Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
ANALYSIS OF COST DATA AND DEVELOPMENT OF EQUIPMENT REPLACEMENT FRAMEWORK	January 2002
	6. Performing Organization Code
7. Author(s) José Weissmann and Angela Jannini Weissmann	8. Performing Organization Report No. 4941-1
9. Performing Organization Name and Address The University of Texas at San Antonio Department of Civil Engineering 6900 North Loop 1604 West San Antonio, TX 78249-0668 University of Texas at El Paso Center for Highway Materials Research El Paso, TX 79968-0516	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-4941
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Section/Construction Division P.O. Box 5080 Austin, TX 78763-5080	13. Type of Report and Period Covered Research Report (9/00 — 5/01) 14. Sponsoring Agency Code

15. Supplementary Notes

Project conducted in cooperation with the Federal Highway Administration.

Research Project Title: "EQUIPMENT REPLACEMENT CRITERIA BASED ON LIFE CYCLE COST BENEFIT ANALYSIS (LCCBA) TERM: Transportation Equipment Replacement Methodology"

16. Abstract

The primary function of equipment managers is to provide the proper equipment, at the right time and at the lowest overall cost. A major task in accomplishing this function is fleet planning, which involves identifying the requirements of equipment users, developing optimal strategies to meet those needs, and putting the plan into action. Economic equipment replacement is a complex portion of this process, and the main thrust of this research project is to develop an automated computer software to assist in replacement decisions and prioritize units for replacement. This research report is an interim documentation of the first two phases of this research project, namely the data analysis and the development of a framework for the computerized system. The next reports of this project will respectively document in detail the research conducted and the software development, providing a user manual for software implementation. The final report of this series is a brief project summary report (PSR) of the research development and implementation.

17. Key Words	18. Distribution Statement
Equipment replacement, life-cycle cost, cost analysis, Fleet Management	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	32	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ANALYSIS OF COST DATA AND DEVELOPMENT OF EQUIPMENT REPLACEMENT FRAMEWORK

José Weissmann
Angela Jannini Weissmann

Research Report 4941-1

Research Project 7-4941
"Equipment Replacement Criteria Based On Life Cycle Cost Benefit Analysis (LCCBA)
TERM: TxDOT Equipment Replacement Model"

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration

by the

THE UNIVERSITY OF TEXAS AT SAN ANTONIO

and the

UNIVERSITY OF TEXAS AT EL PASO

January 2002

ABSTRACT

The primary function of equipment managers is to provide the proper equipment, at the right time and at the lowest overall cost. A major task in accomplishing this function is fleet planning, which involves identifying the requirements of equipment users, developing optimal strategies to meet those needs, and putting the plan into action. Economic equipment replacement is a complex portion of this process, and the main thrust of this research project is to develop an automated computer software to assist in replacement decisions and prioritize units for replacement. This research report is an interim documentation of the first two phases of this research project, namely the data analysis and the development of a framework for the computerized system. The next reports of this project will respectively document in detail the research conducted and the software development, providing a user manual for software implementation. The final report of this series is a brief project summary report (PSR) of the research development and implementation.

DISCLAIMERS

JOSÉ WEISSMANN, P.E. (Texas No. 79815)
Research Supervisor

IMPLEMENTATION RECOMMENDATIONS

It is recommended that this report be used as a guideline for the development of the reminder of the project.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION, OBJECTIVES, AND RESEARCH APPROACH

BACKGROUND

Equipment replacement planning is one of the most complex aspects of equipment management and is extensively covered and discussed in the technical literature (for example, refs. 1,2,3). Replacement planning is a continuing process. Long range replacement planning allows the fleet manager to coordinate the replacement process with budget cycles. Advance planning also allows the fleet manager to spread purchases of equipment over several replacement cycles to minimize the impact of a short-term replacement funds shortfall.

Currently, TxDOT uses TxDOT Equipment Replacement Model (TERM) to identify candidates for replacement one year in advance. TERM uses threshold values for equipment age and cumulative usage of an equipment unit as inputs for replacement. For example, current threshold values for dump trucks with tandem rear axles (class code 540020) for age and usage are respectively 10 years and 150,000 miles.

In addition to target life and usage, units with exceptionally high repair costs are also targeted, by establishing an exception threshold, targeting units that exceeded a certain predetermined threshold of the repair costs represented as a percentage of the original purchase cost. Using the dump trucks with tandem rear axles again as an example, the current threshold in TxDOT's TERM system for the repair cost is 100 percent.

PROJECT OBJECTIVES

The current TERM provides TxDOT with a very good tool to make equipment replacement decisions. However, the equipment life-cycle costs are taken into account in a simplified manner, and the data reports are not fully automated. A comprehensive equipment replacement method should include the following steps:

(1) Identify units targeted for replacement,
(2) Obtain replacement requests from users,
(3) Apply an economic analysis model,
(4) Prioritize replacement units,
(5) Develop new equipment specifications,
(6) Acquire new equipment, and
(7) Dispose of old equipment.

Replacement decisions should ideally consider some form of economic analysis such as Life Cycle Cost Benefit Analysis (LCCBA), which requires the accumulation of accurate cost historical data. TxDOT's Equipment Operations Systems (EOS) database is very comprehensive, containing a wealth of information relevant to life cycle cost analysis and replacement decisions.

The main thrust of this research project is the development of a comprehensive, computerized TxDOT Equipment Replacement Model (TERM) system to implement steps 1 through 5, making full use of the information periodically stored in the EOS database. Once implemented, the system will support equipment replacement decisions for the wide variety of equipment class codes existing in the TxDOT equipment inventory.

RESEARCH APPROACH

This project is organized into three phases. Phase I is the development of an equipment replacement model based on life cycle cost analysis. Phase II is the statistical analysis of historical cost data from TxDOT's EOS database, and Phase III is the development of software for supporting equipment replacement decisions at TxDOT.

These phases are interrelated. For example, the equipment replacement models (phase I) and computerized procedure (Phase III) go hand in hand with an analysis of equipment historical data available from EOS database (Phase II). The computer programs developed during the analysis of phase II will have to be included in the final deliverable (Phase III); and findings of Phase II (data analysis) affect the development of Phases I and III.

REPORT OBJECTIVES AND ORGANIZATION

Report Objectives

The nature of this project implies a strong interaction between the project staff, TxDOT Project Director, and the Project Advisory committee. Several decisions were made in concert with TxDOT, especially at two important points: at the end of Phase II, and at the beginning of Phase III. A seminar with the Project Director, the Project Advisory committee, and the researchers was held on April 19, 2001, to discuss data validation, format of the software output, replacement criteria, and overall system framework.

The objectives of this report are twofold:

(1) To document the research progress to date, and

(2) To document the decisions made about the direction of the remainder of the project.

There are three other reports in the 4941 series. Report 4941-2 documents in detail the data analysis, the literature review, the development of the life-cycle cost models, the development of the replacement methodology, and the development of the software framework. Report 4941-3 is a standalone software manual. It explains in detail the software framework, installation and practical use. Report 4941-S, the final report of this series, is a brief summary of the research development and implementation.

Report Organization

Report 4941-1 is organized into four chapters. Chapter 1, Introduction, Objectives, and Research Approach (this chapter), presents a background and introduction, and discusses the project objectives, the research approach, and the report objectives.

Chapter 2, Data Analysis and Validation, discusses the information on the EOS database that is relevant to this project, and the Advisory Panel's decisions regarding data treatment by the system. Chapter 3, Development of the System Framework, discusses the basic architecture of the new TERM system components, as decided by TxDOT and the researchers, based on the results of the interim results of project. Chapter 4, Summary of Project Status and Recommendations, presents a summary the project status, the results of the tasks accomplished so far, and the recommendations for the remainder of the project.

CHAPTER 2
DATA ANALYSIS AND VALIDATION

Replacement or sometimes remanufacturing decisions should ideally consider some form of economic analysis such as Life Cycle Cost Analysis (LCCA), which requires the accumulation of accurate cost historical data. TxDOT's Equipment Operations Systems (EOS) database is very comprehensive, containing a wealth of information relevant to life cycle cost analysis and replacement decisions (ref. 4).

This project extracted a historical cost and replacement data set from TxDOT's larger and more comprehensive EOS database. The data set contains 118,158 records of 51 variables each. It is relevant to note that the data validation checks resulted in a remarkable overall level of accuracy of 99.5%. Nevertheless, the replacement system (being developed when this report was written) contains code to flag data inconsistencies that may be present. The levels of tolerance to be used for each variable were selected in concert with the project Advisory Committee. The objective of this report is to document the results of the data validation phase of this project, and the decisions made in concert with the Advisory Committee.

VARIABLES SELECTED FOR ANALYSIS

TxDOT's Equipment Operations Systems (EOS) database is very comprehensive, containing a wealth of information relevant to life cycle cost analysis and replacement decisions. The variables selected from EOS for use in the new TERM are listed below. They were later organized into two separate data sets, one with retired, the other with active equipment. The system data sets are documented in detail in reports 4941-2 and 4941-3.

Date Variables

Date of last database update
Date equipment was received
Date retired

Life-Cycle Cost Variables

Purchase cost
Resale value, only if retirement code is 2,7,8 or 9
Repair expenses during database update year
Gasoline expenses during database update year
Gallons of gasoline consumed during database update year
Diesel expenses during database update year
Gallons of diesel consumed during database update year

Oil expenses during database update year
Quarts of oil consumed during database update year
Other fuel expenses during database update year
Gallons of other fuel consumed during database update year
Hydraulic fluids expenses during database update year
Quarts of hydraulic and other fluids consumed during database update year
Indirect expenses during database update year
Miles or hours of usage during database update year
Code for usage, (miles or hours)
Hours of downtime during database update year

Note: all variable storing usage, cost and fuel quantity data are available in two types: the cumulative (from equipment purchase to the record date), and for the year of the record date.

Equipment Identification and Status

Equipment unit identification
Equipment class code
Equipment class description
Equipment make code
Model name
District
Section
Equipment status, P through Z, according to EOS data dictionary page 2
Retirement code, 1 through 9, according to EOS data dictionary page 13.

DATA VALIDATION RESULTS

Date Variables

A remarkable 100% accuracy was found for these types of variables. For example, the retirement date was always greater than the receipt date, the receipt date was always less than the corresponding database update, and so on.

The only instances of equipment units in use without a receipt date refer to recently received units whose receipt date has not yet been logged. This is of no concern for the replacement methodology, since new equipment units are not candidates for replacement. The receipt date will become available in later EOS files, for future use when the equipment unit gets older and closer to replacement.

Cost Variables

Purchase cost and resale values are consistent. There were no negative numbers for purchase costs or resale values. There were no instances where purchase cost was less than the resale value. There were no instances of resale values attributed to the wrong equipment status or retirement code.

Negative numbers for prices or fuel quantities. There were 109 negative repair costs. Zero and negative values represent accounting correction for overcharges in the previous fiscal year. Equipment units containing these corrections will be flagged be the system. The occurrences are summarized in table 2.1 (from 1995 through 2000).

Table 2.1 Records Containing Negative Cost Data

Item	Expense<0 and Quantity <0	Expense<0 and Quantity >0	Expense>0 and Quantity <0
Gas	88	2	2
Diesel	49	0	0
Other fuels	7	2	4
Hydraulic and other fluids	21	5	2
Oil	8	3	0
Purchase cost*	0	N/a	N/a
Resale price*	0	N/a	N/a
Repair expenses*	109	N/a	N/a

* Quantities not applicable

Consistency between fuel quantities and their price. Price ranges were estimated dividing the recorded fuel expenses by the recorded fuel quantities. Results should be within a reasonable unit price for all categories except "other fuels". For the latter type, the recorded value includes the fuel price and the tax sticker, so the quotient between expenses and quantity is meaningless. Table 2.2 shows the tolerances established by the Advisory Committee, and the number of records containing unit prices above the tolerance. Gasoline and diesel records are almost 100 percent within range, while generic items, such as "other fluids" and "oil", have more records outside range. Perhaps the tolerance should be greater for these types of generic expenses.

Table 2.2 Tolerance and Consistency of Fuel and Fluids Prices (expenses/quantity)

Item	Tolerance ($/gallon or quart)	Records outside tolerance range	Accuracy
Gas	$0.50—$2.00	379	99.7%
Diesel	$0.40—$2.00	274	99.8%
Hydraulic and other fluids	$1.00—$5.00	12,112	89.8%
Oil	$1.00—$4.00	31,571	73.8%

Downtime and Usage

Downtimes. Downtime values ranged from 1 to 4,879 hours at a mean of 112 hours. The 90% percentile was at 288 hours (12 days). The Advisory Committee recommends a tolerance for downtimes equal to the maximum working hours in a year, which is equal to 2,080. Table 2.3 shows a summary of downtimes equal to or greater than 2,080. There were only 18 points outside the range—11 of them for minor equipment. This means an accuracy level of 100.000% if rounded to the third decimal place. The system will flag these occurrences, in spite of their negligible frequency.

Table 2.3 Downtimes Greater than 2,080 hours/ year

Downtimes	Number of Data Points
2080<=down<3000	11
3000<=down<4000	3
4000<=down<5000	4
>=5000	0
Total	18

Usage in hours ranges from 1 to 13,023, at a mean of 273. The maximum number of hours in a working year of 52 weeks and 8-hour working day is 2,080. Table 2.4 shows a summary of the hours of usage greater than 2,080. There were 272 records with usage values greater than 2,080, resulting in an accuracy level of 99.8%.

Values below 3,000 could represent full-time or full-time plus weekend overtime, as long as downtime values are zero. There were 180 data points with usage between 2,080 and 3,000 hours and downtime greater than zero. Since there are 8,760 hours in a year, values greater than this number are impossible. There were only 6 records with impossible values, as shown in the sixth row of table 2.4. In spite of their negligible frequency, these records will be flagged.

Mileage ranged from 1 to 120,684. The maximum number of hours in a working year of 52 weeks and 8-hour days is 2,080. Assuming an average speed of 40 mph, and full-time, 5-days-a-week, year-round usage, the maximum mileage per year should be 83,000. There were only 24 instances of mileage≥80,000 in the combined 6-year database. One instance was an automobile and the others were trucks. A frequency of occurrence of 24 data points is negligible, so mileage data below 80,000 miles/year will be considered accurate, while values greater than 80,000 will be flagged.

Table 2.4 Usage Greater than 2,080 hours/ year

Hours of usage	Number of Data Points
2080<=usage<3000	223
3000<=usage<4000	23
4000<=usage<5000	12
5000<=usage<6000	3
7000<=usage<8760	5
usage>=8760	6
Total	272

Variables to Identify Equipment Units and their Status

Equipment ID is not always unique. There was no duplication of ID numbers within each fiscal year, but the same equipment ID may refer to a different unit in a previous and/or in a subsequent fiscal year. There were 232 instances of equipment IDs that appear as repetitions in the 6-year history (therefore, 464 records in all). They can be classified as follows:

1. Equipment units that changed classcodes when the voucher was processed, i.e., the classcodes are different in the voucher (status V) and the purchase order (status P). **Advisory Committee recommendation: assume that the classcode is correct in the voucher.**
2. Equipment units that changed to a different size/power category. Example: Unit 01246, received on 09/16/87, appears as classcode 90030 (grader, motor, class III, 125 to 149 H.P.) in the 08/25/97 database update, and as classcode 90040 (same equipment, 150 H.P. and greater) in the 08/30/95 database update. **Advisory Committee recommendation: use the latest classcode**.
3. Truck mounted devices previously classified as a more generic truck classification. For example. Units 03555F and 033556F changed from classcode 530010 (truck, all body styles except conv. dump/wrecker,25500-28900gvwr) to 1010 (aerial personnel device, truck mounted). **Advisory Committee recommendation: assume that the classification is accurate, since it is more detailed.**
4. IDs from retired equipment being assigned to newer equipment. If both units are remaining in the analysis, one of them should be assigned a different ID for analysis purposes. For example, ID=02031E was assigned to a classcode 174020 pneumatic roller that was retired in 1994, and then reassigned to a classcode 170010 roller received in 1996. If the analysis includes the year 1995, then one unit should have a different ID. **Advisory Committee**

recommendation: this practice has been abandoned. Flag these records for user examination and decision.

5. Significant changes, such as unit 02451 (received 4/17/85), classified as 192020 (sprayer, herbicide/Insecticide trailer mounted, self-powered) from 1995 to 1999, and changing to 230030, tractor, pneumatic tired, 65 H.P. and above (tractor only), in 2000. This could have resulted from removal of the sprayer and the trailer, leaving only the tractor. **Advisory Committee recommendation: flag these records for user examination and decision.**

Multiple-Variable Consistency Checks

Do retired units remain in databases subsequent to retirement?

Yes. The results indicated that retired units may remain in the data base for 2 years. The 1999 data base, for example, contained 411 units retired in 1997, and 1249 units retired in 1998. The system will contain code to ensure that retired units appear in the analysis only if they have usage greater than zero (i.e., before retirement).

Can a retired equipment ID be absent from previous databases (instead of appearing as not retired)?

Yes. For example, there were 408 equipment units that appeared as "retired in 1997" in the 1998 database, but were absent from previous databases.

Summary: Two flags for retired units:

1. They may appear as retired in a database but not appear before retirement.
2. They may appear in more than one database as retired.

Equipment status, retirement code, and fuel consumption

Equipment status, retirement code (if retired), usage and fuel consumption must be consistent. For example, equipment status "Q" (requisitioned) must have zero usage and fuel consumption; and so must retired equipment after retirement date.

For every record, the results indicate that the equipment status variable is consistent with the retirement code (when appropriate) and with the maintenance and usage values.

Are the resale prices and the equipment status consistent?

Yes. All equipment pieces that had a recorded resale price also had status of either X (retired, payment pending) or Z (retired).

SUMMARY AND CONCLUSIONS

Summary

The data validation checks resulted in a remarkable overall level of accuracy of 99.5%. Nevertheless, the following inconsistencies will be flagged by the system.

1. Negative costs and prices represent accounting correction for overcharges in the previous fiscal year. Equipment units containing these corrections will be flagged by the system.
2. Retired units that appear as retired in a database but do not appear on previous databases will be deleted from the analysis, due to lack of data.
3. Retired units will be deleted from databases subsequent to the retirement year, if the data indicate no usage.
4. Repeated equipment ID's will be flagged. IDs that are repeated in very different classcodes in different databases may be deleted from the analysis. Equipment that changed categories after it was received, and from then on maintains the same category, will be assigned the most recent category throughout the analysis database. Truck-mounted devices previously classified as trucks take the most recent classification.
5. Maintenance expenses: flagged and set to missing whenever the recorded expenses and recorded quantities do not obey the tolerances set by the Advisory Committee.
6. Hourly usage values greater than 8,760 hours/year, as well as mileage values greater than 80,000 miles/year, will be flagged.
7. Downtime values greater than 2080 hours/year will be flagged. In addition, values greater than 8,760 will also be flagged.
8. Equipment units with status "P" (purchase order), and no entry for date of receipt, are not part of the life-cycle database, because it is not necessary to create another record for units that don't have a cost history yet. They will become part of the system data set when the next EOS file is added to it.

Summary and Conclusion

The historical data base, extracted from TxDOT comprehensive EOS database is remarkably accurate, with 99.5% of all data records passing all consistency checks devised by the research team. Nevertheless, the equipment replacement software will contain code to flag these inconsistencies and, whenever applicable, options to enter corrections. The levels of tolerance and other actions for data validation were selected in concert with the project's Advisory Committee.

CHAPTER 3
DEVELOPMENT OF THE SYSTEM FRAMEWORK

Background

The current replacement criteria in use by TxDOT are based on threshold values for variables that capture the equipment usage and condition such as mileage, downtimes, and repairs. The objective of this project was to develop a more sophisticated replacement methodology based on life-cycle costs, taking advantage of the EOS database, which contains most of the data necessary to study the life-cycle cost history of equipment units.

Research project 7-4941 originated within TxDOT's General Services Division–Purchase and Equipment Sections as a response to the need for developing equipment replacement analysis procedures based on sound engineering economics. The project staff assigned to this research project envisions its product as a computerized TxDOT Equipment Replacement Model (TERM), programmed into a menu-driven software. This system should coordinate the activities related to equipment replacement analysis in Texas, and generate reports and graphs to support equipment replacement decisions.

Suggested System Framework

The currently available historical data set has complete life-cycle histories only for equipment units received on fiscal year 1990 (09/01/1990) or later. These units comprise about 43 percent of the database. The other 57 percent were received before the oldest available data records, and as such have a truncated life-cycle history. There is a need to develop a methodology for immediate use with the older units, which are more likely to be in need of replacement.

Another important result to consider is the literature review conducted in the beginning of this project. It indicated that most agencies do not rely on life-cycle cost alone, for several reasons. Among these are controversies in inflation and discount rates, the fact that the equipment usage (mileage or hours) cannot explicitly appear in the life-cycle cost function, the fact that real life-cycle curves are not as smooth as theory indicates, and difficulties in discriminating between high repair costs (which should indicate high replacement priority) and cost of a major equipment upgrade (which should indicate the opposite).

Considering that life-cycle cost methodology has inherent disadvantages and should not be used as a sole criteria to replace equipment, and considering that right now it can only be applied to the newest 43 percent of the fleet, the research team recommends the system framework depicted in figure 3.1. This framework has four

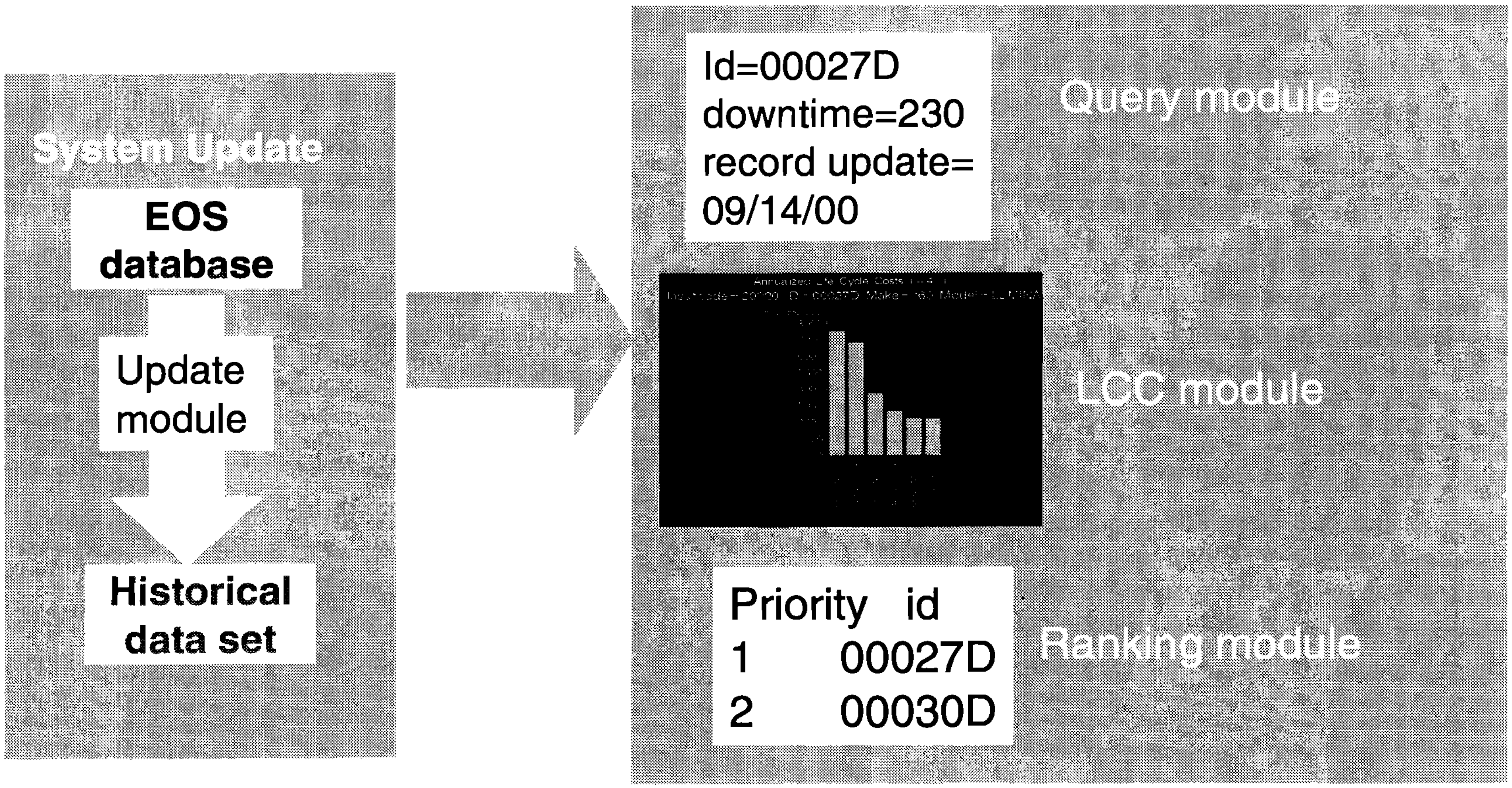

Figure 3.1 Recommended System Framework

modules, as follows:

- Data update module,
- Reporting module,
- Life-cycle cost module, and
- Multi-attribute, frequency-based ranking module.

Data Update Module

The data update module should be used once a year, to include the newest EOS database records in the historical data set. This module will read the appropriate records from the EOS file, apply the data validation criteria discussed in chapter 2, remove retired equipment from the existing historical file, and append the new data to the existing one.

The data update module will also check the date of the latest data set update and warn the user when his/her data set should be updated with the most recent EOS file.

Reporting and Query Module

The reporting and query module will be used to retrieve specific data from the historical data, using a menu. It can also print data tables and graphs. The user will utilize the interface menu select equipment units (by ID) or class codes, as well as the types of tables or graphs to display and/or print. The user will be able to generate reports by district and activity.

Life-Cycle Module

The life-cycle module will be used to inspect the status of the equipment life-cycle history and use it as one of the criteria for replacement. It will calculate a life-cycle cost (LCC) value using the variables listed in chapter 2, allowing the user to input inflation and discount rates.

The module can also rank units for replacement based on LCC. This would result in a replacement priority list based on LCC alone: the higher the slope of the life-cycle cost curve, the higher the replacement priority. The reader is referred to research report 4941-2 for details on the development of the life-cycle cost functions and replacement criteria.

Multi-Attribute Ranking Module and Proposed Replacement Criteria

The ranking module is an improvement on the currently used threshold method. It will rank units for replacement based on a weighted average of the percentiles of different attributes selected by the user, such as downtimes, repair costs, usage, life cycle cost, and others. The ranking is made based on equation 3.1

$$Rank = \sum_{i=1}^{n} w_i P_i \tag{3.1}$$

Where:

w = weight of attribute "i"

i = attribute (such as age, downtime, etc.)

P = percentile ranking of attribute, i.e., percent of units that have an attribute "i" value better than that of the unit being ranked

The weights ("w") will be input by the user and will represent the relative importance s/he places on each attribute. For example, if the user feels that downtimes and repair costs should be twice as important as the operational cost and the mileage, the weights of these attributes could be respectively 2, 2, 1, and 1. If the user does not wish to consider an attribute, s/he can set its weight to zero.

The percentiles ("P") are calculated from the historical data set, and represent the percent of equipment units that have better attribute values than those of the specific unit being ranked (within any desired grouping criteria, such as classcode, make, model, District, etc.). For example, the module could perform the following steps for the attributes "downtime" and "mileage":

- Calculate the cumulative percentiles for recorded downtimes and mileages within a certain class code and District selected by the user (e.g. the highest downtime will have a 100 percentile the highest mileage will also have a 100 percentile).
- Compare the recorded downtimes for each individual unit with the percentiles, to obtain the percentile rank of each unit within that particular class code and District.
- Do the same for the mileage.
- Calculate the weighed average for each unit using equation 3.1. Weights are provided by the user.
- Sort the resulting variable "rank" in descending order to and print the replacement priority list based on downtime and mileage, for that particular class code in the selected District.

The main advantages of the multi-attribute based ranking method are:

- The methodology relies on current status rather than on a complete history, and is therefore immediately applicable to the entire fleet.
- The methodology uses attributes that are easy to visualize, such as mileage, downtimes, repair expenses, etc.
- The manager can make replacement decisions based on a comparison of the challenged with the rest of the fleet, rather than pre-determined values for life-cycle cost parameters.
- By choosing appropriate weights for the ranking formula, the ranking can reflect relative importance of attributes, and the user has flexibility to change such priorities. The user may also compare two or more different replacement schedules based on different attribute priorities.

The researchers feel that this four-module software will allow TxDOT to use the new system immediately for the entire fleet. The system will also allow TxDOT to compare the LCC and multi-attribute ranking methodologies, developing a basis not only for equipment replacement, but also for future modifications and upgrades on the software developed by this project.

The Advisory Panel examined these research proposals and concurred with them. As such, the research team developed, in addition to life-cycle cost functions, a replacement methodology based on multi-attribute ranking. The next report of this series documents the literature review, and the development of these functions, models and procedures underlying the TERM Software.

Research Report 4941-2 documents in detail the research that led to the system, including the literature review, and the development of the analysis data sets, the life-cycle cost functions, the frequency functions for the replacement priorities, the replacement criteria, and the system supporting data files.

Research Report 4941-3 documents in detail the development of the software framework, and is a standalone user manual for the automated TERM (TxDOT Equipment Replacement Model).

CHAPTER 4
PROJECT STATUS, CONCLUSIONS AND RECOMMENDATIONS

PROJECT STATUS

The project was organized in three phases, each one with several tasks. Table 4.1 presents a summary of the proposed phases and tasks, along with the status as of May 2001. The areas filled with gray represent the proposed schedule, while the areas filled in a pattern represent the modifications in schedule. This table shows a revised schedule with the three-month extension discussed during the 4/19/01 meeting. This extension was granted for two reasons: one, the project started late, and two, the researchers and TxDOT agreed that the system should include two different replacement models rather than just one as initially proposed.

In Phase III, there is new a task, added in April 2001, which is the development of the multi-attribute-based ranking module. This task was not part of the original proposal or contract. It was suggested by the research team for the following reasons:

- To ensure immediate utilization of the replacement software for the entire fleet,
- To broaden the spectrum of attributes used in replacement decisions, and
- To allow the manager to rank replacement priorities based on a comparison with the rest of the fleet's condition, instead of threshold values or minimum values of any kind.

The proposed approach requires a comprehensive historical database of equipment attributes, and it is the only approach that allows the manager compare the challenged unit to all other active units within a desired class or group. The attributes used for comparison can be selected by the manager, and include, but are not restricted to, life-cycle costs, operational costs, repair costs, cumulative usage, and other criteria. The priority ranking is calculated for the combination of attributes and relative weighs selected by the manager. The replacement budget can be matched to the units on the top of the replacement priority list.

The development of this proposed approach is thoroughly discussed in the next report of this series (4941-2). This approach was programmed into the software and will be implemented at TxDOT's General Services Division–Purchase and Equipment Sections for immediate use. The software manual is documented in research report 4943-3.

CONCLUSIONS AND RECOMMENDATIONS

During Phase I, the research team investigated the practices of other DOTs, the literature on life-cycle cost models, and the data available at TxDOT. During Phase II, the research team obtained copies of TxDOT's historical data, and performed the statistical analysis and data validation checks of the data elements selected during the development of the LCC model. Next, the team worked in concert with TxDOT Project Director and the Project Advisory Committee to validate the results of phases I and II, and wrote this report.

Deciding when it is the proper time to replace an operating system with a new system depends on how age, usage and obsolescence affected the productivity and costs of the defender. External conditions such as depreciation and tax also enter into the decision making process. There are other considerations in the areas of safety, environment and even prestige that enter into the replacement decision. A replacement decision based on sound reasoning and experience can save time and effort; the wrong decision will waste money.

The survey of replacement methodologies indicated that, for the most part, agencies rely on ad-hoc threshold values and managers' experience for their replacement decisions. Virginia DOT developed a more sophisticated system. Other agencies took the opposite route. Philips Petroleum Company has recently abandoned a complex model they had been using in favor of decisions based on threshold values and managers' experience.

It is next to impossible to log all factors affecting the replacement decisions into a database, and program a computer to analyze all their interactions. For example, sometimes frequency of failure is more important to a replacement decision than its duration, sometimes it is the opposite.

The overview of mathematical models for replacement indicates that, in real life, the factors affecting replacement decisions are too complex to be reduced to a mathematical equation, and qualitative opinions from experienced managers must be considered for optimal decisions. Apparently, this is why strategies based solely on mathematical or economical models have not received wide acceptance.

Conclusions

In summary, the overall results of the survey and the literature search indicated that:

- The prevalent mentality in the private sector is that replacement decisions should be based on experience, and a sophisticated replacement program is not cost-effective. However, the few private agencies that did develop replacement strategies reported savings.

- Public agencies are required to justify replacement decisions and, unless the replacement budget is historically greatly deficient, they have strategies in place. These strategies, for the most part, are based on threshold values for age.
- Managers' experience is extremely important for sound replacement decisions. Efficient replacement decisions depend on some factors that cannot be easily quantified or automated (such as technical obsolescence).
- Cost models developed using existing historical data reflect management's efforts to remove equipment with high operational costs. As such, any adjusted function or curve of cost versus time cannot predict what will happen if the equipment remains in use. Any such cost predictions will underestimate the future operational cost.
- Life-cycle costs are a useful attribute for replacement decisions, but are not widely utilized as a sole basis for replacement decisions. The main reasons are controversies in inflation and discount rates, the fact that the equipment usage (mileage or hours) cannot explicitly appear in the life-cycle cost function, the fact that real life-cycle curves are not as smooth as theory indicates, and difficulties in discriminating between high repair costs (which should indicate high replacement priority) and cost of a major equipment upgrade (which should indicate the opposite).
- Managers' efforts always result in priority lists for replacement.
- Of all DOT's responding to the survey, only TxDOT, which is currently finalizing this project, and NY-DOT, are in the process of updating their replacement methodology.
- One of the most useful tools for managers is a way to easily rank replacement priorities within a desired group.
- TxDOT seems to have one of the best organized methodologies, and one of the most comprehensive databases, allowing replacement priorities to be automatically calculated.

Some companies indicated lack of a comprehensive equipment data base as one of the hurdles that preclude a more sophisticated replacement strategy. TxDOT already has a very comprehensive database, as well as a working replacement methodology. Any improvement over the existing methodology must take full advantage of the EOS database, adding new criteria without losing sight of a wealth of experience using the current method.

Significant Finding

Replacement strategies are very important for fleet managers, and as such have been and still are the subject of many studies. The literature review, along with the survey of replacement strategies and approaches currently in use, indicated that replacement programs can be classified into the following six groups:

(1) **Threshold criteria**. Equipment units become candidates for replacement when they reach predetermined threshold values of indicators such as age, mileage, repair cost, and downtimes. This is the method currently in use by TxDOT.

(2) **Historical costs as percent of new costs**. Equipment units become candidates for replacement when their lifetime maintenance costs reach a predetermined percentage of the cost of a new unit.

(3) **Probability of failure**. Probability models are used to predict when a unit is approaching failure.

(4) **Unit cost (e.g., cost per mile)**. Equipment units become candidates for replacement when their cost per mile reach a predetermined percentage of the cost per mile for a given class of equipment.

(5) **Life-cycle cost analysis**. Equipment units become candidates for replacement when their estimated total cost of ownership and operation reach its minimum. A variation of this method uses incremental costs rather than costs over the entire life.

(6) **Weighted factors method**. Predetermined parameters (such as age, usage, downtimes, etc.) are divided by base figures, and the resulting ratios are weighted and added up. Equipment units become candidates for replacement when their sums exceed a predetermined threshold value.

The most important finding of all this literature review is that, conceptually, all strategies above are the same. They compare the condition of a challenged unit to some pre-determined threshold, which can be age, usage, downtimes, etc. (groups 1 and 6), cost ratios (groups 2, 4 and 5), or a probability of failure (group 3). None of these strategies provide a way to directly compare units with the rest of the fleet—in other words, a way to look at the entire fleet (or a desired subgroup) and see where the challenged unit stands in comparison with the fleet, rather than pre-determined values, thresholds, or cost ratios.

Recommended Strategy

This project proposed and developed a **new** equipment replacement approach, the **multi-attribute priority ranking**. It balances elements of several of the approaches above, and allows the manager to rank replacement priorities based on comparison with the rest of the fleet instead of threshold values or minimum values of any kind. This approach requires a comprehensive historical database of equipment attributes, and it is the only approach that allows the manager to compare the challenged unit to all other active units within a desired class or group. The attributes used for comparison can be selected by the manager, and include, but are not restricted to, life-cycle costs, operational costs, repair costs, cumulative usage, and other criteria. The priority ranking is calculated for the combination of attributes and relative weighs selected by the manager. The replacement budget can be matched to the units on the top of the replacement priority list.

The system framework will be modified to include a multi-attribute decision module based on weighted average of frequencies of attributes selected by the user, with relative importance also selected by the user. This module will not have the limitations of the life-cycle method, and will ensure immediate implementation of the new system to the entire fleet.

WORK PLANNED

Table 4.1 shows the planned schedule in detail. The work planned for the remainder of the project includes:

- Implementing the Advisory Committee's decisions regarding the historical data set and the modules.
- Finalizing the user interface.
- Finalizing the life-cycle module.
- Finalizing the ranking module.
- Finalizing the reporting module.
- Writing reports 4941-2 (research documentation) and 4941-3 (software user manual). The researchers will also write the required PSR (Project Summary Report) in the standard format.

Table 4.1 . Summary of Project Status

Phase	Phase.Task	% Compl	FY2000 1st Q	2nd Q	3rd Q	4th Q	FY2001 1st Q	2nd Q	3rd Q	4th Q	FY2002 1st Q
I: Development of an Equipment Replacement Model based on Life Cycle Cost Analysis procedures	I.1 Literature survey	100%			task	100%	completed				
	I.2. Sample of State DOTs' practices.	100%			task	100%	completed				
	I.3. System framework.	100%			task	100%	completed				
	I.4. Data availability	100%			task	100%	completed				
II Statistical analysis of equipment historical data available at TxDOT	II.1.Obtain TxDOT data	100%			task	100%	completed				
	II.2. Develop statistical analysis	90%									
	II.3. Summarize LCC profiles	50%									
	II.4. Validation of phases I and II.	90%									
	II.5. Research interim report.	100%			task	100%	completed				
III: Development of a computerized procedure for supporting equipment replacement decisions at TxDOT	III.1. Develop LCCBA module	50%									
	III.2. Develop the data update module.	50%									
	III.3. Develop the reporting module	20%									
	III.4. Develop the front-end interface	20%									
	New task: Develop the frequency module	10%									
	III.5 Two research reports and Summary	40%									

REFERENCES

1. Bennett, C.R., and R.M.C. Dunn. *Depreciation of Motor Vehicles in New Zealand.* Transportation Research Record, isue 1262, pp. 12-20. TRB, 1990.
2. Bibona, Salvatore. *Vehicle Replacement Strategies.* Utility Fleet Manager, October 1996, pp. 19-27.
3. National Cooperative Highway Research Program. *Fleet Management and Selection Systems for Highway Maintenance Equipment.* Synthesis of Highway Practice 283, National Academy Press, Washington, D.C. 2000.
4. Texas Department of Transportation. *Equipment Operations Systems (EOS) Database.* (Issued yearly). 1990—2001.