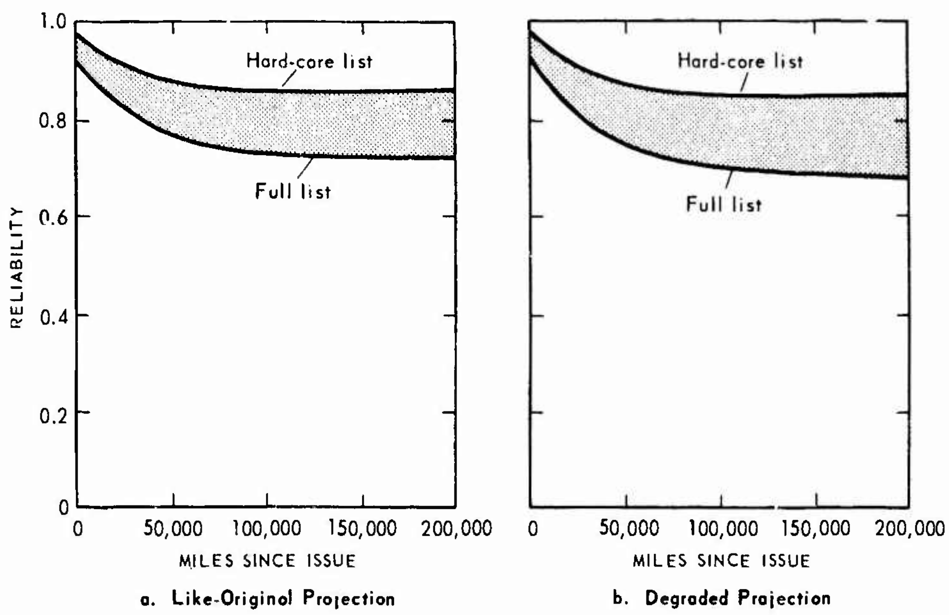
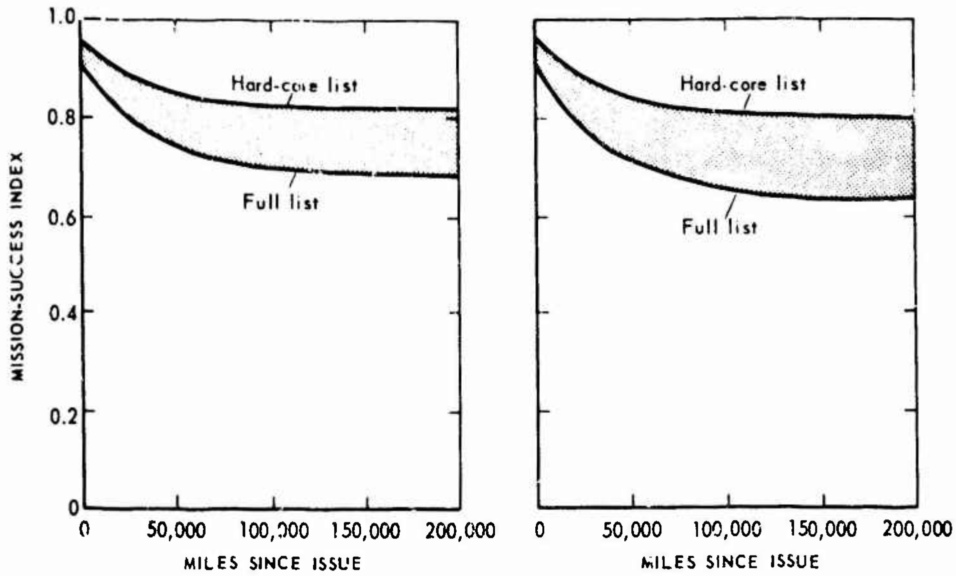


Fig. A9—Reliability

Mission: 500 miles.

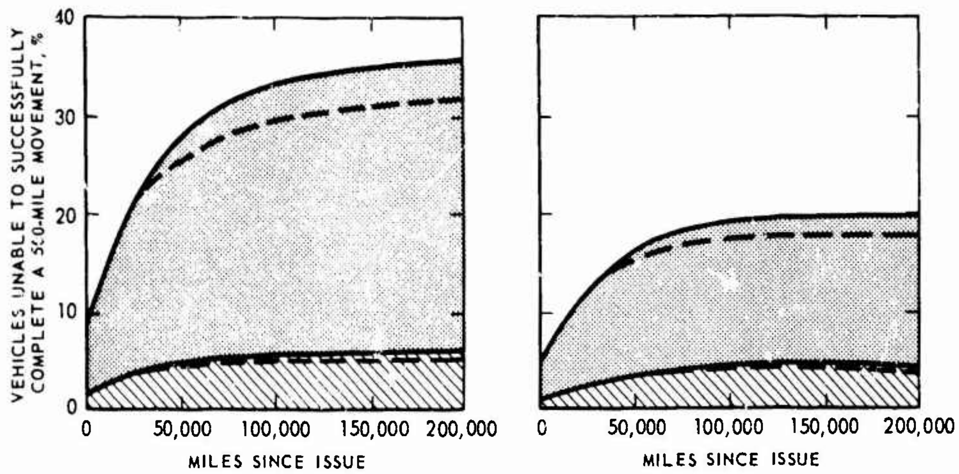


a. Like-Original Projection

b. Degraded Projection

Fig. A10—Mission-Success Index

Use rate: 550 miles/month; mission: 500 miles.



a. Based on Full List of Prime Mobility Parts

b. Based on Hard-Core Prime Mobility Parts

Fig. A11—Degraded Projection of Mission Failure

Use rate: 550 miles/month; mission: 500 miles.

Dropouts   Nonstarters   —— Like original

200,000-mile-old ¼-ton trucks, but rather to take account of presently detectable long-range trends to better estimate performance in some intermediate range—20,000 to 80,000 miles. The projections now shown are included simply as reference material. Projections are shown for both like-original and degraded estimates of performance. The important implications of these projections for the study are presented in Chap. 4.

PROJECTIONS OF UNSCHEDULED MAINTENANCE COSTS

Maintenance costs were assumed to parallel breakdown rate and so to proceed to equilibrium according to the same curve form as that used to project breakdown rate. In Tables A8 and A9 the data points and the derived points and

TABLE A8

Data Points on Which Projections of Maintenance Costs Were Based

Age interval, in units of 5000 miles	Maintenance costs, dollars per 1000 miles	
	Like-original	Degraded
1	23.91	23.91
2	34.27	34.27
3	46.32	46.32
4	62.37	62.37
.		
.		
.		
Equilibrium	77.14	89.42

TABLE A9

Equation Parameters and Derived Points Corresponding to Data Points for Projected Maintenance Costs

Age interval, in units of 5000 miles	Derived maintenance costs, dollars per 1000 miles	
	Like original[a]	Degraded[b]
1	23.76	23.96
2	35.86	36.02
3	45.27	45.99
4	52.53	54.04
.		
.		
.		
40	77.14	89.40
.		
.		
.		
Equilibrium	77.14	89.42

[a] P(0) 8.00; ρ 0.258.
[b] P(0) 9.00; ρ 0.205.

curve parameters respectively are shown. The curves are shown in Fig. A17. As with breakdown rate, the projections fit the equilibrium points exactly, asymptotically. The like-original projection is an unacceptable fit by the χ^2 level of less than 0.95, the criterion for acceptability. The degraded projection is acceptable at a χ^2 level of about 0.80. The unit cost used in the χ^2 tests was \$25, approximately the mean cost per unscheduled maintenance action (\$27.33) derived in Chap. 2.

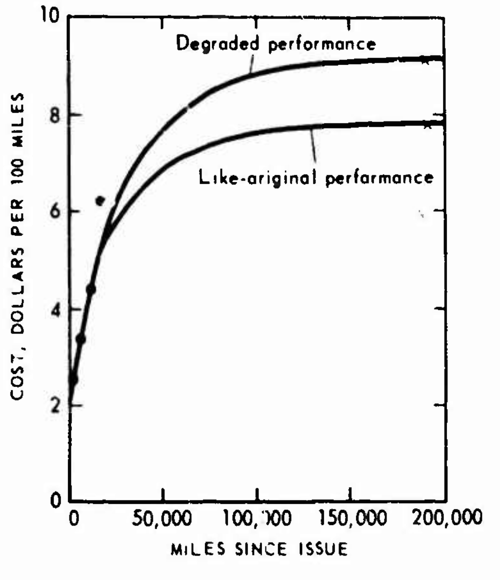


Fig. A12—Projected Maintenance Costs

● Data points
× Estimated equilibriums

Parts costs, labor man-hours, and man-hour costs were not projected separately. (Apparently their projections would be similar in form to the projections costs shown in Fig. A12.) However, Figs. A13 through A17 do show their observed values compared with their expected equilibriums.

REPRESENTABILITY OF TOTAL SAMPLE BY DETAIL SAMPLE

In costing, the detail sample was relied on as the source of all costs except those of prime mobility parts replaced. In particular, the ratios of labor costs and other (not prime mobility) parts costs to prime-mobility-parts costs in the detail sample were applied to the prime-mobility-parts costs of the total sample to estimate total costs. The validity of this procedure depends to a considerable extent on similarities between the samples. The only direct comparison possible is between the costs of prime mobility parts in each sample. Figure A18 reveals the samples to be similar in this respect. The coefficient of correlation between the two sets of cost points is 0.742.

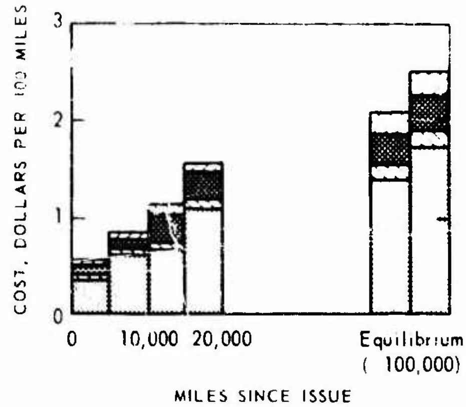


Fig. A13—Cost of Parts Replaced as a Function of Vehicle Age

DX items costed at 30 percent of list price.

Engine Tires
Transmission Other

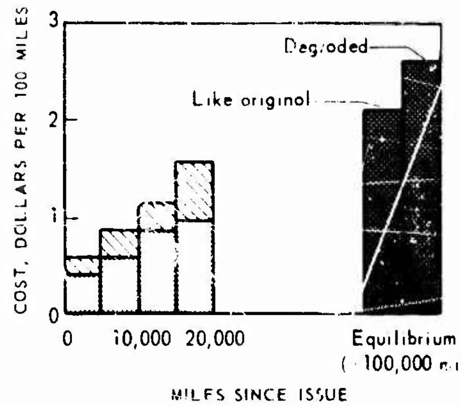


Fig. A14—Cost of Parts Replaced as a Function of Vehicle Age, by Echelon

DX items costed at 30 percent of list price.

3d echelon 2d echelon

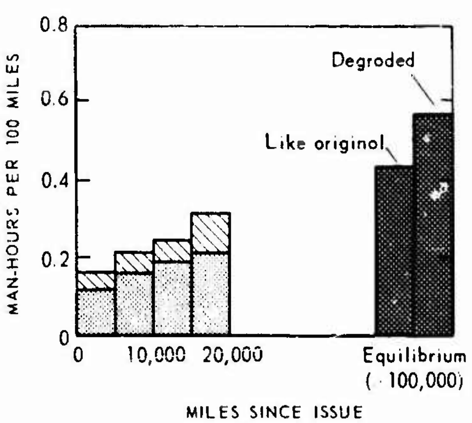


Fig. A15—Direct Maintenance Labor Consumed as a Function of Vehicle Age

3d echelon 2d echelon

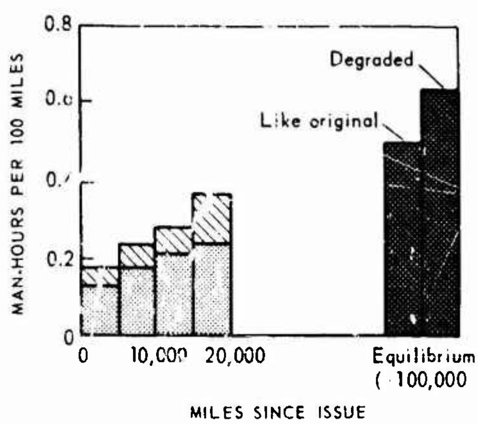


Fig. A16—Direct and Supervisory Maintenance Labor Consumed as a Function of Vehicle Age

3d echelon 2d echelon

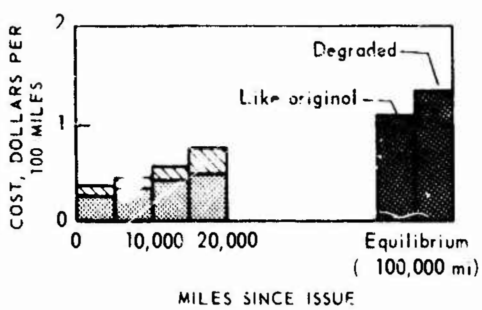


Fig. A17—Cost of Direct and Supervisory Maintenance Labor as a Function of Vehicle Age

3d echelon   2d echelon

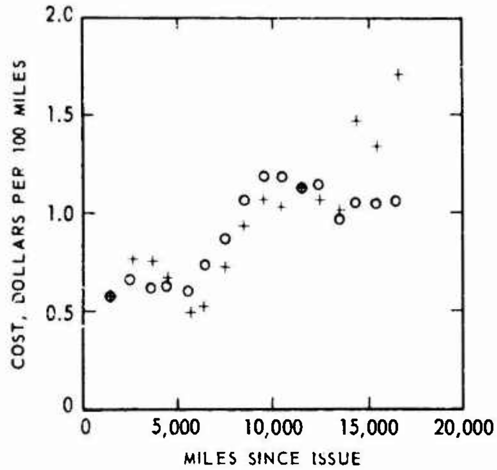


Fig. A18—Cost of Prime Mobility Parts Replaced in the Detailed Sample and in the Total Sample

Coefficient of correlation is 0.742.

+ Detailed sample   o Total sample

PROCUREMENT AND PREMATURE LOSSES

The constant procurement quantity p required to maintain a constant fleet size when the member vehicles have lifetime L and premature-loss rate w (discussed at the end of Chap. 6 and presented graphically in Fig. 52) was derived as follows. Consider p to consist of two parts: (1) p_n , replacements for vehicles attaining age L during the procurement year, and (2) p_w , replacements for vehicles not attaining age L during the procurement year but lost for other reasons (e.g., accidents). Thus

$$p = p_n + p_w \, . \tag{A1}$$

Current year	
1 year ago	$pw(1-w)^{L-2}$
2 years ago	$pw(1-w)^{L-3}$
. . .	. . .
$(L-3)$ years ago	$w[p - pw(1-w) - pw] = pw(1-w)^2$
$(L-2)$ years ago	$w(p - wp) = pw(1-w)$
$(L-1)$ year ago	wp
L years ago	

Fig. A19—Premature Losses by Year of p Vehicles Bought L Years Ago

Loss rate is w per year.

Now p_n is just p, the number of vehicles bought L years ago, less those that have been lost meanwhile. As Fig. A19 shows, the latter quantity is just $pw \sum_{k=0}^{L-2} (1-w)^k$. Hence

$$p_n = p\left[1 - w \sum_{k=0}^{L-2} (1-w)^k\right]. \qquad \text{(A2)}$$

Noting that the sum in Eq 2 is just the sum of a geometric series with L-1 terms, first term 1, and ratio $(1-w)$, Eq 2 may be rewritten

$$p_n = p(1-w)^{L-1}. \qquad \text{(A3)}$$

The other part of p (i.e., p_w) is just the premature-loss rate times the fleet size less those that will attain age L and so will be replaced anyway this year, namely p_n. Thus

$$p_w = w(1-p_n). \qquad \text{(A4)}$$

Combining Eqs 1, 3, and 4 and solving for p yields

$$p = \frac{w}{1-(1-w)^L}. \qquad \text{(A5)}$$

Appendix B

REPLACEMENT RATES OF PRIME MOBILITY PARTS

INTRODUCTION

This appendix contains tables and graphs of the replacement rates of M151 prime mobility parts on which the performance analyses of Chaps. 3 and 4 were based and the cost analysis of Chap. 5 heavily relied. The rates were produced by a computer routine described briefly in RAC-T-460[5] and in greater detail in RAC-T-465.[26]

RATES

Rates of occurrence of two kinds of replacement actions were calculated as a function of vehicle age. One kind is called a "replacement job," the other simply a "replacement." The distinction is relevant for parts used in the M151 in numbers greater than one, e.g., spark plugs and tires. For such parts, a replacement job is a maintenance action involving the replacement of any number of parts, including replacement of the complete set. A replacement, on the other hand, is the maintenance action constituted by replacing one part. Thus a replacement job consists of one or more replacements.

The rate of occurrence of replacement jobs was taken to be a measure of vehicle reliability. The rate of occurrence of replacements was regarded as a measure of part life and part reliability; it was also used in conjunction with part prices to develop costs of parts consumed.

The rates were calculated as follows: for each 1000-mile-usage interval j in which M151 activity was observed, counts were made of the number of vehicles V_j observed throughout the interval and, for these vehicles, the number of replacement jobs J_j and replacements Q_j experienced by each prime mobility part. Replacement job rates RJ were then calculated for each usage interval j by

$$RJ_j = J_j/V_j$$

Replacement rates RQ_j were calculated by

$$RQ_j = Q_j/qV_j$$

where q is the quantity of the part on a vehicle.

For engines and transmissions a more detailed analysis was made. (Because there is only one of each assembly per vehicle the discussion can be confined to only one kind of rate—the replacement rate.) For each assembly type, replacements were identified by order of replacement on a given vehicle as well as by the usage interval in which it occurred; replacements of original assemblies were assigned order number one, replacements of second assemblies were assigned order number two, etc. Also for each usage interval, counts of vehicles that had not yet experienced replacements of a particular order were formed for orders one through four.

Starting with these basic counts, replacement rates of three kinds were computed for each order i. The rate among vehicles that had not yet experienced a replacement of the order were formed by

$$K_{ij} = E_{ij}/V_{ij}$$

where K is the rate, E_{ij} is the number of replacements of order i made in usage interval j, and V_{ij} is the number of vehicles observed in usage interval j that had not yet experienced a replacement of order i. In much literature this rate is called the hazard rate (when a replacement is regarded as a failure).

From this point replacement rates among all vehicles observed in the interval were computed for each order by the recursion

$$R_{ij} = T_j \cdot K_{ij}$$

$$T_j = T_{j-1} - R_{ij-1}, \quad T_1 = 1.0$$

where R_{ij} is the rate of ith order replacements in usage interval j. Replacement rates R_j, analogous to those computed for all prime mobility parts, were calculated by

$$R_j = \sum_i R_{ij}$$

The third kind of rate was just the cumulative of the rate by order for all orders among all vehicles. These were

$$RC_{ij} = \sum_{k=1}^{j} RC_{ik}$$

and

$$RC_j = \sum_{k=1}^{j} R_k$$

where RC represents cumulative R.

SAMPLE

The M151 sample on which the rates presented here were based was that described in Chap. 1. Its distribution in usage (shown graphically in Fig. 3) is shown in tabular form in Table B1. These are the vehicle counts V_j mentioned in the previous section.

As discussed in Chap. 1, the introduction of TAERS, which occurred subsequent to the issue of many of the vehicles, made available maintenance data on many more parts usually attended to at second echelon. For such parts only the period of observation covered by TAERS was used as the basis of their replacement rates. Indeed, in what was in retrospect a possibly conservative de-

TABLE B1

Usage Distribution of M151 Sample

Usage interval, miles		Vehicles in full sample	Vehicles in TAERS-covered sample
Greater than or equal to	Less than		
0	1,000	762[a]	0
1,000	2,000	761	190
2,000	3,000	755	299
3,000	4,000	747	324
4,000	5,000	735	334
5,000	6,000	720	343
6,000	7,000	710	360
7,000	8,000	680	351
8,000	9,000	634	353
9,000	10,000	598	370
10,000	11,000	550	376
11,000	12,000	484	342
12,000	13,000	392	300
13,000	14,000	315	260
14,000	15,000	260	227
15,000	16,000	218	202
16,000	17,000	172	167
17,000	18,000	138	137
18,000	19,000	113	111
19,000	20,000	88	88
20,000	21,000	63	63
21,000	22,000	46	46
22,000	23,000	35	35
23,000	24,000	28	28
24,000	25,000	18	18
25,000	26,000	11	11
26,000	27,000	7	7
27,000	28,000	4	4
28,000	29,000	1	1
29,000	30,000	1	1
Total		10,046	5348

[a]This sample, from which parts-replacement rates were developed, inadvertently has ten fewer vehicles than that shown as the total sample in Chap. 1. Having included the ten would have altered the computed rates negligibly.

cision, only engine and transmission replacement rates were developed for the full sample of life observed.

TABLES

The tables of replacement job and replacement rates (see Tables B2 through B4) are essentially self-explanatory. Engine and transmission rates are presented in two different formats. In one they are presented the same as are all the other parts. In the other they are shown by order and as rates among vehicles yet to experience the order (hazard rates), as rates among all vehicles, and as cumulative rates among all vehicles.

TABLE B2

Replacement Rates of Prime Mobility Parts

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
		Clutch Bearing[a]			
0	1	—	—	—	—
1	2	0	0	0	0
2	3	2	2	0.007	0.007
3	4	5	5	0.015	0.015
4	5	5	5	0.015	0.015
5	6	4	4	0.012	0.012
6	7	3	3	0.008	0.008
7	8	6	6	0.017	0.017
8	9	4	4	0.011	0.011
9	10	5	5	0.013	0.013
10	11	5	5	0.013	0.013
11	12	3	3	0.009	0.009
12	13	2	2	0.006	0.006
13	14	6	6	0.022	0.022
14	15	2	2	0.009	0.009
15	16	2	2	0.009	0.009
16	17	3	3	0.017	0.017
17	18	1	1	0.007	0.007
18	19	7	7	0.059	0.059
19	20	3	3	0.031	0.031
20	21	0	0	0	0
21	22	0	0	0	0
22	23	2	2	0.055	0.055
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	70	70	—	—
		Clutch Disk[a]			
0	1	—	—	—	—
1	2	1	1	0.005	0.005
2	3	2	2	0.007	0.007
3	4	4	4	0.012	0.012
4	5	6	6	0.018	0.018
5	6	1	1	0.003	0.003
6	7	5	5	0.014	0.014
7	8	5	5	0.014	0.014
8	9	4	4	0.011	0.011
9	10	2	2	0.005	0.005
10	11	4	4	0.010	0.010
11	12	1	1	0.003	0.003

TABLE B2 (continued)

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
12	13	3	3	0.009	0.009
13	14	4	4	0.015	0.015
14	15	0	0	0	0
15	16	2	2	0.009	0.009
16	17	1	1	0.006	0.006
17	18	1	1	0.007	0.007
18	19	3	3	0.026	0.026
19	20	1	1	0.011	0.011
20	21	0	0	0	0
21	22	0	0	0	0
22	23	1	1	0.027	0.027
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	51	51	—	—
		Clutch Plate°			
0	1	—	—	—	—
1	2	0	0	0	0
2	3	2	2	0.007	0.007
3	4	1	1	0.003	0.003
4	5	4	4	0.012	0.012
5	6	1	1	0.003	0.003
6	7	3	3	0.008	0.008
7	8	4	4	0.011	0.011
8	9	4	4	0.011	0.011
9	10	6	6	0.016	0.016
10	11	7	7	0.018	0.018
11	12	1	1	0.003	0.003
12	13	2	2	0.006	0.006
13	14	4	4	0.015	0.015
14	15	1	1	0.004	0.004
15	16	1	1	0.005	0.005
16	17	2	2	0.011	0.011
17	18	1	1	0.007	0.007
18	19	4	4	0.034	0.034
19	20	2	2	0.021	0.021
20	21	0	0	0	0
21	22	0	0	0	0
22	23	1	1	0.027	0.027
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0

TABLE B2 (continued)

Usage interval, thous of miles: Greater than or equal to	Usage interval, thous of miles: Less than	Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
28	29	0	0	0	0
29	30	0	0	0	0
	Total	51	51	—	—
		Clutch Parts Kit[a]			
0	1	—	—	—	—
1	2	1	1	0.005	0.005
2	3	0	0	0	0
3	4	0	0	0	0
4	5	0	0	0	0
5	6	1	1	0.003	0.003
6	7	2	2	0.006	0.006
7	8	3	3	0.008	0.008
8	9	1	1	0.003	0.003
9	10	2	2	0.005	0.005
10	11	5	5	0.013	0.013
11	12	1	1	0.003	0.003
12	13	5	5	0.016	0.016
13	14	1	1	0.004	0.004
14	15	2	2	0.008	0.008
15	16	3	3	0.014	0.014
16	17	5	5	0.029	0.029
17	18	3	3	0.021	0.021
18	19	1	1	0.009	0.009
19	20	0	0	0	0
20	21	0	0	0	0
21	22	0	0	0	0
22	23	1	1	0.025	0.025
23	24	1	1	0.032	0.032
24	25	1	1	0.050	0.050
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	39	39	—	—
		Differential[b]			
0	1	—	—	—	—
1	2	0	0	0	0
2	3	0	0	0	0
3	4	2	2	0.006	0.003
4	5	0	0	0	0
5	6	0	0	0	0
6	7	1	1	0.003	0.001
7	8	0	0	0	0
8	9	1	1	0.003	0.001
9	10	2	2	0.005	0.003

TABLE B2 (continued)

Usage interval, thous of miles: Greater than or equal to	Usage interval, thous of miles: Less than	Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
10	11	3	3	0.008	0.004
11	12	1	1	0.003	0.001
12	13	1	1	0.003	0.002
13	14	0	0	0	0
14	15	0	0	0	0
15	16	0	0	0	0
16	17	0	0	0	0
17	18	2	2	0.015	0.007
18	19	1	1	0.009	0.005
19	20	0	0	0	0
20	21	0	0	0	0
21	22	0	0	0	0
22	23	0	0	0	0
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	11	14	—	—
		Engine[a]			
0	1	2	2	0.003	0.003
1	2	3	3	0.004	0.004
2	3	4	4	0.005	0.005
3	4	2	2	0.003	0.003
4	5	6	6	0.008	0.008
5	6	4	4	0.006	0.006
6	7	4	4	0.006	0.006
7	8	2	2	0.003	0.003
8	9	7	7	0.011	0.011
9	10	6	6	0.010	0.010
10	11	4	4	0.007	0.007
11	12	5	5	0.010	0.010
12	13	5	5	0.013	0.013
13	14	4	4	0.013	0.013
14	15	3	3	0.011	0.011
15	16	1	1	0.005	0.005
16	17	3	3	0.017	0.017
17	18	1	1	0.007	0.007
18	19	2	2	0.017	0.017
19	20	2	2	0.022	0.022
20	21	2	2	0.031	0.031
21	22	0	0	0	0
22	23	0	0	0	0
23	24	0	0	0	0
24	25	1	1	0.052	0.052

TABLE B2 (continued)

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	73	73	—	—
		Front Prop Shaft[b]			
0	1	—	—	—	—
1	2	0	0	0	0
2	3	4	4	0.013	0.007
3	4	1	1	0.003	0.002
4	5	4	4	0.012	0.006
5	6	2	2	0.006	0.003
6	7	1	1	0.003	0.001
7	8	0	0	0	0
8	9	2	2	0.006	0.003
9	10	0	0	0	0
10	11	1	1	0.003	0.001
11	12	3	3	0.009	0.004
12	13			0.010	0.005
13	14			0.011	0.006
14	15	3	3	0.013	0.007
15	16	1	1	0.005	0.003
16	17	1	1	0.006	0.003
17	18	0	0	0	0
18	19	1	1	0.009	0.004
19	20	2	2	0.021	0.011
20	21	1	1	0.015	0.008
21	22	0	0	0	0
22	23	0	0	0	0
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	33	33	—	—
		Rear Prop Shaft[b]			
0	1	—	—	—	—
1	2	0	0	0	0
2	3	1	1	0.003	0.002
3	4	5	5	0.015	0.008
4	5	2	2	0.006	0.003
5	6	1	1	0.003	0.001
6	7	1	1	0.003	0.001

TABLE B2 (continued)

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
7	8	2	2	0.006	0.003
8	9	1	1	0.003	0.001
9	10	0	0	0	0
10	11	0	0	0	0
11	12	0	0	0	0
12	13	1	1	0.003	0.002
13	14	1	1	0.004	0.002
14	15	1	1	0.004	0.002
15	16	1	1	0.005	0.002
16	17	1	2	0.006	0.006
17	18	0	0	0	0
18	19	0	0	0	0
19	20	1	2	0.011	0.011
20	21	0	0	0	0
21	22	1	1	0.022	0.011
22	23	0	0	0	0
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0		0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	20	22	—	—
		Transmission[a]			
0	1	6	6	0.008	0.008
1	2	3	3	0.004	0.004
2	3	3	3	0.004	0.004
3	4	4	4	0.005	0.005
4	5	7	7	0.010	0.010
5	6	3	3	0.004	0.004
6	7	8	8	0.011	0.011
7	8	6	6	0.009	0.009
8	9	8	8	0.013	0.013
9	10	14	14	0.023	0.023
10	11	13	13	0.023	0.023
11	12	14	14	0.028	0.028
12	13	5	5	0.012	0.012
13	14	11	11	0.034	0.034
14	15	7	7	0.026	0.026
15	16	4	4	0.017	0.017
16	17	10	10	0.054	0.054
17	18	4	4	0.028	0.028
18	19	2	2	0.016	0.016
19	20	2	2	0.021	0.021
20	21	3	3	0.045	0.045
21	22	2	2	0.037	0.037
22	23	0	0	0	0

TABLE B2 (continued)

Usage interval, thous of miles: Greater than or equal to	Usage interval, thous of miles: Less than	Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
23	24	1	1	0.030	0.030
24	25	1	1	0.047	0.047
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	141	141	—	—
	Battery[b]				
0	1	—	—	—	—
1	2	1	2	0.005	0.005
2	3	5	7	0.017	0.012
3	4	1	1	0.003	0.002
4	5	0	0	0	0
5	6	1	2	0.003	0.003
6	7	2		0.006	
7	8	1		0.003	
8	9	1	2	0.003	0.003
9	10	2	4	0.005	0.005
10	11	3	6	0.008	0.008
11	12	3	4	0.009	0.006
12	13	0	0	0	0
13	14	5	7	0.019	0.013
14	15	3	4	0.013	0.009
15	16	5	5	0.021	0.012
16	17	2	4	0.012	0.012
17	18	0	0	0	0
18	19	0	0	0	0
19	20	0	0	0	0
20	21	1	2	0.015	0.015
21	22	0	0	0	0
22	23	0	0	0	0
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	36	54	—	—
	Generator Belt[b]				
0	1	—	—	—	—
1	2	1	2	0.005	0.005
2	3	1	1	0.003	0.002
3	4	0	0	0	0
4	5	0	0	0	0
5	6	0	0	0	0

FOR OFFICIAL USE ONLY

TABLE B2 (continued)

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
6	7	0	0	0	0
7	8	1	2	0.003	0.003
8	9	1	1	0.003	0.001
9	10	4	6	0.011	0.008
10	11	4	6	0.011	0.011
11	12	5	7	0.015	0.010
12	13	1	2	0.003	0.003
13	14	0	0	0	0
14	15	0	0	0	0
15	16	0	0	0	0
16	17	1	1	0.006	0.003
17	18	1	1	0.007	0.004
18	19	1	1	0.009	0.004
19	20	0	0	0	0
20	21	1	1	0.016	0.008
21	22	0	0	0	0
22	23	0	0	0	0
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	22	33	—	—
		Coil[a]			
0	1	—	—	—	—
1	2	0	0	0	0
2	3				
3	4				
4	5	0	0	0	0
5	6	1	1	0.003	0.003
6	7	0	0	0	0
7	8	2	2	0.006	0.006
8	9	0	0	0	0
9	10	0	0	0	0
10	11	1	1	0.003	0.003
11	12	3	3	0.009	0.009
12	13	1	1	0.003	0.003
13	14	1	1	0.004	0.004
14	15	1	1	0.004	0.004
15	16	0	0	0	0
16	17	0	0	0	0
17	18	0	0	0	0
18	19	0	0	0	0
19	20	0	0	0	0
20	21	0	0	0	0
21	22	0	0	0	0

FOR OFFICIAL USE ONLY

TABLE B2 (continued)

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
22	23	0	0	0	0
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	10	10	—	—
		Distributor[a]			
0	1	—	—	—	—
1	2	1	1	0.005	0.005
2	3	4	4	0.013	0.013
3	4	8	8	0.025	0.025
4	5	7	7	0.021	0.021
5	6	7	7	0.020	0.020
6	7	9	9	0.025	0.025
7	8	3	3	0.008	0.008
8	9	8	8	0.022	0.022
9	10	5	5	0.013	0.013
10	11	10	10	0.025	0.025
11	12	6	6	0.017	0.017
12	13	2	2	0.006	0.006
13	14	8	8	0.029	0.029
14	15	0	0	0	0
15	16	2	2	0.009	0.009
16	17	4	4	0.021	0.021
17	18	2	2	0.013	0.013
18	19	3	3	0.023	0.023
19	20	3	3	0.027	0.027
20	21	5	5	0.069	0.069
21	22	0	0	0	0
22	23	0	0	0	0
23	24	1	1	0.033	0.033
24	25	0	0	0	0
25	26	1	1	0.105	0.105
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	99	99	—	—
		Generator[a]			
0	1	—	—	—	—
1	2	1	1	0.005	0.005
2	3	3	3	0.010	0.010
3	4	6	6	0.019	0.019

TABLE B2 (continued)

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
4	5	9	9	0.027	0.027
5	6	4	4	0.012	0.012
6	7	8	8	0.022	0.022
7	8	9	9	0.025	0.025
8	9	7	7	0.020	0.020
9	10	11	11	0.029	0.029
10	11	13	13	0.034	0.034
11	12	6	6	0.017	0.017
12	13	8	8	0.025	0.025
13	14	4	4	0 014	0.014
14	15	2	2	0.008	0.008
15	16	0	0	0	0
16	17	0	0	0	0
17	18	1	1	0.006	0.006
18	19	1	1	0.009	0.009
19	20	1	1	0.010	0.010
20	21	0	0	0	0
21	22	0	0	0	0
22	23	0	0	0	0
23	24	0	0	0	0
24	25	1	1	0.046	0.046
25	26	0	0	0	0
26	27	1	1	0.016	0.016
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	96	96	—	—
		Generator Regulator[a]			
0	1	—	—	—	—
1	2	1	1	0.005	0.005
2	3	6	6	0.020	0.020
3	4	9	9	0.028	0.028
4	5		4	0.012	0.012
5	6	2	2	0.006	0.006
6	7	6	6	0.017	0.017
7	8	5	5	0.014	0.014
8	9	9	9	0.025	0.025
9	10	10	10	0.027	0.027
10	11	9	9	0.024	0.024
11	12	10	10	0.028	0.028
12	13	7	7	0.023	0.023
13	14	3	3	0.011	0.011
14	15	3	3	0.013	0.013
15	16	7	7	0.032	0.032
16	17	2	2	0.011	0.011
17	18	1	1	0.007	0.007
18	19	2	2	0.017	0.017
19	20	0	0	0	0

TABLE B2 (continued)

Usage interval, thous of miles: Greater than or equal to	Less than	Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
20	21	1	1	0.015	0.015
21	22	0	0	0	0
22	23	1	1	0.025	0.025
23	24	0	0	0	0
24	25	0	0	0	0
25	26	1	1	0.088	0.088
26	27	2	2	0.268	0.268
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	101	101	—	—
		Spark Plug[c]			
0	1	—	—	—	—
1	2	3	12	0.016	0.016
2	3	5	20	0.017	0.017
3	4	9	28	0.028	0.022
4	5	7	20	0.021	0.015
5	6	16	64	0.046	0.047
6	7	9	38	0.025	0.026
7	8	10	31	0.028	0.022
8	9	13	48	0.036	0.034
9	10	12	42	0.031	0.028
10	11	10	32	0.025	0.020
11	12	13	47	0.036	0.033
12	13	8	26	0.025	0.021
13	14	17	54	0.060	0.049
14	15	1	4	0.004	0.004
15	16	6	18	0.028	0.021
16	17	2	10	0.012	0.015
17	18	1	4	0.007	0.007
18	19	1	4	0.009	0.009
19	20	4	10	0.041	0.026
20	21	1	1	0.015	0.004
21	22	0	0	0	0
22	23	0	0	0	0
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	1	4	0.137	0.138
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	149	517	—	—
		Starter[a]			
0	1	—	—	—	—
1	2	0	0	0	0

TABLE B2 (continued)

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
2	3	0	0	0	0
3	4	1	1	0.003	0.003
4	5	0	0	0	0
5	6	0	0	0	0
6	7	1	1	0.003	0.003
7	8	0	0	0	0
8	9	1	1	0.003	0.003
9	10	2	2	0.005	0.005
10	11	3	3	0.008	0.008
11	12	1	1	0.003	0.003
12	13	0	0	0	0
13	14	0	0	0	0
14	15	0	0	0	0
15	16	2	2	0.010	0.010
16	17	0	0	0	0
17	18	0	0	0	0
18	19	0	0	0	0
19	20	1	1	0.011	0.011
20	21	0	0	0	0
21	22	0	0	0	0
22	23	0	0	0	0
23	24	1	1	0.035	0.035
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	13	13	—	—
		Carburetor[a]			
0	1	—	—	—	—
1	2	1	1	0.005	0.005
2	3	7	7	0.023	0.023
3	4	5	5	0.015	0.015
4	5	5	5	0.015	0.015
5	6	2	2	0.006	0.006
6	7	3	3	0.008	0.008
7	8	6	6	0.017	0.017
8	9	6	6	0.017	0.017
9	10	5	5	0.013	0.013
10	11	2	2	0.005	0.005
11	12	10	10	0.028	0.028
12	13	8	8	0.025	0.025
13	14	2	2	0.007	0.007
14	15	5	5	0.021	0.021
15	16	5	5	0.023	0.023
16	17	4	4	0.022	0.022
17	18	0	0	0	0
18	19	2	2	0.016	0.016

TABLE B2 (continued)

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
19	20	1	1	0.011	0.011
20	21	4	4	0.059	0.059
21	22	1	1	0.021	0.021
22	23	0	0	0	0
23	24	0	0	0	0
24	25	1	1	0.055	0.055
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	87	87	—	—
		Fuel Pump[a]			
0	1	—	—	—	—
1	2	3	3	0.016	0.016
2	3	3	3	0.010	0.010
3	4	5	5	0.015	0.015
4	5	2	2	0.006	0.006
5	6	3	3	0.009	0.009
6	7	2	2	0.006	0.006
7	8	1	1	0.003	0.003
8	9	2	2	0.006	0.006
9	10	1	1	0.003	0.003
10	11	8	8	0.021	0.021
11	12	9	9	0.026	0.026
12	13	3	3	0.010	0.010
13	14	4	4	0.015	0.015
14	15	4	4	0.017	0.017
15	16	4	4	0.019	0.019
16	17	1	1	0.006	0.006
17	18	2	2	0.014	0.014
18	19	4	4	0.035	0.035
19	20	3	3	0.034	0.034
20	21	3	3	0.048	0.048
21	22	0	0	0	0
22	23	1	1	0.030	0.030
23	24	1	1	0.037	0.037
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	69	69	—	—
		Brake Cylinder[a]			
0	1	—	—	—	—
1	2	0	0	0	0

TABLE B2 (continued)

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
2	3	1	1	0.003	0.003
3	4	0	0	0	0
4	5	0	0	0	0
5	6	0	0	0	0
6	7	0	0	0	0
7	8	1	1	0.003	0.003
8	9	1	1	0.003	0.003
9	10	0	0	0	0
10	11	1	1	0.003	0.003
11	12	0	0	0	0
12	13	2	2	0.007	0.007
13	14	1	1	0.004	0.004
14	15	1	1	0.004	0.004
15	16	0	0	0	0
16	17	0	0	0	0
17	18	0	0	0	0
18	19	0	0	0	0
19	20	1	1	0.011	0.011
20	21	0	0	0	0
21	22	0	0	0	0
22	23	0	0	0	0
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	9	9	—	—
		Suspension Arm[b]			
0	1	—	—	—	—
1	2	0	0	0	0
2	3	1	1	0.003	0.002
3	4	0	0	0	0
4	5	1	1	0.003	0.001
5	6	2	2	0.006	0.003
6	7	0	0	0	0
7	8	0	0	0	0
8	9	0	0	0	0
9	10	2	3	0.005	0.004
10	11	2	2	0.005	0.003
11	12	0	0	0	0
12	13	2	2	0.007	0.003
13	14	0	0	0	0
14	15	0	0	0	0
15	16	0	0	0	0
16	17	0	0	0	0
17	18	0	0	0	0

TABLE B2 (continued)

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
18	19	0	0	0	0
19	20	0	0	0	0
20	21	0	0	0	0
21	22	0	0	0	0
22	23	0	0	0	0
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	10	11	—	—
		Tire[c]			
0	1	—	—	—	—
1	2	4	11	0.021	0.014
2	3	2	7	0.007	0.006
3	4	2	2	0.006	0.002
4	5	4	6	0.012	0.005
5	6	4	9	0.012	0.007
6	7	3	4	0.008	0.003
7	8	7	12	0.020	0.009
8	9	5	10	0.014	0.007
9	10	6	6	0.016	0.004
10	11	8	17	0.021	0.011
11	12	12	21	0.034	0.016
12	13	8	14	0.026	0.012
13	14	7	14	0.026	0.014
14	15	6	16	0.025	0.018
15	16	6	10	0.027	0.013
16	17	9	17	0.048	0.026
17	18	4	7	0.027	0.013
18	19	3	5	0.025	0.012
19	20	3	8	0.032	0.024
20	21	2	8	0.029	0.035
21	22	1	1	0.021	0.005
22	23	2	3	0.057	0.026
23	24	1	1	0.033	0.011
24	25	0	0	0	0
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	109	209	—	—

TABLE B2 (continued)

Usage interval, thous of miles: Greater than or equal to	Usage interval, thous of miles: Less than	Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
		Wheel Bearing[c,d]			
0	1	—	—	—	—
1	2	1	4	0.017	0.017
2	3	0	0	0	0
3	4	0	0	0	0
4	5	1	2	0.009	0.004
5	6	1	1	0.009	0.002
6	7	4	5	0.036	0.011
7	8	3	4	0.028	0.010
8	9	3	14	0.028	0.035
9	10	4	40	0.036	0.095
10	11	6	13	0.059	0.032
11	12	1	2	0.011	0.006
12	13	1	4	0.011	0.014
13	14	3	6	0.049	0.025
14	15	0	0	0	0
15	16	1	1	0.019	0.005
16	17	3	9	0.072	0.054
17	18	1	2	0.026	0.014
18	19	1	1	0.030	0.008
19	20	1	4	0.033	0.037
20	21	0	0	0	0
21	22	0	0	0	0
22	23	1	2	0.078	0.044
23	24	0	0	0	0
24	25	0	0	0	0
25	26	0	0	0	0
26	27	1	2	0.137	0.083
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	37	116	—	—
		Radiator[a]			
0	1	—	—	—	—
1	2	2	2	0.011	0.011
2	3	4	4	0.013	0.013
3	4	3	3	0.009	0.009
4	5			0.009	0.009
5	6			0.009	0.009
6	7	3	3	0.008	0.008
7	8	4	4	0.011	0.011
8	9	12	12	0.023	0.023
9	10	8	8	0.021	0.021
10	11	8	8	0.020	0.020
11	12	14	14	0.039	0.039
12	13	10	10	0.032	0.032
13	14	3	3	0.011	0.011

FOR OFFICIAL USE ONLY

TABLE B2 (continued)

Usage interval, thous of miles		Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
Greater than or equal to	Less than				
14	15	2	2	0.008	0.008
15	16	7	7	0.032	0.032
16	17	6	6	0.034	0.034
17	18	0	0	0	0
18	19	3	3	0.023	0.023
19	20	2	2	0.022	0.022
20	21	2	2	0.029	0.029
21	22	1	1	0.019	0.019
22	23	0	0	0	0
23	24	1	1	0.031	0.031
24	25	1	1	0.049	0.049
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	102	102	—	—
		Wate Pump[c]			
0	1	—	—	—	—
1	2	0	0	0	0
2	3	0	0	0	0
3	4	1	1	0.003	0.003
4	5	0	0	0	0
5	6	0	0	0	0
6	7	1	1	0.003	0.003
7	8	0	0	0	0
8	9	1	1	0.003	0.003
9	10	1	1	0.003	0.003
10	11	0	0	0	0
11	12	1	1	0.003	0.003
12	13	1	1	0.003	0.003
13	14	2	2	0.008	0.008
14	15	0	0	0	0
15	16	0	0	0	0
16	17	0	0	0	0
17	18	0	0	0	0
18	19	0	0	0	0
19	20	0	0	0	0
20	21	0	0	0	0
21	22	0	0	0	0
22	23	0	0	0	0
23	24	0	0	0	0
24	25	1	1	0.058	0.058
25	26	0	0	0	0
26	27	0	0	0	0

FOR OFFICIAL USE ONLY

TABLE B2 (continued)

Usage interval, thous of miles: Greater than or equal to	Usage interval, thous of miles: Less than	Replacement jobs	Parts replaced	Replacement jobs per vehicle	Parts replacement per part
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0	0	0	0
	Total	9	9	—	—

[a]One per vehicle.
[b]Two per vehicle.
[c]Four per vehicle.
[d]Based on the detail sample (see Chap. 1).

TABLE B3

Replacement Rates and Hazard Rates for M151 Engines, by Replacement Order

a. Replacements per Usage Interval

Usage interval, thous of miles		Replacements already experienced			Vehicles yet to experience replacement		
Greater than or equal to	Less than	1st	2d	All	1st	2d	All
0	1	2	0	2	762	762	762
1	2	3	0	3	759	761	761
2	3	4	0	4	750	755	755
3	4	2	0	2	738	747	747
4	5	6	0	6	725	735	735
5	6	3	1	4	705	720	720
6	7	4	0	4	692	709	710
7	8	2	0	2	659	679	680
8	9	6	1	7	613	633	634
9	10	6	0	6	575	597	598
10	11	3	1	4	524	549	550
11	12	5	0	5	460	482	484
12	13	4	1	5	372	391	392
13	14	3	1	4	293	313	315
14	15	3	0	3	242	258	260
15	16	1	0	1	199	216	218
16	17	3	0	3	157	170	172
17	18	1	0	1	127	137	138
18	19	1	1	2	103	112	113
19	20	2	0	2	79	86	88
20	21	1	1	2	56	63	63
21	22	0	0	0	41	46	46
22	23	0	0	0	30	35	35
23	24	0	0	0	24	28	28

TABLE B3 (continued

c. Replacements per Usage Interval

Usage interval, thous of miles		Replacements already experienced			Vehicles yet to experience replacement		
Greater than or equal to	Less than	1st	2d	All	1st	2d	All
21	25	1	0	1	16	18	18
25	26	0	0	0	8	11	11
26	27	0	0	0	5	7	7
27	28	0	0	0	2	4	4
28	29	0	0	0	1	1	1
29	30	0	0	0	1	1	1
	Total	66	7	73	9718	10,026	10,046

b. Rate per Vehicle per Usage Interval

Usage interval, thous of miles		Vehicles yet to experience replacement		All vehicles		
Greater than or equal to	Less than	1st	2d	1st	2d	All
0	1	0.003	0	0.003	0	0.003
1	2	0.004	0	0.004	0	0.004
2	3	0.005	0	0.005	0	0.005
3	4	0.003	0	0.003	0	0.003
4	5	0.008	0	0.008	0	0.008
5	6	0.004	0.001	0.004	0.001	0.006
6	7	0.006	0	0.006	0	0.006
7	8	0.003	0	0.003	0	0.003
8	9	0.010	0.002	0.009	0.002	0.011
9	10	0.010	0	0.010	0	0.010
10	11	0.006	0.002	0.005	0.002	0.007
11	12	0.011	0	0.010	0	0.010
12	13	0.011	0.003	0.010	0.003	0.013
13	14	0.010	0.003	0.009	0.003	0.013
14	15	0.012	0	0.011	0	0.011
15	16	0.005	0	0.005	0	0.005
16	17	0.019	0	0.017	0	0.017
17	18	0.008	0	0.007	0	0.007
18	19	0.010	0.009	0.008	0.009	0.017
19	20	0.025	0	0.022	0	0.022
20	21	0.018	0.016	0.015	0.016	0.031
21	22	0	0	0	0	0
22	23	0	0	0	0	0
23	24	0	0	0	0	0
24	25	0.062	0	0.052	0	0.052
25	26	0	0	0	0	0
26	27	0	0	0	0	0
27	28	0	0	0	0	0
28	29	0	0	0	0	0
29	30	0	0	0	0	0

TABLE B3 (continued)

c. Cumulative Rate per Usage Interval

Usage interval, thous of miles		All vehicles		
Greater than or equal to	Less than	1st	2d	All
0	1	0.003	0	0.003
1	2	0.007	0	0.007
2	3	0.012	0	0.012
3	4	0.015	0	0.015
4	5	0.023	0	0.023
5	6	0.027	0.001	0.028
6	7	0.032	0.001	0.034
7	8	0.035	0.001	0.037
8	9	0.045	0.003	0.048
9	10	0.055	0.003	0.058
10	11	0.060	0.005	0.065
11	12	0.070	0.005	0.075
12	13	0.080	0.007	0.088
13	14	0.090	0.010	0.100
14	15	0.101	0.010	0.112
15	16	0.106	0	0.116
16	17	0.123	0	0.133
17	18	0.130	0.010	0.140
18	19	0.138	0.019	0.157
19	20	0.160	0.019	0.179
20	21	0.175	0.035	0.210
21	22	0	0	0
22	23	0	0	0
23	24	0.175	0	0.210
24	25	0.226	0	0.261
25	26	0.226	0	0
26	27	0	0	0
27	28	0	0	0
28	29	0	0	0
29	30	0.226	0.035	0.261

TABLE B4

Replacement Rates and Hazard Rates for M151 Transmissions, by Replacement Order

a. Replacements per Usage Interval

Usage interval, thous of miles		Replacements already experienced				Vehicles yet to experience replacement			
Greater than or equal to	Less than	1st	2d	3d	All	1st	2d	3d	All
0	1	6	0	0	6	762	762	762	762
1	2	3	0	0	3	755	761	761	761
2	3	2	1	0	3	746	755	755	755
3	4	4	0	0	4	736	746	747	747
4	5	7	0	0	7	722	734	735	735
5	6	3	0	0	3	700	719	720	720
6	7	7	1	0	8	688	709	710	710
7	8	5	1	0	6	655	678	680	680
8	9	7	0	1	8	606	631	634	634
9	10	12	2	0	14	569	595	597	598
10	11	12	1	0	13	514	545	549	550
11	12	13	1	0	14	447	480	483	484
12	13	4	1	0	5	354	388	391	392
13	14	7	3	1	11	285	311	314	315
14	15	4	3	0	7	231	254	259	260
15	16	4	0	0	4	191	210	217	218
16	17	8	1	1	10	152	167	171	172
17	18	1	2	0	4[a]	118	131	136	138
18	19	0	1	0	2	97	109	111	113
19	20	0	1	0	2	73	84	86	88
20	21	1	1	0	3[b]	55	61	62	63
21	22	2	0	0	2	39	44	45	46
22	23	0	0	0	0	28	33	34	35
23	24	1	0	0	1	23	26	27	28
24	25	1	0	0	1	14	17	17	18
25	26	0	0	0	0	8	10	10	11
26	27	0	0	0	0	6	7	7	7
27	28	0	0	0	0	3	4	4	4
28	29	0	0	0	0	1	1	1	1
29	30	0	0	0	0	1	1	1	1
	Total	116	20	3	141[a,b]	9579	9975	10,026	10,046

TABLE B4 (continued)

b. Rate per Vehicle per Usage Interval

Usage interval, thous of miles		Vehicles yet to experience replacement			All vehicles			
Greater than or equal to	Less than	1st	2d	3d	1st	2d	3d	All
0	1	0.008	0	0	0.008	0	0	0.008
1	2	0.004	0	0	0.004	0	0	0.004
2	3	0.003	0.001	0	0.003	0.001	0	0.004
3	4	0.005	0	0	0.005	0	0	0.005
4	5	0.010	0	0	0.010	0	0	0.010
5	6	0.004	0	0	0.004	0	0	0.004
6	7	0.010	0.001	0	0.010	0.001	0	0.011
7	8	0.008	0.001	0	0.007	0.001	0	0.009
8	9	0.012	0	0.002	0.011	0	0.002	0.013
9	10	0.021	0.003	0	0.020	0.003	0	0.023
10	11	0.023	0.002	0	0.021	0.002	0	0.023
11	12	0.029	0.002	0	0.026	0.002	0	0.028
12	13	0.011	0.003	0	0.010	0.003	0	0.012
13	14	0.025	0.010	0.003	0.021	0.010	0.003	0.034
14	15	0.017	0.012	0	0.015	0.012	0	0.026
15	16	0.021	0	0	0.017	0	0	0.017
16	17	0.053	0.006	0.006	0.043	0.006	0.006	0.054
17	18	0.008	0.015	0	0.006	0.014	0	0.028[a]
18	19	0.010	0.009	0	0.008	0.009	0	0.016
19	20	0.014	0.012	0	0.010	0.011	0	0.021
20	21	0.018	0.016	0	0.013	0.015	0	0.045[b]
21	22	0.051	0	0	0.037	0	0	0.037
22	23	0	0	0	0	0	0	0
23	24	0.043	0	0	0.030	0	0	0.030
24	25	0.071	0	0	0.047	0	0	0.047
25	26	0	0	0	0	0	0	0
26	27	0	0	0	0	0	0	0
27	28	0	0	0	0	0	0	0
28	29	0	0	0	0	0	0	0
29	30	0	0	0	0	0	0	0

TABLE B4 (continued)

c. Cumulative Rate per Usage Interval

Usage interval, thous of miles		All vehicles			
Greater than or equal to	Less than	1st	2d	3d	All
0	1	0.008	0	0	0.008
1	2	0.012	0	0	0.012
2	3	0.014	0.001	0	0.016
3	4	0.020	0	0	0.021
4	5	0.029	0	0	0.031
5	6	0.033	0.001	0	0.035
6	7	0.043	0.003	0	0.046
7	8	0.051	0.004	0	0.055
8	9	0.061	0.004	0.002	0.067
9	10	0.081	0.008	0	0.091
10	11	0.103	0.009	0	0.114
11	12	0.129	0.011	0	0.142
12	13	0.139	0.014	0.002	0.154
13	14	0.160	0.023	0.005	0.188
14	15	0.174	0.035	0.005	0.214
15	16	0.192	0.035	0.005	0.232
16	17	0.234	0.041	0.011	0.286
17	18	0.241	0.055	0	0.314[a]
18	19	0.249	0.064	0	0.330[a]
19	20	0.259	0.075	0	0.352[a]
20	21	0.272	0.090	0	0.396[a,b]
21	22	0.310	0	0	0.434[a,b]
22	23	0.310	0	0	0.434[a,b]
23	24	0.340	0	0	0.464[a,b]
24	25	0.387	0	0	0.511[a,b]
25	26	0	0	0	0
26	27	0	0	0	0
27	28	0	0	0	0
28	29	0	0	0	0
29	30	0.387	0.090	0.011	0.511[a,b]

[a] Includes one fourth-order replacement.
[b] Includes one fifth-order replacement.

GRAPHS

The graphs of rates for each part are cumulative plots of the rates presented tabularly (see Fig. B1). The cumulative form was used to show the data more smoothly and because eyeball extrapolation of cumulative replacement rates to the 50 percent level can give rough ideas of mean lives. The plots are cut off at 19,000 miles, the last point at which the sample size was at least 100; thereafter it was regarded as small.

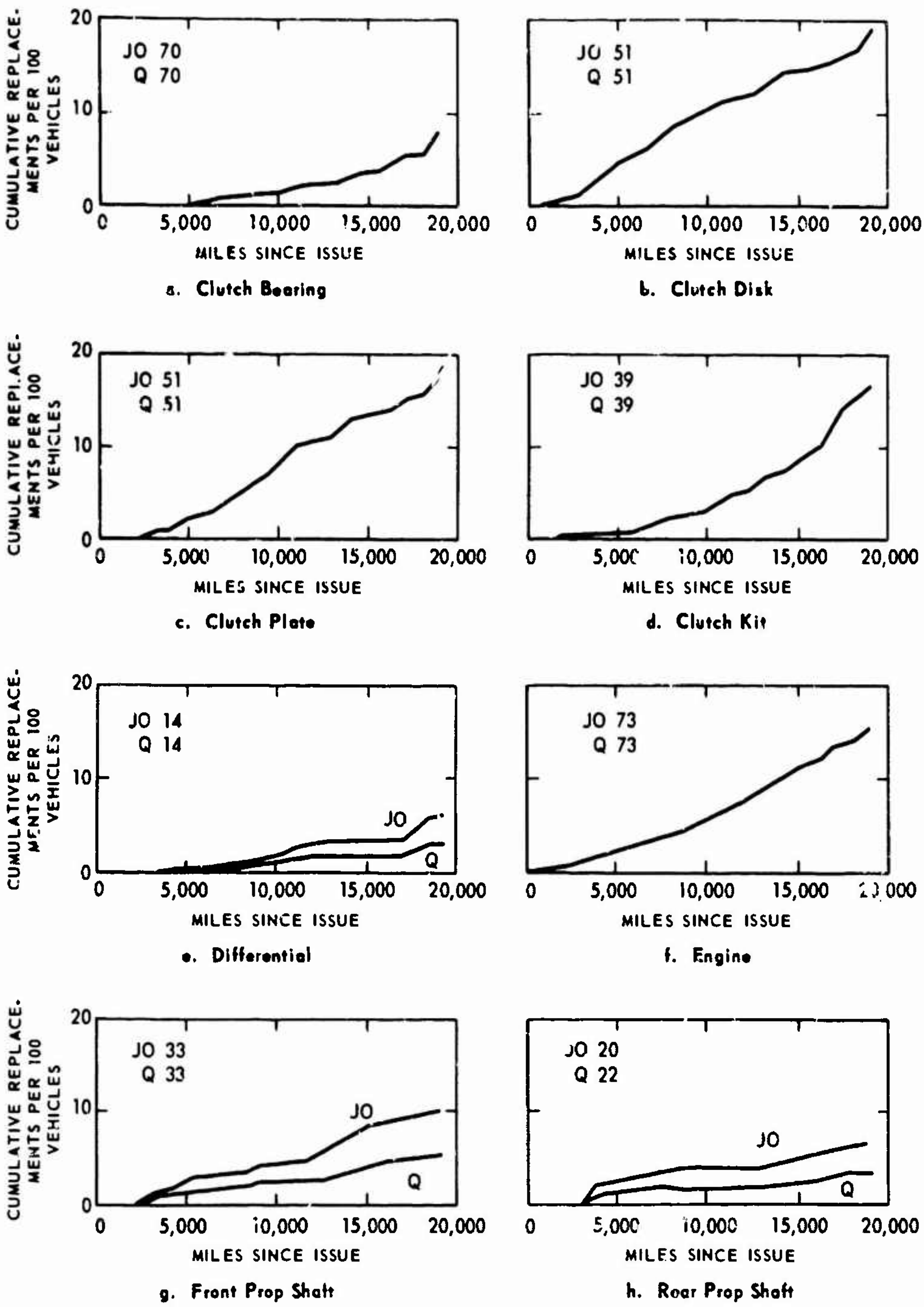


Fig. B1—Cumulative Replacement Rates of Prime Mobility Parts

JO: replacement jobs (job orders); Q: replacements (quantity).

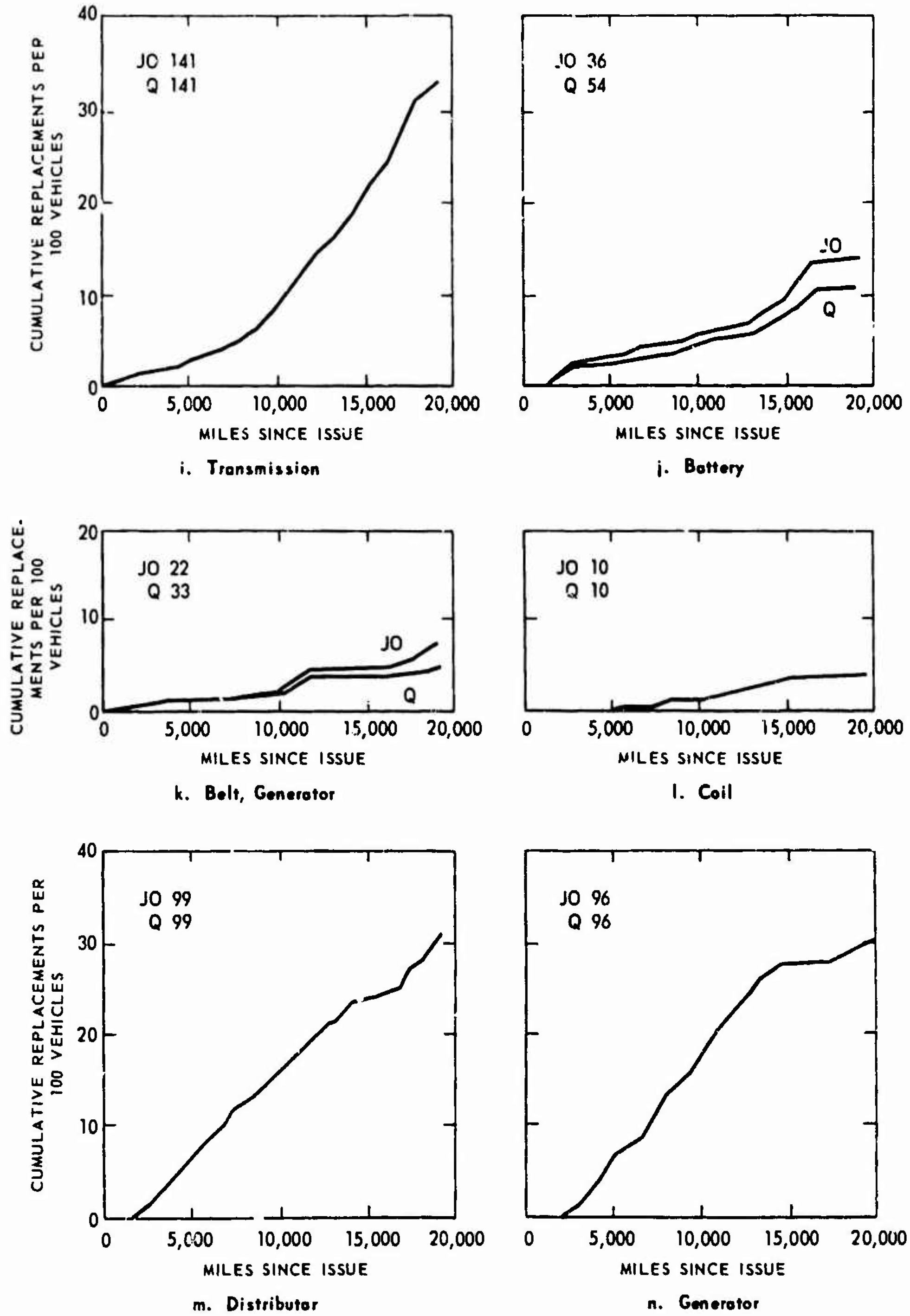
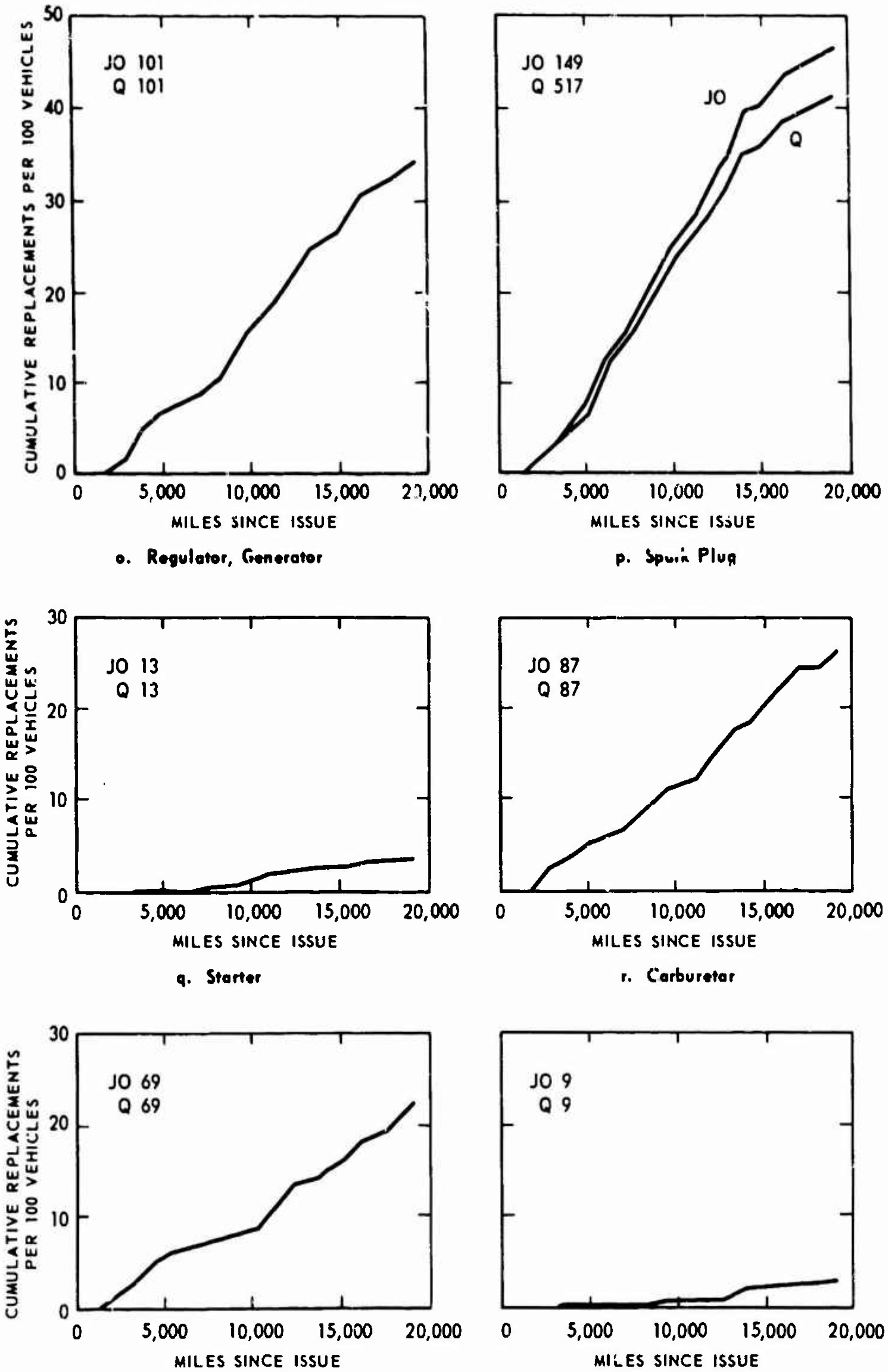


Fig. B1—Continued



o. Regulator, Generator

p. Spark Plug

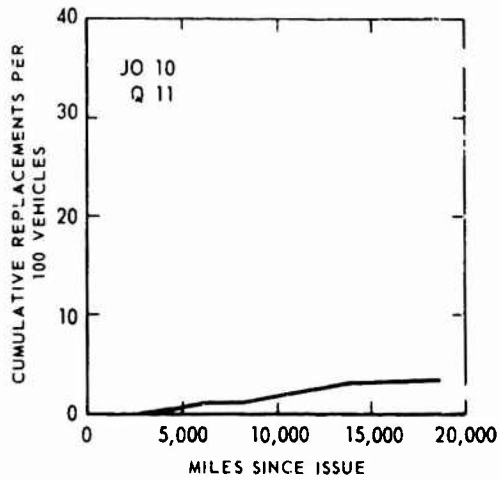
q. Starter

r. Carburetor

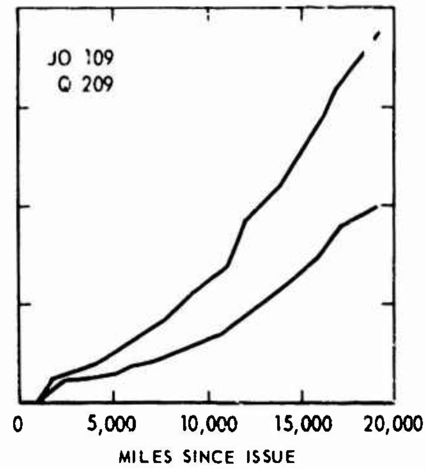
s. Fuel Pump

t. Brake Master Cylinder

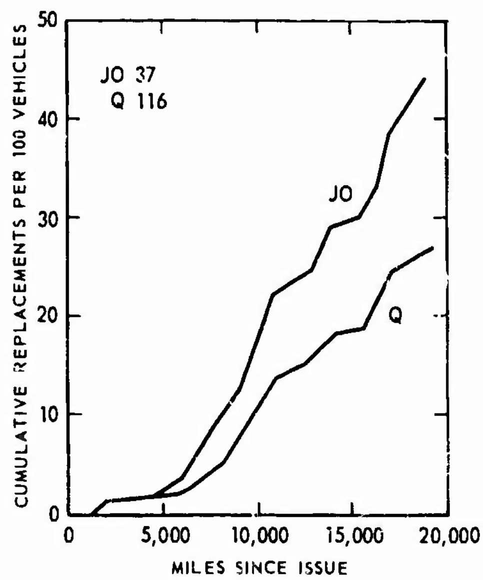
Fig. B1—Continued



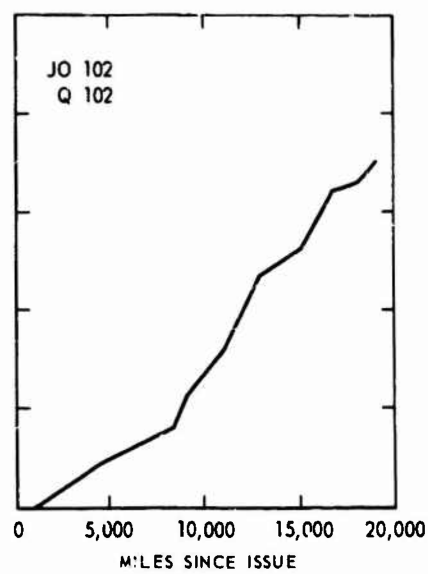
u. Suspension Arm



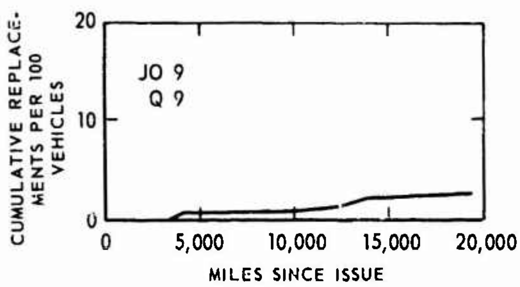
v. Tire



w. Wheel Bearing



x. Radiator



y. Water Pump

Fig. B1—Continued

Appendix C

LIFETIME NOTES

INTRODUCTION

This appendix discusses three topics of vehicle and M151 lifetime in generally more technical detail than Chap. 6. First the lifetime problem is described and set in a more specific context. Then a mathematical statement of the technique used to derive the computed lifetimes of Chap. 6 is presented. The final two sections consider only the cost aspects of M151 operation and derive least-cost lifetimes for cases in which the replacement vehicle is permitted to have different acquisition costs and different maintenance costs from those derived in this study for M151's.

VEHICLE LIFETIMES

Background

In C .p. 1 the basic viewpoint of vehicle lifetime taken in this study was outlined. Briefly, this view was that vehicle life is characterized by increasing costs and decreasing performance as the vehicle ages (substantiated for the M151 in Chaps. 3, 4, and 5); a clear-cut, irrevocable death such as ends biological life does not occur in vehicle life; vehicle life occurs in a dynamic environment in which the role the vehicle was bought to fill is changing in nature and relative importance, the efficiency with which the vehicle is supported may change, and the best kind of vehicle today's technology can produce to fill the role is different in cost and performance from yesterday's. It was also noted that the determination of military vehicle lifetimes includes the problem of making value judgments by which costs specified in monetary terms and performance specified in nonmonetary terms may be considered in combination.

Role and Role Life

It is useful to introduce the notions of "role" and "role life" in establishing a clearer framework in which to view the vehicle lifetime problem because vehicles are bought to fill a role and the fleet managers' goal is taken to be to optimize the filling of the role. The period of time for which the optimization is to be achieved will be generally called "role life."

The idea of role life is depicted in Fig. C1. Role life is the time during which the role contributes significantly to Army operations. The time during which the M151 is the preferred model of $\frac{1}{4}$-ton truck in the role is referred to as the M151 role life or the role life of the M151 generation.

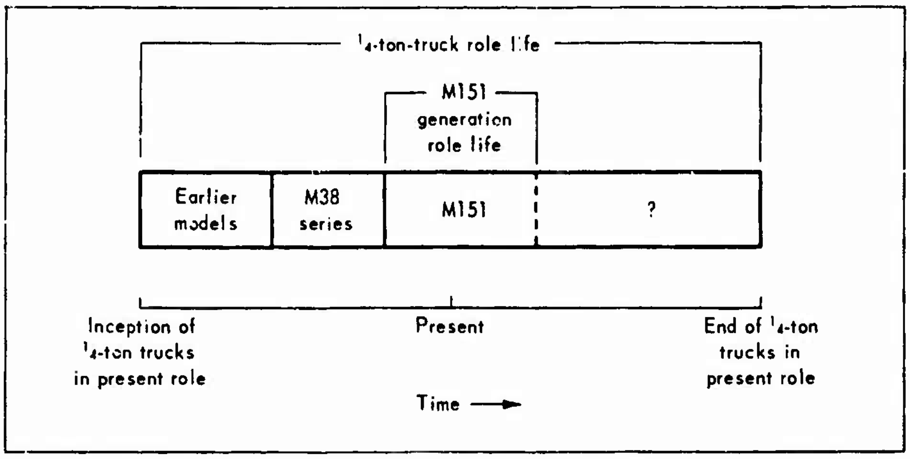


Fig. C1—Role Life and Generation Role Life Depicted

This study did not attempt to establish what the $\frac{1}{4}$-ton-truck role life is. Rather, its considerations of the idea of role life led to the conclusion that the $\frac{1}{4}$-ton-truck role life is considerably less relevant to the choice of an M151 lifetime than is the generation life of M151's, assuming that at least one or two generations of $\frac{1}{4}$-ton trucks will be appropriate after the M151 generation. The basis of this view is that the choice of when to introduce a new generation of vehicles should be made essentially independent of considerations of the age of the current vehicles as long as vehicles age at rates at least comparable to the rate at which technological advances make desirable the introduction of new models and any particular new model is introduced into the fleet gradually over a time period at least as long as vehicle lifetimes. Such a situation means that whenever a new model is to be introduced, some vehicles of the current model will be of sufficient age that when they are displaced by new model vehicles little good vehicle life will be lost. The introduction of a new model when much of the current fleet is relatively new would, on the other hand, be costly for that reason. The Army $\frac{1}{4}$-ton truck fleet has the desirable characteristics mentioned, and hence the introduction of new models may be made at a time chosen independently of consideration of current vehicle ages.

Thus the lifetime problem for M151's may be confined to choosing a replacement age that optimizes the filling of the M151 generation role life.

LIFETIME TECHNIQUE USED IN CHAP. 6

The lifetime technique used to compute lifetimes in Chap. 6 is presented here in mathematical terms. As was noted in Chap. 1, any procedure in which cost and performance are considered jointly and weighed against each other involves making value judgments of the kind "performance level x is worth cost y but not cost z." The technique described here incorporates a relatively simple value system, although to describe it fully would be very complex. Basically the three elements considered—cost, performance, and obsolescence—were given their natural weight; thus a value half that of another was regarded as half as good or twice as good depending on whether it was desirable to have it high or low.

Technique

The in-use effective life of the equipment under study is defined as the age at which the minimum of a specific mathematical function occurs when the function's parameters are those determined from field experience data.

Two monetary costs are considered: initial investment cost and maintenance cost. Costs are amortized in equal amounts for each time period remaining in the life of the item beginning with the time period in which the cost was incurred. Costs are allocated against a defined effectiveness by attributing the effectiveness over a finite time period to the total of the costs amortized in the same time period.

Relative effectiveness is defined as a product of three factors: a measure of technological competitiveness (the obverse of obsolescence), a measure of equipment reliability, and a measure of equipment availability.

The model assumed that relative competitiveness $C(t)$ decays in time continuously and exponentially as $C(t) = (1 + i)^{-t}$ where i is the obsolescence rate expressed as the ratio of competitiveness lost during a unit of time to the competitiveness at the beginning of the unit of time. With this convention, relative competitiveness can always be assigned unit value at an arbitrary zero time.

Reliability in unit time is defined by $R(t) = 1 - h(t)$, where $h(t)$ is the frequency of equipment failures per end item per time unit. The formula is an approximation to $e^{-h(t)}$. The latter form must be used when $h(t)$ is not small.

Availability is defined by $A(t) = 1 - \lambda h(t)$, where λ is the mean time out of service per equipment failure. The formula is an approximation to $1/[1 + \lambda h(t)]$ for small values of the product $\lambda h(t)$.

The condensed symbolic statement of relative effectiveness, $q(t)$, is $q(t) = C(t) \cdot R(t) \cdot A(t)$.

A perfect ageless item would have to have no decay in competitiveness ($i = 0$) and no failures during use $[h(t) = 0]$. The relative effectiveness of such an item remains at unit value indefinitely. Real items have changing effectiveness values of less than unity.

The model combines costs and effectiveness by forming an unlimited number of quotients $c(t)/q(t)$ that may be regarded as expressing an amortized cost per unit of perfect effectiveness at time t. The model determines the mean $E(T)$ of the quotients over a life T. The effective in-use life is defined as the age T for which $E(T)$ is minimum.

The mathematical statement $E(T)$ is a specific construct using the ideas and notation introduced above. Let I be the cost of replacing the item, c_i the cost of maintenance in time period i, and q_i the relative effectiveness in time period i. For discrete intervals the average cost per unit of perfect effectiveness at the end of the first time period is $(I + c_1)/q_1$; after the second period it is

$\frac{1}{2}\{(\frac{I}{2} + \frac{c_1}{2}) q_1 + (\frac{I}{2} + \frac{c_1}{2} + c_2) q_2\}$; at the end of the nth period it is $\frac{1}{n}\{(\frac{I}{n} + \frac{c_1}{n}) q_1 + [\frac{I}{n} + \frac{c_1}{n} + \frac{c_2}{(n-1)}] q_2 + \ldots + [\frac{I}{n} + \frac{c_1}{n} + \frac{c_2}{(n-1)} + \ldots + \frac{c_{n-1}}{2} + c_n] q_n\}$.

A rearrangement of the last expression gives the following equation as the average cost per unit of perfect effectiveness per time period at the end of n periods.

$$E(n) = \left[\frac{I}{n} \frac{1}{n} \sum_{i=1}^{n} \frac{1}{q_i} + \sum_{i=1}^{n} \left(\frac{c_i}{n - i + 1} \sum_{j=i}^{n} \frac{1}{q_j}\right)\right]$$

The model for discrete intervals has been made continuous by deriving the limiting form as the time periods are made arbitrarily small and the age t represented by the n original intervals is held constant, to yield

$$E(t) = \frac{1}{t}\left\{\frac{I}{t} \int_0^t \frac{ds}{q(s)} + \int_0^t \frac{c(s)}{t-s} \int_s^t \frac{dr}{q(r)}\, ds\right\}$$

as the average cost over age t per unit of perfect effectiveness per unit of time at age t. The effectiveness function $q(s)$ is $q(s) = (1+i)^{-s}[1 - h(s)][1 - \lambda h(s)]$. The term $h(s)$ was approximated from field data by $h(s) = a + bs$, and $q(s)$ was then quite well approximated by $q(s) = fe^{-gs}$. The maintenance cost function $c(s)$ was approximated from field data by $c(s) = A + Bs$. Introducing these functions into the expression for $E(t)$ gives

$$E(t) = \frac{1}{t}\left\{\frac{I}{t} \int_0^t \frac{ds}{fe^{-gs}} + \int_0^t \frac{A + Bs}{t - s} \int_s^t \frac{dr}{fe^{-gr}}\, ds\right\}$$

Integrating $E(t)$ yields the following working expression used in this study for the average cost per unit of perfect effectiveness per unit of time over age t.

$$E(t) = \frac{I(e^{gt} - 1)}{fgt^2} - \frac{A}{f} \frac{e^{gt}}{gt} \sum_{m=1}^{\infty} \frac{(-gt)^m}{m(m!)} - \frac{Bt}{f} \frac{e^{gt}}{gt} \sum_{m=1}^{\infty} \frac{(-gt)^m}{m(m+1)!}$$

$E(t)$ is evaluated for values of t until T such that $E(T) =$ minimum $E(t)$ is found. T is the defined effective in-use life of the item.

Parameters Used

Because the technique requires linear projections of maintenance costs and breakdown rate, the projections of Chaps. 4 and 5 were modified by fitting a least-squares line in the interval 0 to 50,000 miles to the degraded projections of each parameter.

LEAST-COST LIFETIMES

In this section the implications of costs of acquisition and maintenance for M151 lifetime are treated without reference to performance. Although as a consequence this analysis is less appropriate than that of Chap. 6 as a basis for the final lifetime decision, its greater simplicity permits the consideration of some matters less tractable in Chap. 6. In particular, the effect of the acquisition cost and maintenance cost of potential replacement vehicles on the least-cost lifetime are determined. The least-cost lifetime is also shown to depend on the period of time for which the ¼-ton-truck role is to be filled by current-generation vehicles. A major conclusion concerning M151 overhaul, stated briefly near the end of Chap. 6, is formed.

Procedure

For the least-cost lifetime analysis the fleet management goal is assumed to be to render ¼-ton-truck miles at minimum cost, starting with a fleet of new M151's that cost $2900 each to acquire and have age-dependent maintenance costs as shown in Fig. 47. The fleet size is assumed to remain constant. The period of time over which the least-cost goal is to be achieved is the role life of the M151 generation, i.e., the time during which the combined performance and cost characteristics of M151-generation vehicles are the best available to fill the ¼-ton-truck role. (The generation role life of the M151 is assumed to terminate when a model of ¼-ton truck of characteristics sufficiently better than those of the M151 to justify its introduction becomes available.)

The influences on least-cost M151 lifetime of the acquisition cost I and age-dependent maintenance costs $M(a)$ of replacement vehicles and of the M151-generation role life are analyzed for a range of I, a range of generation role life, and two different replacement-vehicle maintenance costs. Acquisition costs of replacement vehicles considered range from $200 up. The two maintenance costs for replacement vehicles are one identical to that of issued-new M151's and one higher, the latter to show the effect of higher maintenance costs that have been observed[3,4,21] for overhauled vehicles.

The analysis, described in technical detail in the concluding section of this appendix, consists of comparing the cost of filling the role with only the original fleet of new M151's (never overhauling them) with the cost of filling the role by replacing the original M151's with other vehicles, called the "replacement vehicles," at some original M151 age. (The replacement vehicles could be new M151's, overhauled M151's, or any other vehicles deemed feasible operational substitutes for deteriorated M151's.) In two cases the analysis was restricted to comparing generation-role-life costs when no replacements were made with the situation in which one replacement was made. A third case considered the situation in which more than one replacement was made.

Generation Role-Life Cost with No Replacements

The cost per vehicle-mile of filling the generation role life with one set of issued-new M151's, without overhaul, is shown in Fig. 49 for a range of generation role lives. In the current discussion the abscissa label "Retention Period" in Fig. 49 must be interpreted as "generation role life," in accordance with the assumption of no replacements during the generation role life. The curve in Fig. 49 is regarded as a basic characteristic of the M151. The remaining discussion is basically a determination of limiting cost characteristics of valid replacement vehicles for a range of generation role lives, given the goal of filling the generation role life at minimum cost per mile, and given that at the beginning of the generation role life the fleet consists of new M151's with costs characterized by Fig. 49.

Three Cases of Vehicle Replacement

Case 1: One Fleet Replacement during Generation Role Life; Replacement-Vehicle Maintenance Costs Same as Those of Issued-New M151's. Figure C2 compares the cost of the generation role life when no replacement is made with that when one replacement is made, when the age-dependent maintenance costs of the replacement vehicle are identical to those of the original issued-new M151's. The figure shows the maximum acquisition cost a replacement vehicle may have for a given generation role life if the generation-role-life cost when

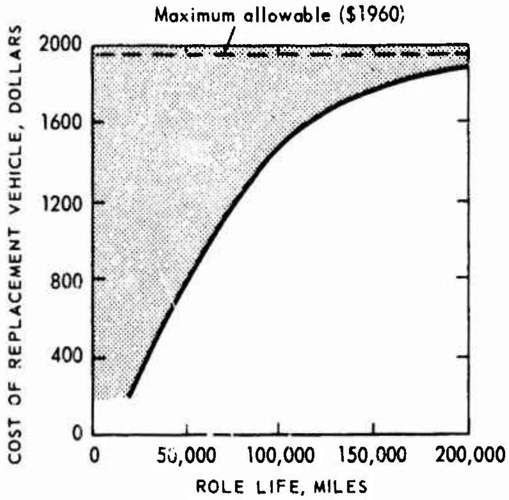


Fig. C2—Maximum Acquisition Cost of Replacement Vehicles for Which Replacement of Issued-New M151's by Vehicles Having the Same Maintenance Costs as the Degraded Estimate Is Justified on a Cost Basis Alone

Optimum replacement age is one-half role life.

one replacement of the fleet is made is not to exceed the generation-role-life cost when no replacement is made. For example, the figure shows that if the generation role life is 50,000 miles, no replacement should be made if the replacement vehicle has an acquisition cost greater than $800; if a replacement is made during the generation role life, the generation-role-life cost will be smaller than if no replacement is made only if the acquisition cost of the replacement vehicle is less than $800. If the replacement-vehicle acquisition cost is just $800, a substitution of these vehicles for the original fleet at 25,000 miles will result in the same generation-role-life cost as if the original vehicles were operated throughout the 50,000 miles.

Notice that a further element has slipped in—when the replacement should be made. The results in Fig. C2 apply when the replacement age is one-half the generation role life. This is the optimum replacement age in the sense that, if the generation role life is to be filled by replacing the original M151 fleet at some point but then making no further replacements, the cost is minimized if the replacement is made at one-half the generation role life. The fact that in Fig. C2 the optimum replacement age is one-half the generation role life is determined by the condition that the maintenance costs of the replacement vehicles are the same as those of the original vehicles. If they were not equal, the optimum age would be different from one-half the generation role life. In case II such a situation is treated.

Thus, if a replacement is to be made, the optimum time to make it in this case is at one-half the generation role life. It may happen, however, that even when the replacement is made at the optimum age, the generation-role-life cost is higher than when no replacement is made. Indeed, it is just this that Fig. C2 is intended to show. If the replacement vehicle costs more than $800, then replacement even at the optimum age of 25,000 miles for a 50,000-mile generation role life costs more than making no replacement at all. If the replacement vehicle costs less than $800, then introducing such vehicles in place of the original vehicles at 25,000 miles will reduce the cost per 50,000 vehicle-miles of a 50,000-mile generation role life by the difference between $800 and the actual acquisition cost of the replacement vehicle. For example, a replacement vehicle costing $600 could be used to reduce the cost of a 50,000-mile generation role life by $200 per fleet member by replacing the original vehicles with the $600 replacement vehicles at 25,000 miles.

An interesting aspect of Fig. C2 is that no matter how long the role life, no replacement vehicle costing more than $1960 is economically justifiable. Thus replacement with a new M151 at a cost of $2900 is not justifiable on economic grounds alone.

The results of the case I analysis (shown in Fig. C2) in conjunction with past experience[21,25,27] are sufficient grounds on which to build a case against M151 overhaul. ORO-T-381,[21] concerning the overhaul of M38-series ¼-ton trucks, found the average cost of overhaul in FY58 to be about $1850. The overhauled vehicles were found to have higher maintenance costs than new vehicles. In ORO-SP-133[25] it was further found that overhauled M38-series ¼-ton trucks experienced more frequent failures of major assemblies than new vehicles.

The results of case I in Fig. C2 show that the maximum allowable cost for a replacement vehicle, if the generation role life is of the order of 15 years—105,000 miles at current rates of use—and if the maintenance costs of the replacement vehicle are as low as for a new vehicle, is about $1500. Of course if the maintenance costs of the replacement vehicle were higher than for a new vehicle, an acquisition cost less than $1500 would be the maximum permissible. Thus, if the generation role life is 15 years, M151's should not be overhauled unless a significant reduction in the cost of overhaul from that experienced by M38-series vehicles several years ago with no further loss in quality of product can be achieved.

Case II: One Fleet Replacement during the Generation Role Life; Replacement-Vehicle Maintenance Costs Higher than Those of Issued-New M151's. The situation considered here differs from that of case I in that the age-dependent maintenance costs of the replacement vehicle are assumed to be higher than those of the original M151, as has been observed previously for overhauled vehicles.[3,4,21] A hypothetical maintenance cost for replacement vehicles was used. It compares with the projected maintenance costs for issued-new M151's

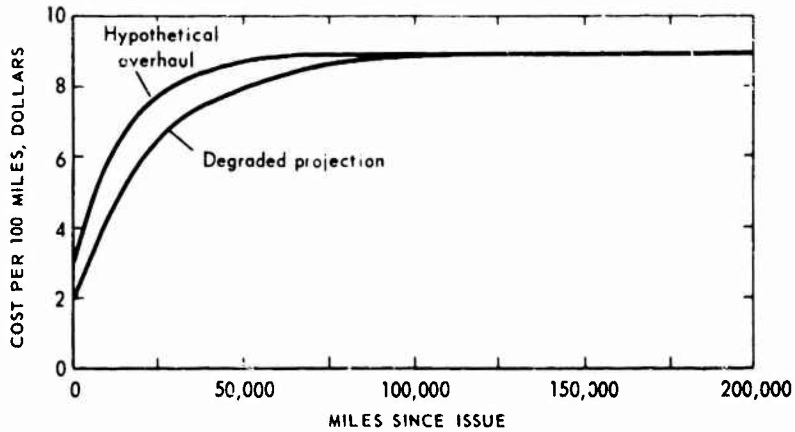


Fig. C3—Hypothetical Maintenance Costs of Overhauled M151's Compared with Projected Degraded Maintenance Costs of M151's Issued New

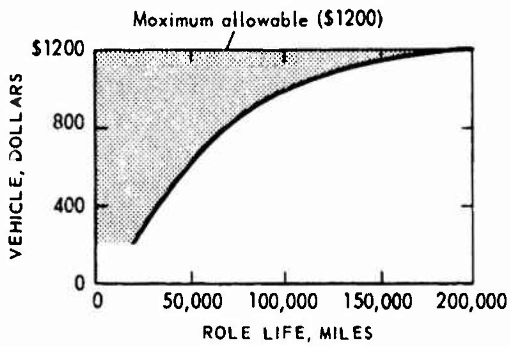


Fig. C4—Maximum Acquisition Cost of Replacement Vehicles for Which Replacement of Issued-New M151's by Vehicles Having Higher Maintenance Costs Is Justified on a Cost Basis Alone

Optimum replacement age is 0.63 role life. Maintenance costs: one-third higher initially; growth: 1.7 times the rate; equilibrium: same as degraded estimate for M151's.

as shown in Fig. C3, i.e., it had an initial value one-third higher, a growth rate 1.7 times as great, and the same equilibrium value.

The results of the analysis of this situation are shown in Fig. C4, which is of the same form as Fig. C2. Here the maximum allowable initial cost of a replacement vehicle is $1200. Eight hundred dollars is now the maximum allowable cost of a replacement vehicle if the generation role life is 70,000 miles (about 10 years). For a 50,000-mile generation role life the maximum allowable replacement-vehicle cost is $600, compared with $800 when the maintenance costs of the replacement vehicle are the same as for a new M151.

The optimum replacement time is now 0.63 of the generation role life rather than 0.50. The worse replacement-vehicle maintenance costs make it desirable to keep the original vehicles with lower maintenance costs longer than in case I.

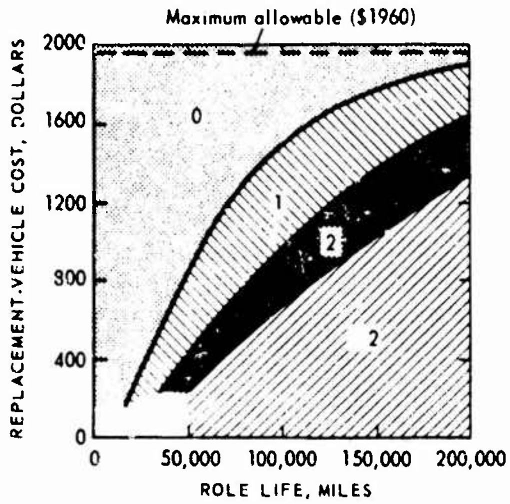


Fig. C4—Replacement Policies Giving Minimum-Cost Role Lives for Various Replacement-Vehicle Costs

The maintenance costs of all replacement vehicles are the same as the degraded estimate for M151's; the first vehicle is a new M151 costing $2900.

The optimum replacement ages are

Replacements	Optimum replacement age as fraction of role life
0	1
1	1/2
2	1/3
3	1/4

If the assumed maintenance costs for replacement vehicles are more representative of what would be experienced by overhauled M151's than are the maintenance costs for issued-new M151's, then the maximum allowable overhaul cost for a 15-year (105,000-mile) generation role life is more like $1000 (shown on Fig. C4) than the $1500 found earlier (see Fig. C2). The economic argument against M151 overhaul is thus strengthened because actual maintenance costs of overhauled vehicles are indeed likely to be significantly higher than those of issued-new vehicles.

Case III: Multiple Fleet Replacements during the Generation Role Life; Case I Maintenance Costs. Cases I and II considered making only one fleet replacement during the generation role life. Case III considered the situation in which more than one fleet replacement is permitted during the generation role life. The maintenance costs of all replacement vehicles are assumed to be the same as for issued-new M151's. All replacement vehicles are assumed to have the same acquisition costs.

The results are shown in Fig. C5. When the maintenance costs of replacement vehicles are the same as those of issued-new M151's, Fig. C5 shows maximum allowable replacement-vehicle acquisition costs for which not only one replacement is justified (as in Fig. C2) but also for which two replacements and three replacements are justified. For example, if the role life is 50,000 miles, Fig. C5 shows that if the replacement vehicle cost more than $800, no replacement should be made; this is as for Fig. C2. And, like Fig. C2, Fig. C5 shows that if the replacement vehicle costs less than $800, one replacement at 25,000 miles results in a lower generation-role-life cost than no replacements. But unlike Fig. C2, Fig. C5 further shows that if the replacement vehicle costs less than $400, two replacements—at 16,700 miles and at 33,400 miles—result in a still lower cost than one replacement at 25,000 miles. Fig. C5 also shows that if the replacement vehicle costs less than $200, three replacements—at 12,500 miles, 25,000 miles, and 37,500 miles—will result in an even lower generation-role-life cost than two replacements.

TABLE C1

Effect of Replacement-Vehicle[a] Cost on Least-Cost Lifetime of Issued-New M151's

Cost of replacement vehicle, dollars	Least-cost lifetime of issued-new M151's
Generation Role Life: 70,000 Miles	
·1100	70,000
700 –1100	35,000
400 – 700	23,300
250[b]– 400	17,500
Generation Role Life: 105,000 Miles	
1500	105,000
1000 –1500	52,500
650 –1000	35,000
450[b]– 650	26,250

[a]Maintenance costs the same as issued-new M151's.
[b]Rough estimate; table may be extended downward indefinitely.

The replacement ages implied by Fig. C5 may be interpreted as least-cost lifetimes determined by the initial cost of replacement vehicles and the generation role life, given that the fleet originally consists of new M151's with an initial eost of $2900, the age-dependent maintenance costs are as shown in Fig. 50, and the replacement vehicles have maintenance costs the same as the original M151's. Thus, if the generation role life is taken to be 10 years (70,000 miles), the effect of the initial cost of replacement vehicles may be shown as in Table C1. The second half of Table C1 shows the corresponding result if the generation role life is taken to be 15 years (105,000 miles).

Conclusions

1. Least-cost lifetime of the M151 depends on the role life its generation is to fill and the costs of acquisition and maintenance of potential replacement vehicles as follows:
   a. M151 life increases as role life increases.
   b. M151 life decreases as replacement-vehicle price decreases.
2. If replacement-vehicle maintenance costs are no less than those of the M151, they are eligible replacement vehicles only if they cost less than $1960. Thus a new M151 (at a cost of $2900) may never be used to replace an M151 in hand if a minimum cost per role mile is to be achieved. In this circumstance, M151 life is equal to the role life.
3. If maintenance costs of a potential replacement vehicle are no less than one-third higher at issue than those of a new M151, grow in M151 age at no less than 1.7 times the degraded rate for issued-new M151's, and have the same equilibrium as the degraded estimate for issued-new M151's, replacement of issued-new M151's by such vehicles is economically justifiable only if the vehicle costs $1200 or less.
4. The number of replacements giving least-cost role life is greater the lower the cost of the replacement vehicle.

LEAST-COST LIFETIME TECHNIQUE

This section describes the development of the least-cost results of the previous section summarized in Figs. C2, C4, and C5.

For Figs. C2 and C4 the situation considered is the following. One has a vehicle which costs I_1 to acquire and $C_{\infty 1} - (C_{\infty 1} - C_{01})e^{-\gamma_1 t}$ to maintain at age t. Another vehicle is available that costs I_2 to acquire and $C_{\infty 2} - (C_{\infty 2} - C_{02})e^{-\gamma_2 t}$ to maintain at age t. One wishes to furnish a total vehicle mission of size n age intervals. Possessing vehicle 1, he is regarded as having two ways to furnish the n intervals of vehicle life: he may operate vehicle 1 through them all or he may replace vehicle 1 with vehicle 2 at some point. What conditions justify replacement, and what is the optimum age?

The problem posed was treated by fixing the initial cost of the first vehicle, the maintenance costs of both vehicles, and optimum replacement times expressed in terms of n, and then determining allowable I_2 for a range of n.

In particular, the cost of providing n intervals of operation solely with vehicle 1 was expressed by

$$C_{1n} = I_1 + C_{\infty 1} n - \left[\frac{C_{\infty 1} - C_{01}}{\gamma_1}\right]\left[(1 - e^{-\gamma_1 n})\right] \tag{1}$$

The cost of providing n intervals of operation when k are provided by vehicle 1 and $(n - k)$ by vehicle 2 was taken as

$$C_{1k} + C_{2,n-k} = I_1 + C_{\infty 1} k - \left[\frac{C_{\infty 1} - C_{01}}{\gamma_1}\right]\left[1 - e^{-\gamma_1 k}\right]$$
$$+ I_2 + C_{\infty 2}(n-k) - \left[\frac{C_{\infty 2} - C_{02}}{\gamma_2}\right]\left[1 - e^{-\gamma_2 (n-k)}\right] \tag{2}$$

The problem was to determine $k = r$ such that the difference

$$D(k) = C_{1n} - [C_{1k} + C_{2,n-k}] \tag{3}$$

was maximized within the constraint $D(r) \geq 0$. Partial differentiation of Eq 3 with respect to k, setting equal to zero, and solving for k yields for r

$$r = k = \frac{\gamma_2 n + \log_e \left[\dfrac{C_{\sim 1} - C_{01}}{C_{\sim 2} - C_{02}}\right]}{\gamma_1 + \gamma_2} \tag{4}$$

when $C_{\sim 1} = C_{\infty 2}$, the condition assumed here. The parameter values used are shown in Table C2.

TABLE C2

Values of Cost Parameters Used in Analysis of Least-Cost Lifetimes

Parameter	Dimensions	Value	
		Case I	Case II
I_1	\$	2900.00	2900.00
$C_{\infty 1}$	\$/5000 mi	477.10	477.10
C_{01}	\$/5000 mi	75.00	75.00
γ_1	/5000 mi	0.205	0.205
$C_{\sim 2}$	\$/5000 mi	477.10	477.10
C_{02}	\$/5000 mi	75.00	100.00 ($1.33C_{01}$)
γ_2	/5000 mi	0.205	0.349 ($1.7\gamma_1$)

Using these values in Eq 4 yielded for case I a value $r = 0.500n$ and for case II $r = 0.630n$.

Combining Eqs 4, 3, and the constraint of Eq 3 yielded expressions in which only I_2 and n were unknown. These expressions were of the form

$$f(n) \geq g(I_2) \tag{5}$$

Figures C2 and C4 are graphs of pairs (n, I_2), which satisfy the equality of Eq 5.

Case III, in which more than one replacement was allowed, was analyzed by an analogous scheme. In that instance all the replacement vehicles were assumed to have the same initial costs and maintenance costs as issued-new M151's. An interesting result of that case is that if m replacements are desirable, the optimum replacement points are at $in/m, i = 1, 2, \ldots, m-1$.

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