Southwest Region University Transportation Center

A Model for Evaluating Automation in Road Maintenance

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16. Abstract

Automated road and highway maintenance has extremely high potential because of its many benefits including direct and indirect cost savings (economic factors); improvements in safety, quality, working environment, and productivity (qualitative factors); and reduction in emissions and fuel/oil consumption due to the expedited maintenance operations (environmental & energy factors). A comprehensive Automated Road Maintenance Evaluation (ARME) model was developed through which the benefits of all these factors can be evaluated by a system's approach. Using the analysis tools of the model, the automation feasibility of the major maintenance activities was evaluated using the ARME model's needs assessment phase tools, and the feasibility of an Automated Crack Sealer (ACS) system was evaluated using the ARME model's technology evaluation phase tools. Of the 25 maintenance activities evaluated, only 13 were found out to be feasible for automation. Most of these activities (7 out of the 13) are pavement related, four are roadside maintenance activities, and two are traffic related. In evaluating the feasibility of the automated crack sealer; estimated maintenance cost savings, user-cost savings, reduction in emissions/energy consumption, and the improvements in the qualitative factors were determined. Several scenarios, from both the Texas Department of Transportation and private contractors' perspectives, were analyzed; and in every scenario the system proved to be very feasible for all the analysis factors (economic, qualitative, environmental & energy).

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A MODEL FOR EVALUATING AUTOMATION IN ROAD MAINTENANCE

by

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Research Report SWUTC/94/60035-2

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EXECUTIVE SUMMARY

Automated road maintenance can produce direct and indirect cost savings, improvements in safety, quality, working environment, and productivity, and reduction of vehicle emissions and energy consumption due to expedited maintenance operations. The objectives of the research described in this report were to: (1) develop a systematic methodology to evaluate the costs and benefits of automated road maintenance, (2) to identify the maintenance activities which are conceptually feasible for automation, and (3) to evaluate the technical feasibility of specific automated systems.

These objectives were achieved by the development of a comprehensive Automated Road Maintenance Evaluation (ARME) model. The ARME model provides procedures through which maintenance activities or systems designed to automate those activities can be evaluated from economic, qualitative, environmental and energy perspectives. The conceptual feasibility of automating the major maintenance activities of TxDOT was evaluated using the ARME model's needs assessment procedure. The technical feasibility of implementing an Automated Crack Sealer (ACS) system in Texas was evaluated using the ARME model's technology evaluation procedure.

Of the 25 maintenance activities evaluated, 13 were found out to be conceptually feasible for automation. These activities are:

- Base removal and replacement
- Crack and joint sealing
- Leveling or Overlays (currently done with maintainer, drag-box, etc.)
- Leveling or Overlays (currently done with laydown machines)
- Pothole repairs
- Strip and spot seal
- Seal coat
- Ditch maintenance
- Reshaping ditches and slopes
- Guard fence maintenance
- Installing and re-installing signs
- Traffic assistance
- Paint and bead striping

It is recommended that detailed technical feasibility studies be conducted for each of the maintenance activities identified as conceptually feasible. The major objective of these studies would be to identify the sub-activities or tasks which are technically feasible to automate. Technology feasibility studies have already been done for some of the maintenance activities including crack sealing and pothole repairs but a comprehensive and extensive effort is required. The results of detailed technology feasibility studies will help to expedite implementation of innovative automated systems for road maintenance activities.

In evaluating the feasibility of automated crack sealing (ACS), estimated maintenance cost savings, user-cost savings, reduction in emissions and energy consumption, and the improvements in qualitative factors (safety, quality, working environment, etc.) were determined. Several scenarios, from both the TxDOT and private contractors' perspectives, were analyzed, and in every scenario the system proved to be feasible for all the analysis parameters (economic, qualitative, environmental and energy).

If the ACS systems are implemented at the statewide level, in the next several years alone, direct savings are estimated to be $5 million. Over the same period, the user-cost savings are estimated to be $11 million for the 3229 miles of the interstate highways in Texas, and the total user-cost savings would be much higher since the savings on urban freeways, farm-to-market roads, secondary roads, and urban streets are not included in this estimate. To realize these savings, it is recommended that an automated crack sealer be implemented in Texas.

ABSTRACT

Automated road and highway maintenance has extremely high potential because of its many benefits including direct and indirect cost savings (economic factors); improvements in safety, quality, working environment, and productivity (qualitative factors); and reduction in emissions and fuel/oil consumption due to the expedited maintenance operations (environmental & energy factors). A comprehensive Automated Road Maintenance Evaluation (ARME) model was developed through which the benefits of all these factors can be evaluated by a system's approach. Using the analysis tools of the model, the automation feasibility of the major maintenance activities was evaluated using the ARME model's needs assessment phase tools, and the feasibility of an Automated Crack Sealer (ACS) system was evaluated using the ARME model's technology evaluation phase tools. Of the 25 maintenance activities evaluated, only 13 were found out to be feasible for automation. Most of these activities (7 out of the 13) are pavement related, four are roadside maintenance activities, and two are traffic related. In evaluating the feasibility of the automated crack sealer; estimated maintenance cost savings, user-cost savings, reduction in emissions/energy consumption, and the improvements in the qualitative factors were determined. Several scenarios, from both the Texas Department of Transportation and private contractors' perspectives, were analyzed; and in every scenario the system proved to be very feasible for all the analysis factors (economic, qualitative, environmental & energy).

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Automated road and highway maintenance methods have high potential for implementation because of their many benefits. These benefits include direct and indirect cost savings; improvements in safety, quality, working environment, and productivity; and reduction in vehicle emissions and energy consumption due to the expedited maintenance operations.

This research project began in 1992 to identify the major benefits of automation in the maintenance area including user-cost savings, to identify the commercial and prototype automated systems available, and to determine the impacts of automation on fuel consumption. This report summarizes the second phase of this project, and emphasizes the quantification of the benefits and costs of automation through a system's approach.

1.2 OBJECTIVES OF THE REPORT

There were three major objectives of this research. The first objective was to develop a methodology to evaluate the benefits of automated road maintenance. The second objective was to identify the maintenance activities which are best candidates for automation. Finally, the third objective was to evaluate the feasibility of automated systems.

1.3 METHODOLOGY

To achieve the first objective of this research, a comprehensive Automated Road Maintenance Evaluation (ARME) model was developed. This ARME model can evaluate most of the factors which can benefit from automation. These factors included cost factors, qualitative factors (safety, quality, etc.), and environmental/ energy factors.

The ARME model deals with three basic phases of automation: Needs Assessment phase, Technology Evaluation phase, and Field Testing phase. In the needs assessment phase, the model identifies the maintenance activities feasible for automation, and then these maintenance activities are relatively ranked in terms of their feasibility for automation. In the technology evaluation phase, the model determines the expected feasibility of Automated Road Maintenance (ARM) systems, which are available in the market; and then relatively ranks the evaluated ARM systems. In the field testing phase, the model evaluates the field results of an

ARM system selected from the technology evaluation phase. In each phase, the model provides the tools to evaluate the benefits of automation from economic, qualitative and/or environmental & energy perspectives.

For the qualitative analysis of the model, a survey was also performed to develop the relative weights for the different "qualitative factors" or "concerns." The people surveyed for this purpose included Texas Department of Transportation (TxDOT) maintenance personnel and the University of Texas faculty members having broad experience in the maintenance area.

A computer program called QUEWZ-E was also used to determine the additional user-costs, emissions and energy (fuel/oil) consumption values, due to road closures, for typical maintenance-operation scenarios. A factorial, which encompassed most of these scenarios, was tested on QUEWZ-E to develop easy-to-use tables for determining the additional user-costs, emissions and energy consumption values.

For the second objective of this research effort, identification of feasible maintenance activities, the state of Texas was selected as the analysis area. Detailed cost data was collected for the routine maintenance activities performed by TxDOT, and this data was evaluated using the economic analysis tools developed from the ARME model. A survey was also conducted to evaluate these maintenance activities from qualitative and environmental/ energy perspectives. The people surveyed included engineers from the TxDOT division of maintenance and operations (maintenance section), maintenance supervisors/inspectors from TxDOT district 14, and some University of Texas faculty members having vast experience in the maintenance area.

The third objective of the research, to evaluate the feasibility of automated systems, was achieved by performing a detailed evaluation study on an automated crack sealing system being developed at the University of Texas at Austin. The results of this evaluation study included the estimated maintenance cost savings, user-cost savings, reduction in emissions/energy consumption, and the improvements in the qualitative factors (safety, quality, working environment, etc.).

1.4 ORGANIZATION OF THE REPORT

The report is divided into seven chapters. Chapter 2 describes the current maintenance practices in the United States. Detailed economic data for all the maintenance activities performed by the TxDOT is also provided in this chapter. Chapter 3 describes the road/highway maintenance automation in general and identifies the benefits of automation. Chapter 4 describes the ARME model in detail. Also included in this chapter are the results of the relative-weight development surveys for the qualitative concerns; and the results of the factorial tested on the QUEWZ-E model to develop the user-costs, emissions, and fuel/oil consumption charts. Chapter 5 describes the results of an automation needs assessment study performed to identify the TxDOT maintenance activities feasible for automation. Chapter 6 provides the results of the feasibility study on an automated crack sealing system. A current inventory of the automated systems available is also reported in the chapter 6. Chapter 7 concludes the report with summary and recommendations.

CHAPTER 2. CURRENT MAINTENANCE PRACTICES

This chapter describes the current maintenance practices in the United States with special emphasis on Texas. Several aspects of maintenance activities are discussed in this chapter. These include definition and description of maintenance (section 2.1), a macro-level view of the maintenance costs and trends in the United States (section 2.2), and a micro-level view of the maintenance costs and trends in Texas (section 2.3).

2.1 DEFINITION OF MAINTENANCE

Highway maintenance is typically defined as including work such as repair of travel-way surfaces, shoulders, roadsides, drainage facilities, bridges, tunnels, signs, markings, lighting fixtures, and truck weighing and inspection facilities; traffic services such as lighting and signal operation, and snow and ice control; and operation of roadside rest areas, movable span bridges, and the like [AASHTO 1987].

Although AASHTO's definition of maintenance seems quite thorough, most public agencies and organizations interpret maintenance differently. For example, some agencies may define all work that takes place after the original construction on a highway as maintenance, including major rehabilitation and reconstruction, while others might account for these under different headings. But, for most agencies, highway maintenance expenditures are spent on the following five major areas:

- Pavements,
- Roadway & Median,
- Bridges,
- Traffic Services, and
- Office Management & Other.

In the pavements area, there is a wide range of maintenance activities including pothole repairs, crack & joint sealing, leveling/overlays, and base removal/repairs, etc. In the roadway and median area, maintenance activities include mowing, litter removal, sweeping, parking & rest areas' maintenance, and silt & erosion control, etc. In the bridges area, maintenance activities include repairs to joints, deck, super -structures and sub-structures, etc. In the traffic services area, maintenance activities include paint/bead stripping, pavement markings, and maintenance of guard fences, median barriers, signs and signals, etc. A detailed list of activities under each area is discussed in more detail in the following sections.

2.2 MAINTENANCE COST AND TRENDS IN THE UNITED STATES

With the completion of the interstate system in 1993, the United States now has one of the most developed highway and road networks in the world. With the completion of this *development and growth* phase of the highway network, the emphasis of most of the highway agencies is now shifting to maintenance and rehabilitation. The main objectives of highway maintenance are the following [McMullen 1986]:

- To conserve the capital investment made in constructing the highway and road facilities,
- To sustain adequate levels of service,
- To minimize the operating costs of users, and
- To enhance the safety of the traveling public.

In order to achieve these objective, maintenance activities require large sums of money. Although in recent years, the share of maintenance in the total highway expenditures has increased considerably, higher maintenance needs due to the aging of the facilities and a tremendous inflation in the maintenance costs has outpaced this increase in the supply of money. The effects of the aging of the highway facilities on the costs of the maintenance can be seen in Table 2.1 [FHWA 1990].

As a result of these higher maintenance needs due to the aging of the system, aggravated by the tremendous inflation in costs, most agencies are now trying to improve the efficiency of their maintenance programs by incorporating several new strategies. The main target of these newer strategies is to accomplish the most possible maintenance at the least possible cost. Some of these strategies include

- Maintenance contracting practices,
- Better management of available resources,
- Standardizing and improving production processes,
- Prioritizing of the work activities, and
- Incorporation of new technologies.

In 1990, the maintenance expenditures in the United States accounted for about 26% of

TABLE 2.1 INFLATION IN THE MAINTENANCE COSTS [FHWA 1990]
(COST INDEX OF 1977 = 100)

Year	Labor	Material	Equipment	Overhead	Total
1970	57.59	54.79	54.88	73.69	**57.55**
1971	61.20	57.91	55.59	77.45	**60.46**
1972	65.23	61.37	61.79	81.20	**64.89**
1973	69.87	64.35	68.86	84.95	**69.86**
1974	75.83	84.09	79.05	88.71	**78.18**
1975	81.72	95.60	87.85	92.46	**85.24**
1976	91.08	95.11	94.95	96.21	**92.69**
1977*	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
1978	106.99	115.17	107.45	103.72	**107.83**
1979	114.51	136.26	120.84	107.48	**118.17**
1980	129.21	157.11	142.60	111.23	**134.58**
1981	136.96	159.31	167.84	130.36	**146.29**
1982	150.79	171.58	182.78	141.44	**160.04**
1983	157.58	170.04	188.08	159.40	**166.28**
1984	165.93	181.77	188.64	177.57	**173.93**
1985	176.05	195.68	197.13	195.86	**184.37**
1986	183.80	192.79	218.14	204.73	**193.71**
1987	192.30	185.27	232.36	220.05	**202.53**
1988	204.19	182.37	235.79	234.50	**210.77**
1989	209.63	177.59	254.43	256.10	**219.09**
1990	217.53	181.71	268.63	270.50	**228.23**

** Cost changes based on the year 1977*

the total highway expenditures, as shown in figure 2.1; and this share is expected to go up due to further aging of the system. A macro level view of the current maintenance expenditures, both for the United States and Texas, is shown in table 2.2 [FHWA 1990]. This table provides an overview of the maintenance expenditure pattern in the United States and the relevant share of Texas in it.

From this table, it can be observed that for the Interstate system on the national level, the expenditures per mile for the urban areas are almost three times that for the rural areas; whereas in Texas the same ratio is about 7:1. Although these ratios depend a lot on the number of lane miles as the average number of lanes in the urban highways are more than in rural highways (for which the data is not available), still this large difference 3:1 (United States) vs. 7:1 (Texas) gives an impression that the urban interstate highways in Texas get much more relative attention than the general urban interstate highways in the United States. Moreover, a similar ratio (urban/rural) for all the highways/roads under the state control in Texas is about 7:1, which also shows that the urban network gets much more attention than the rural network in Texas.

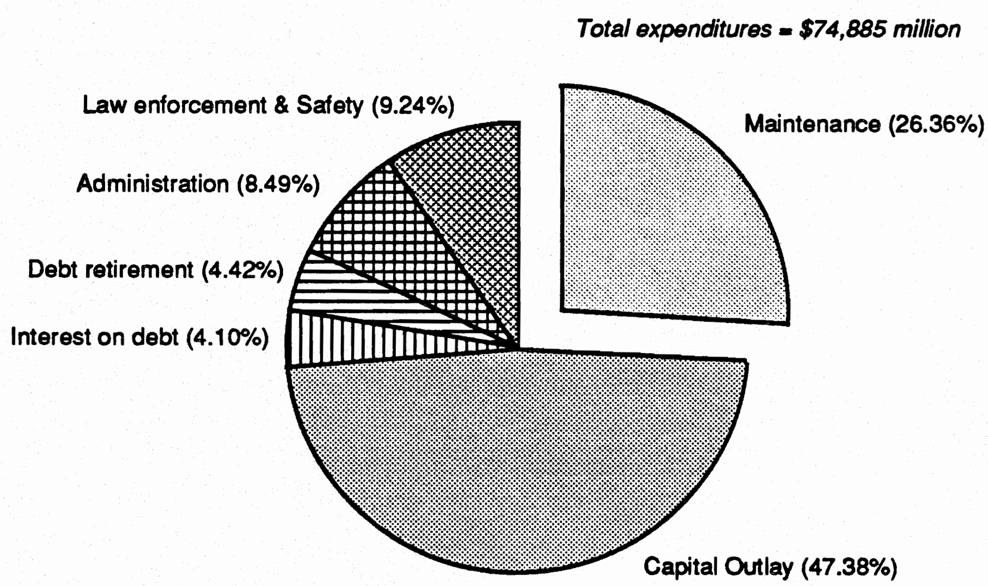


Figure 2.1 Share of Maintenance in total highway expenditures [FHWA 1990]

TABLE 2.2 A MACRO-LEVEL VIEW OF MAINTENANCE EXPENDITURES IN THE UNITED STATES IN 1990 [FHWA 1990]

	United States			Texas		
	Centerline Mileage	Expenditures (Million $)	Expenditures per mile ($)	Centerline Mileage	Expenditures (Million $)	Expenditures per mile ($)
Total*	3,880,151	19,742	5,088	305,951	1,131*	3,696*
Rural	3,122,788	N/A	N/A	217,175	N/A	N/A
Urban	757,363	N/A	N/A	88,776	N/A	N/A
Interstate System	45,074	1,718	38,115	3,229	63	19,491
Rural	33,547	876	26,113	2,282	17	7,494
Urban	11,527	842	73,046	947	46	48,401
State Controlled	798,352	8,266	10,354	76,612	570	7,443
Rural	702,562	N/A	N/A	68,669	322	4,691
Urban	95,790	N/A	N/A	7,943	248	31,233

**1989 data*

In the next section, emphasis is placed on a micro level view of the type and size of maintenance activities performed in Texas.

2.3 MAINTENANCE COSTS AND TRENDS IN TEXAS

The maintenance expenditures of the Texas Department of Transportation (TxDOT) for the last eight years are shown in Table 2.3 [TxDOT 1992A]. From this table, it can be observed that the maintenance costs increased steadily till reaching a range of $550-600 million per year. In 1992, the total maintenance expenditures of TxDOT were $ 557.3 million, and almost 75% of these expenditures ($ 417.7 million) were spent under the routine maintenance category whereas the rest of the funds were spent on the preventive/heavy maintenance and rehabilitation projects.

The routine maintenance expenditures of the TxDOT are tracked by a computerized management system called the Maintenance Management Information System (MMIS). MMIS was implemented in late 1989 to combine the databases of all the previous management and data processing systems developed, and the final target of the MMIS was to arrive at the unit prices of the work done for different maintenance activities. The databases of three previous systems; Equipment Operating System (EOS), Material Supply Management System (MSMS)

TABLE 2.3 THE TREND IN THE TXDOT MAINTENANCE EXPENDITURES [TXDOT 1992A]

Year	Expenditures (Million $)
1985	385,990,819
1986	425,176,560
1987	435,684,221
1988	556,749,064
1989	552,955,893
1990	597,159,726
1991	567,962,664
1992	557,257,708

and Salary and Labor Distribution report (SLD); were consolidated together into one database for the MMIS [Klemens 1990].

In the MMIS database, the maintenance activities are divided into 9 major areas:

1. Base and Subgrade,
2. Bituminous Roadway Surfaces,
3. Concrete Pavements,
4. Shoulder & Approaches,
5. Roadway and Median,
6. Bridges,
7. Traffic Services,
8. Extraordinary Maintenance and Emergency Repairs,
9. Office Management and Roadway Evaluation.

The relative share of these areas, in the total expenditures for 1992, is shown in figure 2.2 [After TxDOT 1993A]. As can be seen from this figure, pavement related maintenance activities (base & subgrade - 4%, bituminous roadway surfaces - 20%, concrete pavements - 1%, and shoulder & approaches - 4%) are the most significant ones with a 29% share in the total expenditures. Roadway & median maintenance (26%), office management & other (20%), and traffic services (20%) are the other major maintenance areas in terms of expenditures. These nine maintenance areas are sub-divided into specific maintenance activities (e.g. potholes repairs, crack sealing, mowing, litter removal, etc.), and each activity is assigned a specific code number.

The MMIS data can be reported in several formats, both at the statewide and district levels. One of these formats is the overall summary format in which the expenditures categorized by maintenance activities are sub-divided into Labor, Equipment, Material, Others and Contract expenditures. The number of TxDOT Man-hours for each activity is also reported in a separate column in this report. This report is very useful as it not only provides the total expenditures per year for a specific maintenance activity; but it also provides important secondary data like the labor intensity, equipment, material, and overhead (other) proportions for that activity. The Statewide Summary of maintenance expenditures for 1992 is shown in Table 2.4 [After TxDOT 1993A].

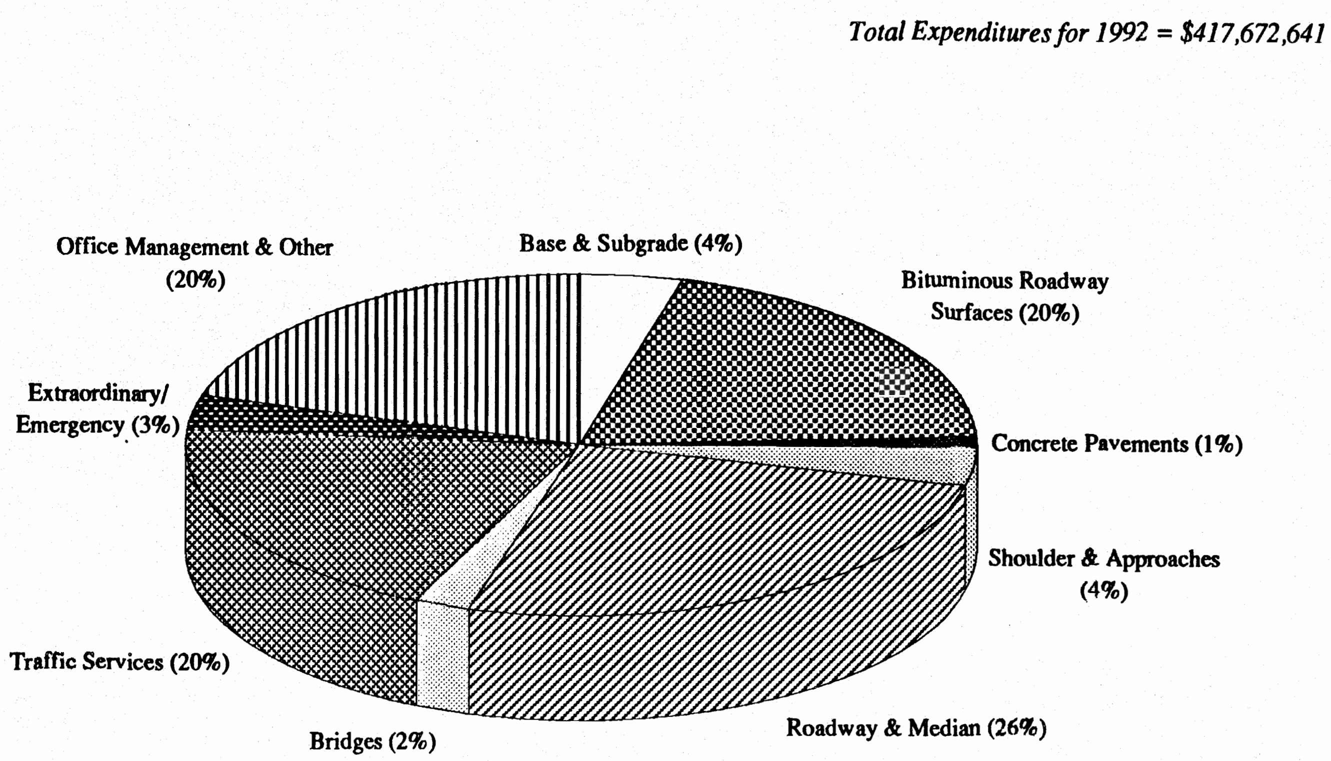


Figure 2.2 TxDOT Maintenance Expenditures by major areas for 1992 [After TxDOT 1993A]

TABLE 2.4 TXDOT MAINTENANCE EXPENDITURE SUMMARY FOR 1992 [AFTER TXDOT 1993A]

Code	Activity Type	% Budget	Amount	Contract	Labor	Equipment	Material	Other
110	**Base Removal & Repl.**	**3.31%**	**$13,825,508**	**4.75%**	**34.60%**	**21.47%**	**38.72%**	**0.45%**
120	Base in Place Repair	0.95%	$3,986,647	5.74%	41.76%	30.91%	21.10%	0.49%
130	Install &/or maintain Sub-drains	0.05%	$192,522	24.62%	34.75%	16.45%	22.42%	1.75%
140	Unpaved Road Maintenance	0.05%	$226,202	0.00%	45.97%	41.18%	12.84%	0.01%
211	**Leveling or overlay w/laydown**	**2.62%**	**$10,948,608**	**18.25%**	**14.67%**	**7.15%**	**59.29%**	**0.65%**
212	**Leveling or overlay w/blade**	**8.36%**	**$34,911,237**	**0.48%**	**22.44%**	**13.90%**	**62.81%**	**0.36%**
213	Leveling by hand	0.83%	$3,457,522	13.35%	50.63%	16.81%	18.49%	0.71%
220*	**Sealing cracks & joints**	**1.06%**	**$4,409,472**	**40.54%**	**26.61%**	**8.69%**	**18.81%**	**5.34%**
231	**Mn Ln Aggr Seal coat**	**1.53%**	**$6,379,703**	**0.34%**	**22.10%**	**12.04%**	**65.14%**	**0.38%**
232	**Mn Ln Aggr strip or spot seal**	**1.69%**	**$7,070,662**	**6.29%**	**28.78%**	**14.57%**	**49.96%**	**0.40%**
233	Mn Ln Fog or skeet sealing	0.58%	$2,433,330	2.47%	37.32%	16.64%	42.61%	0.96%
240	**Potholes**	**1.91%**	**$7,959,761**	**0.75%**	**61.69%**	**17.76%**	**19.13%**	**0.66%**
251	Sprinkle Treatment	0.01%	$29,425	0.00%	44.48%	23.93%	31.14%	0.46%
252	Milling or Planing	0.47%	$1,978,854	9.30%	51.11%	37.51%	0.96%	1.12%
260	Treat Bleading Pavement	0.15%	$643,363	0.00%	40.13%	22.26%	37.41%	0.20%
270	Mn Ln Edge Repair	0.63%	$2,625,439	2.41%	51.62%	15.35%	30.23%	0.39%
310	Conc. Leveling or Overlay	0.06%	$258,340	9.02%	26.36%	13.26%	50.79%	0.57%
320	Cleaning/Sealing Joints (Conc.)	0.11%	$478,769	39.42%	25.39%	7.01%	26.15%	2.03%
330	Blowups & Stress Relief	0.05%	$220,095	0.43%	59.36%	25.70%	14.24%	0.26%
340	Repair Spalling	0.06%	$236,811	2.79%	67.21%	17.56%	12.40%	0.04%
350	Improve Texture	0.01%	$62,361	1.31%	69.77%	22.48%	3.82%	2.63%
360	Full Depth remove & replace	0.87%	$3,615,166	67.47%	15.26%	5.82%	9.07%	2.37%
410	Shld. Leveling or Overlay	0.31%	$1,304,635	0.11%	26.33%	16.14%	57.00%	0.41%
431	Shld. Aggr. Seal Coat	0.18%	$744,726	0.00%	23.30%	12.71%	63.68%	0.31%
432	Shld. Strip or Spot Seal Coat	0.07%	$298,391	7.10%	28.15%	13.45%	50.95%	0.35%
433	Shld. Fog or Skeet Scaling	0.12%	$487,636	0.62%	33.28%	15.34%	49.49%	1.26%
441	Shld. Pothole Repair	0.07%	$296,215	5.65%	60.03%	15.24%	18.28%	0.80%
442	Shld. Edge Repair	0.24%	$1,003,719	16.78%	38.11%	15.77%	28.39%	0.96%
451	Recondition Sod Shoulder	0.61%	$2,553,509	0.00%	54.08%	39.01%	6.20%	0.70%

TABLE 2.4 TXDOT MAINTENANCE EXPENDITURE SUMMARY FOR 1992 [AFTER TXDOT 1993A] (CONT.)

Code	Activity Type	% Budget	Amount	Contract	Labor	Equipment	Material	Other
452	Blade Flexible Base Shoulder	0.75%	$3,124,733	0.80%	46.77%	33.90%	18.28%	0.25%
460	Shld. Base or Subgrade Repairs	0.21%	$873,679	18.01%	32.07%	22.66%	26.50%	0.76%
470	**Side Road Approaches & Turnouts**	**1.15%**	**$4,821,823**	**2.40%**	**44.95%**	**24.52%**	**26.77%**	**1.36%**
480	Concrete Shoulders	0.00%	$4,269	0.00%	64.81%	24.11%	10.52%	0.56%
490	Parking Area Maintenance	0.02%	$92,167	-5.39%	31.36%	17.50%	56.32%	0.21%
511	**Mowing**	**7.04%**	**$29,404,289**	**81.11%**	**9.37%**	**7.37%**	**0.05%**	**2.09%**
521	**Litter**	**2.19%**	**$9,134,339**	**83.85%**	**10.90%**	**3.26%**	**0.38%**	**1.62%**
522	**Routine Street Sweeping**	**1.82%**	**$7,584,105**	**58.25%**	**21.05%**	**18.51%**	**0.05%**	**2.13%**
524	Litter, Spot	0.87%	$3,645,664	1.80%	72.79%	23.10%	0.32%	1.98%
525	Adopt-A-Highway	0.11%	$476,726	0.48%	42.79%	12.68%	43.25%	0.80%
526	Sweeping Ice Rock	0.03%	$145,760	0.00%	51.13%	48.66%	0.00%	0.21%
527	Removal of Graffiti	0.02%	$98,096	0.13%	72.10%	16.02%	11.44%	0.31%
531	**Picnic Areas**	**1.19%**	**$4,963,245**	**41.56%**	**37.77%**	**14.21%**	**3.29%**	**3.17%**
532	**Rest Areas**	**1.28%**	**$5,328,191**	**66.04%**	**12.24%**	**2.79%**	**4.75%**	**14.18%**
535	Rest Area Facility Maint.	0.35%	$1,447,620	16.04%	50.61%	10.88%	16.05%	6.42%
541	Herbicide, Edges	0.54%	$2,272,428	0.01%	24.77%	17.89%	57.29%	0.03%
542	Herbicide, Overspray	0.62%	$2,585,185	0.48%	20.93%	16.36%	62.20%	0.04%
543	Herbicide, Spot	0.71%	$2,984,373	0.01%	33.55%	21.51%	44.90%	0.03%
550	**Land Scaping**	**1.06%**	**$4,427,591**	**26.62%**	**47.13%**	**15.72%**	**4.80%**	**5.74%**
560	**Silt & Erosion Control**	**1.14%**	**$4,750,698**	**8.86%**	**50.46%**	**34.29%**	**5.86%**	**0.53%**
561	**Silt & Erosion Control**	**1.34%**	**$5,583,094**	**4.02%**	**58.51%**	**36.32%**	**0.86%**	**0.29%**
570	**Culvert & Storm Maintenance**	**1.55%**	**$6,484,928**	**16.90%**	**47.10%**	**22.73%**	**10.53%**	**2.74%**
591	Utilities & Driveway Inspection	0.37%	$1,543,932	0.64%	75.30%	17.75%	2.22%	4.09%
592	**Misc. Roadside Maintenance**	**1.45%**	**$6,045,162**	**9.34%**	**60.71%**	**24.85%**	**3.42%**	**1.69%**
593	Driveway Installation	0.59%	$2,445,742	5.16%	50.16%	27.40%	16.72%	0.57%
594	**Driveway Maintenance**	**1.10%**	**$4,580,472**	**1.46%**	**47.53%**	**25.26%**	**25.14%**	**0.61%**
610	Bridges, Movable Span	0.18%	$760,728	0.85%	85.48%	4.59%	2.80%	6.28%
620	Channel Maintenance	0.62%	$2,586,063	28.15%	38.74%	22.73%	8.02%	2.35%
625	Bridge Channel Maintenance	0.13%	$555,137	8.36%	50.74%	31.98%	7.02%	1.90%

TABLE 2.4 TXDOT MAINTENANCE EXPENDITURE SUMMARY FOR 1992 [AFTER TXDOT 1993A] (CONT.)

Code	Activity Type	% Budget	Amount	Contract	Labor	Equipment	Material	Other
630	Bridges, Rail	0.19%	$812,281	22.16%	41.11%	11.56%	23.72%	1.44%
640	Bridges, Joints	0.16%	$666,629	37.28%	36.62%	11.31%	8.04%	6.75%
650	Bridges, Deck	0.33%	$1,397,873	70.56%	18.28%	4.80%	4.04%	2.32%
660	Bridges, Superstructure	0.21%	$883,450	48.56%	34.52%	6.55%	7.74%	2.63%
670	Bridges, Substructure	0.42%	$1,748,663	55.23%	24.98%	8.12%	4.35%	7.32%
711	**Paint & Bead Striping**	**4.48%**	**$18,722,575**	**14.47%**	**15.87%**	**7.38%**	**61.39%**	**0.90%**
712	Thermoplastic Striping	0.10%	$427,106	51.97%	5.54%	0.78%	40.18%	1.53%
713	Speciality Markings	0.45%	$1,897,618	20.49%	51.63%	10.82%	14.97%	2.08%
714	Speciality Markings, Other	0.23%	$976,409	32.18%	31.01%	6.48%	28.12%	2.21%
715	Pavement Markings	0.03%	$144,669	4.47%	67.53%	22.11%	4.82%	1.08%
721	Delineators and/or Delineators	0.67%	$2,788,509	0.13%	60.75%	15.70%	23.15%	0.27%
722	**Guard Fence**	**1.65%**	**$6,902,209**	**41.73%**	**15.46%**	**4.23%**	**36.75%**	**1.83%**
723	Median Barrier	0.16%	$678,915	31.84%	34.20%	10.40%	21.78%	1.78%
724	Roadway Access Control	0.10%	$401,212	21.28%	35.42%	10.15%	30.99%	2.15%
725	Vehicle Attenuators	0.20%	$841,333	12.33%	24.36%	5.79%	56.71%	0.80%
731	Special Sign Studies	0.00%	$11,921	0.00%	73.37%	14.60%	3.45%	8.58%
732	**Install or Re-Install Signs**	**3.74%**	**$15,628,941**	**0.34%**	**35.12%**	**9.19%**	**54.87%**	**0.47%**
733	Maintain Vandalized Signs	0.41%	$1,704,126	0.02%	47.11%	13.51%	39.19%	0.17%
734	**Misc. Sign Maintenance**	**1.58%**	**$6,597,754**	**0.16%**	**74.30%**	**21.31%**	**3.87%**	**0.36%**
736	Mailboxes	0.39%	$1,636,693	0.00%	64.96%	17.96%	16.74%	0.33%
741	**Maintain Signals**	**2.51%**	**$10,484,608**	**7.06%**	**27.64%**	**9.21%**	**18.62%**	**37.48%**
742	**Illumination**	**1.85%**	**$7,722,911**	**4.53%**	**12.43%**	**5.37%**	**8.20%**	**69.48%**
745	Freeway & Advanced System	0.23%	$951,569	18.51%	35.89%	7.09%	23.82%	14.69%
750	Raised Pavement Markings	0.73%	$3,055,063	40.35%	12.77%	3.10%	41.94%	1.84%
789	Freeway Traffic Surveys	0.02%	$87,168	0.00%	93.37%	3.52%	0.55%	2.56%
793	Misc. Traffic Surveys	0.22%	$908,359	0.64%	81.46%	9.56%	3.50%	4.83%
809	Assistance to Traffic (Special)	0.10%	$409,417	2.04%	68.50%	21.01%	6.90%	1.55%
810	**Assistance to Traffic**	**1.68%**	**$7,018,613**	**1.93%**	**64.85%**	**26.71%**	**5.12%**	**1.39%**
821	Emergency Repairs to Base/Sub-grade	0.23%	$965,300	2.65%	45.94%	24.52%	26.07%	0.82%

TABLE 2.4 TXDOT MAINTENANCE EXPENDITURE SUMMARY FOR 1992 [AFTER TXDOT 1993A] (CONT.)

Code	Activity Type	% Budget	Amount	Contract	Labor	Equipment	Material	Other
822	Emergency Repairs to Bituminous Surfa	0.66%	$2,765,041	27.34%	31.46%	14.49%	25.36%	1.35%
823	Emergency Repairs to Concrete Paveme	0.01%	$35,095	0.56%	61.61%	17.78%	18.18%	1.87%
824	Emergency Repairs to Shld. & Approach	0.12%	$507,813	0.00%	43.21%	26.83%	29.37%	0.59%
825	Emergency Repairs to Roadsides	0.22%	$911,429	11.35%	46.80%	31.76%	9.14%	0.95%
826	Emergency Repairs to Bridges	0.13%	$544,566	29.93%	39.40%	15.80%	12.51%	2.36%
827	Emergency Repairs to Traffic Services	0.10%	$424,876	1.59%	59.77%	18.95%	18.20%	1.49%
830	Hazardous Material Clean-up	0.02%	$102,081	55.42%	22.96%	11.48%	8.89%	1.25%
910	**Section Administration**	**10.34%**	**$43,199,512**	**0.32%**	**88.24%**	**10.15%**	**0.47%**	**0.83%**
912	Preliminary Engineering	0.18%	$749,056	1.03%	86.65%	10.69%	0.36%	1.27%
920	**Section Headquarters' Operation**	**3.75%**	**$15,669,219**	**10.13%**	**55.98%**	**7.58%**	**7.03%**	**19.28%**
925	Standby Work	0.02%	$71,948	0.00%	99.10%	0.85%	0.01%	0.03%
931	Skid Testing	0.01%	$58,649	3.73%	78.63%	12.50%	0.00%	5.14%
932	Profilometer	0.00%	$5,765	0.00%	24.48%	21.39%	0.00%	54.14%
933	Dynaflect	0.00%	$8,989	0.00%	54.23%	42.96%	0.00%	2.81%
934	Visual Survey	0.07%	$299,817	0.04%	82.84%	16.39%	0.02%	0.71%
935	Photologging or Videologging	0.00%	$4,070	0.00%	36.04%	6.76%	56.81%	0.39%
941	Bi-annual Night Sign Inspection	0.06%	$248,557	0.00%	74.75%	24.83%	0.42%	0.00%
960	**Misc. Section Expense**	**4.95%**	**$20,681,667**	**4.32%**	**48.75%**	**13.99%**	**23.71%**	**9.23%**
970	Bridge Inspection	0.76%	$3,192,572	56.62%	36.26%	3.18%	0.13%	3.81%
971	Bridge Routine Inspection	0.02%	$99,738	0.13%	72.01%	18.43%	0.28%	9.15%
980	Surveying	0.06%	$231,422	9.49%	82.33%	7.15%	0.68%	0.35%
	Total		**$417,672,643**					

** Code 420 expenditures were added with Code 220 expenditures due to similar specifications of both codes.*

Bold Activities have expenditures more than 1% of the total expenditures.

Another important reporting format of MMIS is the Maintenance Efficiency and Analysis Reporting System (MEARS). In MEARS, the data for selected maintenance activities, which are relatively easy to measure in terms of unit work (e.g. $/sqyd., $/acres, $/each, etc.), is analyzed; and the unit prices (both in-house and contracted) are reported for these activities. Since this system is still in the development and growth phase, only 44 out of the total of 139 maintenance activities (with MMIS codes) were being reported by MEARS till June 1993. The target is to calculate the unit prices of all the maintenance activities by MEARS in the future. The unit costs reported for 1992 and the first nine months of 1993 are shown in table 2.6 for In-house work and table 2.7 for Contracted work [TxDOT 1992B, 1993B].

TABLE 2.6 UNIT PRICES FOR IN-HOUSE WORK BY MEARS [TXDOT 1992B, TXDOT 1993B]

Code	Activity Type	In-House Work			
		Amount, $ (92)	Unit Price, $ (92)	Amount, $ (93)	Unit Price, $ (93)
110	Base Removal & Repl.	12,062,773	5.23/SQYD	8,637,167	4.00/SQYD
120	Base In Place Repair	3,524,765	1.79/SQYD	3,285,394	1.49/SQYD
211	Leveling or overlay w/laydown	8,142,248	2.24/SQYD	2,833,017	2.02/SQYD
212	Leveling or overlay w/blade	31,856,667	1.57/SQYD	23,709,158	1.64/SQYD
213	Leveling by hand	2,813,981	6.12/SQYD	2,292,821	5.21/SQYD
221	Sealing cracks & joints	NA	NA	1,115,725	0.73/LB
222	Sealing cracks & joints	NA	NA	455,874	4.76/GAL
231	Mn Ln Aggr Seal coat	5,829,951	0.51/SQYD	3,498,816	0.63/SQYD
232	Mn Ln Aggr strip or spot seal	5,856,272	0.75/SQYD	5,580,231	0.65/SQYD
233	Mn Ln Fog or skeet sealing	2,243,412	0.05/SQYD	1,842,241	0.04/SQYD
234	Strip or Spot Fog Seal	NA	NA	474,115	0.12/SQYD
240	Potholes	7,494,948	5.82/EACH	NA	NA
241	Potholes, Semi-permenant repairs	NA	NA	4,416,957	5.47/EACH
242	Potholes, Permenant repairs	NA	NA	322,145	8.11/EACH
245	Adding or Widening Pavement	NA	NA	451,052	1.21/SQYD
252	Milling or Planing	NA	NA	1,112,188	0.89/SQYD
270	Mn Ln Edge Repair	2,407,984	0.44/LFT	3,653,901	0.32/LFT
310	Conc. Leveling or Overlay	168,408	2.37/SQYD	NA	NA
360	Full Depth remove & replace	723,516	50.79/SQYD	395,558	49.65/SQYD
410	Shld. Leveling or Overlay	1,251,926	2.38/SQYD	NA	NA
431	Shld. Aggr. Seal Coat	624,457	0.52/SQYD	NA	NA
432	Shld. Strip or Spot Seal Coat	237,315	0.60/SQYD	NA	NA
433	Shld. Fog or Skeet Scaling	473,613	0.06/SQYD	NA	NA
441	Shld. Pothole Repair	260,787	6.46/EACH	NA	NA
442	Shld. Edge Repair	719,079	0.32/LFT	NA	NA
460	Shld. Base or Subgrade Repairs	671,427	1.87/SQYD	NA	NA
511	Mowing	3,129,559	25.70/ACR	1,678,114	19.10/ACR
513	Spot Mowing	NA	NA	108,364	27.06/ACR

TABLE 2.6 UNIT PRICES FOR IN-HOUSE WORK BY MEARS [TXDOT 1992B, TXDOT 1993B] (CONT.)

Code	Activity Type	In-House Work			
		Amount, $ (92)	Unit Price, $ (92)	Amount, $ (93)	Unit Price, $ (93)
521	Litter	372,878	3.36/ACR	256,001	2.96/ACR
522	Routine Street Sweeping	NA	NA	1,787,699	14.47/MILE
524	Litter, Spot	3,298,238	3.06/EACH	3,001,379	2.94/EACH
531	Picnic Areas	1,845,087	NA	1,171,865	NA
532	Rest Areas	1,102,371	NA	860,127	NA
535	Rest Area Facility Maint.	1,062,698	NA	901,823	NA
541	Herbicide, Edges	2,120,989	42.71/ACR	1,400,774	43.73/ACR
542	Herbicide, Overspray	2,197,953	17.09/ACR	823,612	17.30/ACR
543	Herbicide, Spot	2,723,726	47.73/ACR	1,569,570	43.89/ACR
544	Chemical Vegetation Control	NA	NA	12,117	17.33/ACR
555	Sealing & Blanketing	NA	NA	226,172	0.01/SQYD
556	Hydromulching	NA	NA	25,209	0.25/SQYD
557	Sodding	NA	NA	119,779	0.24/SQYD
560	Silt & Erosion Control	4,038,270	0.20/LFT	3,199,035	0.15/LFT
561	Silt & Erosion Control	5,062,188	2.79/CUYD	4,698,677	2.79/CUYD
580	Removal of Illegal Signs (Temp.)	NA	NA	62,700	2.72/EACH
581	Removal of Illegal Signs (Perm.)	NA	NA	5,281	1.92/SF
593	Driveway Installation	NA	NA	1,642,448	4.48/SQYD
594	Driveway Maintenance	NA	NA	3,139,729	2.31/SQYD
595	Guard Fence	NA	NA	807,839	6.26/LFT
650	Bridges, Deck	NA	NA	200,289	0.96/SF
711	Paint & Bead Striping	10,467,891	0.03/LFT	7,828,851	0.03/LFT
721	Delineators and/or Delineators	2,564,333	5.48/EACH	1,983,089	5.33/EACH
722	Guard Fence	1,135,333	4.82/LFT	NA	NA
732	Install or Re-install Signs	14,444,563	9.29/SQFT	11,670,715	9.09/SQFT
750	Raised Pavement Markings	517,509	2.18/EACH	385,355	2.41/EACH
999	Non-MMIS	103,420,952		69,902,164	
	Total	**246,868,068**		**183,545,136**	

TABLE 2.7 UNIT PRICES FOR CONTRACTED WORK BY MEARS [TXDOT 1992B, TXDOT 1993B]

Code	Activity Type	Contracted Work			
		Amount, $ (92)	Unit Price, $ (92)	Amount, $ (93)	Unit Price, $ (93)
110	Base Removal & Repl.	872,628	7.84/SQYD	1,998,179	10.09/SQYD
120	Base in Place Repair	205,447	5.68/SQYD	2,526,466	5.34/SQYD
211	Leveling or overlay w/laydown	2,166,982	1.19/SQYD	1,966,512	1.79/SQYD
212	Leveling or overlay w/blade	372,973	2.09/SQYD	371,822	3.38/SQYD
213	Leveling by hand	435,458	60.10/SQYD	1,131,352	56.25/SQYD
221	Sealing cracks & joints	NA	NA	2,859,756	0.70/LB
222	Sealing cracks & joints	NA	NA	202,347	8.40/GAL
231	Mn Ln Aggr Seal coat	23,727	4.05/SQYD	99,447	5.18/SQYD
232	Mn Ln Aggr strip or spot seal	724,648	1.09/SQYD	615,751	1.05/SQYD
233	Mn Ln Fog or skeet sealing	37,738	0.12/SQYD	146,073	0.15/SQYD
234	Strip or Spot Fog Seal	NA	NA	164,615	1.11/SQYD
240	Potholes	93,405	16.80/EACH	NA	NA
241	Potholes, Semi-permanent repairs	NA	NA	196,338	11.47/EACH
242	Potholes, Permanent repairs	NA	NA	36,119	187.10/EACH
245	Adding or Widening Pavement	NA	NA	0	0.00//SQYD
252	Milling or Planing	NA	NA	260,664	1.65/SQYD
270	Mn Ln Edge Repair	70,029	8.27/LFT	531,999	2.22/LFT
310	Conc. Leveling or Overlay	26,145	181.56/SQYD	NA	NA
360	Full Depth remove & replace	2,381,062	90.16/SQYD	2,368,104	189.69/SQYD
410	Shld. Leveling or Overlay	517	0.00/SQYD	NA	NA
431	Shld. Aggr. Seal Coat	0	0.00/SQYD	NA	NA
432	Shld. Strip or Spot Seal Coat	27,159	0.91/SQYD	NA	NA
433	Shld. Fog or Skeet Scaling	6,026	0.14/SQYD	NA	NA
441	Shld. Pothole Repair	23,505	6.96/EACH	NA	NA
442	Shld. Edge Repair	248,431	3.31/LFT	NA	NA
460	Shld. Base or Subgrade Repairs	173,944	9.06/SQYD	NA	NA
511	Mowing	23,072,796	15.00/ACR	17,565,735	15.56/ACR
513	Spot Mowing	NA	NA	18,409	15.05/ACR

TABLE 2.7 UNIT PRICES FOR CONTRACTED WORK BY MEARS [TXDOT 1992B, TXDOT 1993B] (CONT.)

Code	Activity Type	Contracted Work			
		Amount, $ (92)	Unit Price, $ (92)	Amount, $ (93)	Unit Price, $ (93)
521	Litter	8,035,668	6.11/ACR	6,372,794	6.09/ACR
522	Routine Street Sweeping	NA	NA	3,468,325	39.81/MILE
524	Litter, Spot	84,799	8.60/EACH	125,757	8.99/EACH
531	Picnic Areas	2,705,004	NA	2,251,580	NA
532	Rest Areas	3,806,043	NA	3,227,597	NA
535	Rest Area Facility Maint.	248,570	NA	189,209	NA
541	Herbicide, Edges	215	0.00/ACR	0	0.00/ACR
542	Herbicide, Overspray	39,586	19.97/ACR	12,205	6.13/ACR
543	Herbicide, Spot	316	0.00/ACR	40	0.00/ACR
544	Chemical Vegetation Control	NA	NA	0	0.00/ACR
555	Sealing & Blanketing	NA	NA	4,011	2.91/SQYD
556	Hydromulching	NA	NA	62,582	0.33/SQYD
557	Sodding	NA	NA	6,843	4.38/SQYD
560	Silt & Erosion Control	368,290	5.89/LFT	1,045,310	5.42/LFT
561	Silt & Erosion Control	176,271	4.63/CUYD	400,326	6.53/CUYD
580	Removal of Illegal Signs (Temp.)	NA	NA	5	0.00/EACH
581	Removal of Illegal Signs (Perm.)	NA	NA	0	0.00/SF
593	Driveway Installation	NA	NA	364,642	4.62/SQYD
594	Driveway Maintenance	NA	NA	124,575	12.49/SQYD
595	Guard Fence	NA	NA	3,070,130	5.27/LF
650	Bridges, Deck	NA	NA	620,227	76.35/SF
711	Paint & Bead Striping	6,358,692	0.04/LFT	4,261,680	0.03/LFT
721	Delineators and/or Delineators	6,021	92.57/EA	17,849	19.11/EACH
722	Guard Fence	5,196,450	4.71/LFT	NA	NA
732	Install or Re-install Signs	98,268	39.93/SQFT	321,462	12.83/SQFT
750	Raised Pavement Markings	2,278,135	2.04/EA	1,239,081	1.63/EACH
999	Non-MMIS	568,698	NA	42,790	NA
	Total	**60,933,648**		**60,288,710**	

CHAPTER 3. AUTOMATION IN ROAD/HIGHWAY MAINTENANCE

This chapter gives an overview of automation in the road/highway maintenance area. Several aspects of automation are discussed in this chapter. These include definition and different levels of automation (section 3.1), the benefits of automation from a macro-level (section 3.2), and finally the benefits of automation from a micro-level (section 3.3).

3.1 DEFINITION OF AUTOMATION

Automation is interpreted differently in most regions of the world. For example, most mechanized systems used for current maintenance practices in the United States or other developed industrialized countries are considered to be automated systems in most third world countries. Also, as automation in road/ highway maintenance is a relatively new area, there in no explicit or agreed-upon definition of "automated systems" even in the industrialized countries; and the definition varies from "systems that replace or reduce human labor" to "autonomous cognitive robots". This ambiguity in interpreting automation is basically due to the different levels of automation in road maintenance, and to overcome this ambiguity road/ highway maintenance systems can be divided into three major categories [Skibniewski 1990]:

Mechanized: These systems have the capability to apply large forces, over extended periods of time, due to the hydraulic force actuation and transmission hardware. But, all equipment operations requires human input for execution.

Numerically Controlled (hard automation): These systems have the capability to execute repetitive and large volume tasks with little or no operator assistance. Some limitations of these systems are the following: restricted to the conditions in which one task or a sequence of identical tasks is required, no obstacles in the path of system in the working area, and operator assistance for unexpected obstacles or operational difficulty.

Semi-Autonomous/Autonomous (soft/flexible automation): These systems are capable of partially or fully independent execution of one or a variety of tasks, and are currently the highest level of technical sophistication. The operational autonomy of the system is achieved through sensory data obtained from the environment which, after internal processing, is used in the actuation of relevant system action. Hence, these systems react intelligently to a limited range of unforeseen working conditions, and only require the assistance of an operator for complex conditions which might occur rarely. Also, these systems can be reprogrammed for different types of compatible tasks.

However, for the scope of this report; a devise, equipment or system which is *computer controlled or assisted* is defined as an "automated system" to avoid the ambiguity and confusion in the terminology.

3.2 BENEFITS OF AUTOMATION IN ROAD MAINTENANCE (MACRO-LEVEL)

In the first phase of this research project, several macro-level factors were identified which provide enormous opportunities for new and more efficient methods and management strategies including automation [Hsieh 1992]. These factors include the following:

- the aging of the road/highway system,
- the increase in vehicular traffic,
- stricter and more extensive environmental regulations, and
- an increase in the direct cost of maintenance operations.

Besides these factors, many major benefits of automation in road maintenance were also identified. These included the following:

- Reduction in work zones and the interference of maintenance operations with traffic,
- Increase in the flexibility of maintenance forces,
- Increase in the capacity of maintenance forces,
- Improvements in the quality of maintenance operations,
- Reduction in operation time,
- Reduction in labor requirements,
- Improvement in the worker utilization,
- Conformation to the environmental regulations, and
- Removal of workers from dangerous or hazardous sites.

Based on this work of the first phase and the experiences of other more automated industries including manufacturing and construction, numerous factors which can benefit from automation were identified. This strategy was adopted so as to use the experiences of these more developed or established industries, in terms of successfully automating their tasks and operations, as compared to road maintenance automation which is still in the infancy stage. These factors are discussed in detail in the next section.

3.3 BENEFITS OF AUTOMATION IN ROAD MAINTENANCE (MICRO LEVEL)

Road/Highway maintenance automation, in most cases, has many benefits. Besides direct maintenance cost savings, these benefits include improvements in safety, quality, productivity, environment and other concern areas for maintenance managers and contractors.

To identify these benefits of automation in detail, numerous factors, which can benefit from automation were identified. These factors were used in a model which evaluates all these factors for the following three phases of automation (from a public agency's perspective):

- Needs Assessment phase (evaluating feasibility of maintenance activities for automation),
- Technology Evaluation phase (evaluating feasibility of automated systems), and
- Field Testing phase (field testing of automated systems before implementation).

This strategy was adopted as currently there are not many automated systems available either in the prototype or commercial form. Hence, a needs assessment at this stage can help in setting the pace of automation R&D for the maintenance activities which are most feasible for automation. However, as Automated Systems do exist for some maintenance activities, a set of factors were also identified for technology evaluation and field testing phases of the model.

Based on the different characteristics of these factors, they were divided into three major categories:

- Economic Factors (maintenance costs, user costs, etc.),
- Qualitative Factors (safety, quality, etc.), and
- Environmental/Energy Factors (emissions, fuel consumption, etc.).

The economic factors are identified in detail in table 3.1. Although, not all these factors are applicable for the needs assessment phase, most of these are essential when performing a technology evaluation or field testing of an automated system.

The qualitative factors are identified in detail in table 3.2. These factors are termed as concerns due to the subjective importance placed on them when used in an evaluation. First several broad concern areas (e.g. safety, quality, etc.) were identified, and then more specific concerns for each of these areas were identified. This was done using the experiences of other

TABLE 3.1 ECONOMIC FACTORS REQUIRED FOR EVALUATING BENEFITS OF AUTOMATION IN ROAD/HIGHWAY MAINTENANCE.

FACTORS	NA*	TE*	FT*
1. Direct Costs		X	X
A. Current unit-costs of maintenance activities		X	X
Labor		X	X
Material		X	X
Equipment		X	X
Overheads		X	X
Other		X	X
B. Additional costs due to automated systems		X	X
System's initial cost		X	X
System's operating costs		X	X
System's maintenance costs		X	X
Overheads		X	X
Other		X	X
C. Savings in unit cost from automated systems		X	X
Reduction in labor costs		X	X
Reduction in materials wastage		X	X
Other cost savings		X	X
2. User Costs	X**	X	X
A. User Costs due to maintenance operations		X	X
Extra travel time costs		X	X
Additional vehicle operating costs		X	X
Additional fuel consumption costs		X	X
Additional oil consumption costs		X	X
B. Savings in user-costs from automated systems		X	X
Reduction in extra travel time costs		X	X
Reduction in additional vehicle operating costs		X	X
Reduction in additional fuel consumption costs		X	X
Reduction in additional oil consumption costs		X	X
3. Cost Impacts	X	X	X
A. Cost Impact (Current maintenance practices)	X	X	X
Total maintenance expenditures/year/maint.activity	X	X	X
Total unit-work performed/year/maint. activity		X	X
B. Cost Impact (Automated systems)		X	X
Working capacity of automated system/year		X	X
Estimated efficiency of automated system (%)		X	X
Working life of the automated systems		X	X

** Applicable for NA=Needs Assessment, TE=Technology Evaluation, or FT=Field Testing phases.*

*** Implicitly considered in the qualitative analysis.*

more established industries in terms of automation, and then using these concerns for the road maintenance perspective [Tucker 1992A, 1992B]. Not all of these qualitative concerns were applicable for all the three phases of automation which can be seen in table 3.2.

The environmental/energy factors are identified in table 3.3. For the needs assessment phase, these factors can be evaluated as qualitative factors based on engineering judgment. But, in the technology evaluation phase, these factors can be analyzed in detail, using software packages available commercially. The basic reason behind this approach is that it is impossible to estimate the reduction in emissions or fuel-consumption at the needs assessment phase because a prospective automated system for a particular maintenance activity may or may not result in reducing these variables. Therefore, these variables are treated as qualitative in the needs assessment phase. However, if we are evaluating a prototype or commercial automated system, these environmental/energy factors can be estimated to a certain extent using several software packages available commercially.

All these three types of factors were later used in an Automated Road Maintenance Evaluation (ARME) model. In this model, the effects of all these factors were considered when performing a needs assessment, a technology evaluation or a field testing study. This model in discussed in detail in the next chapter.

TABLE 3.2 QUALITATIVE FACTORS REQUIRED FOR EVALUATING BENEFITS OF AUTOMATION IN ROAD/HIGHWAY MAINTENANCE.

CONCERNS	NA*	TE*	FT*
1. Productivity	**X**	**X****	**X****
Work involves repetitive/cyclic tasks	X		
Work involves time consuming tasks	X		
Work involve environment-dependent tasks	X		
More productivity required (large work demand)	X		
Highly labor intensive area	X		
Low income level of operators/labor	X		
Significant materials wastage	X		
2. Quality	**X**	**X**	
Consistency in work	X	X	
Accuracy in work	X	X	
Other (visual, aesthetics, etc.)	X	X	
3. Safety	**X**	**X**	
Work physically dangerous (operators/labor)	X	X	
Work hazardous to the health (operators/labor)	X	X	
Work physically dangerous (road users)	X	X	
Work hazardous to the health (road users)	X	X	
4. Worker Utilization		**X**	
Lower no. of operators required for the system		X	
Same work crew can be used for the system		X	
5. Working Environment	**X**	**X**	
Noisy conditions in the work area	X	X	
Vibrations in the work area	X	X	
Dirty conditions in the work area	X	X	
Work involve heavy/high lifts	X	X	
Meticulous work	X	X	
Exhaustive work	X	X	

TABLE 3.2 QUALITATIVE FACTORS REQUIRED FOR EVALUATING BENEFITS OF AUTOMATION IN ROAD/HIGHWAY MAINTENANCE (CONTINUED).

CONCERNS	NA*	TE*	FT*
6. Technology Feasibility	**X**	**X**	
Existing level of Automation R&D	X		
Automated systems commercially available	X		
Commercial available system		X	
Spares/Support easily available		X	
Reliable Technology (System/Manufacturer)		X	
Durable Technology (System/Manufacturer)		X	
Risk of failure (not unusual design/operation)		X	
Skill level to operate the system		X	
Additional training for the work crew/operators		X	
Availability of new work crew/operators		X	
Set-up/breakdown time of the system		X	
Transportation of the system to the work site		X	
User friendliness of the system		X	
Clean-up requirements of the system		X	
System can perform multiple tasks		X	
System can operate in most typical situations		X	
7. User-Costs & Emissions	**X**	**X*** **	**X*** **
User-costs and emissions due to the following:			
Road closures	X	X***	X***
Long closure times	X	X***	X***
Night time operations	X	X***	X***
8. Socio-Political	**X**	**X**	
Workers' resistance	X	X	
Workers' motivation to change	X	X	
System's acceptability in the organization		X	

** Applicable for NA=Needs Assessment, TE=Technology Evaluation, or FT=Field Testing phases.*

*** Considered in the economic analysis.*

**** For the Technology Evaluation and Field Testing phases, these factors can be analyzed in more detail using computer software packages available commercially.*

TABLE 3.3 ENVIRONMENTAL FACTORS REQUIRED FOR EVALUATING BENEFITSOF AUTOMATION IN ROAD/HIGHWAY MAINTENANCE.

FACTORS	NA*	TE*	FT*
1. Additional Air Pollution due to maintenance operations	X**	X	X
Carbon monoxide Emissions (CO)	X**	X	X
Hydrocarbons Emissions (HC)	X**	X	X
Oxides of Nitrogen Emissions (NOx)	X**	X	X
2. Additional Noise Pollution due to maintenance operations	NA***	NA***	NA***
3. Additional Energy Consumption due to maintenance operations	X**	X	X
Fuel Consumption	X**	X	X
Oil Consumption	X**	X	X
4. Other	NA***	NA***	NA***

** Applicable for NA=Needs Assessment, TE=Technology Evaluation, or FT=Field Testing phases.*

*** Considered as qualitative factors in the needs assessment phase.*

**** Due to the non-availability of practical analysis procedures for these factors, they were only identified but not used in the model.*

CHAPTER 4. AUTOMATED ROAD MAINTENANCE EVALUATION MODEL

This chapter describes the Automated Road Maintenance Evaluation (ARME) model developed through this research effort. The ARME model deals with three basic phases of automation: Needs Assessment phase, Technology Evaluation phase, and Field Testing phase. In each phase, the model provides the tools to evaluate the benefits of automation from economic, qualitative and/or environmental & energy perspectives.

The chapter first gives an overview of the evaluation methodology (section 4.1), followed by detailed descriptions of analysis tools of each of the three phases: Needs Assessment (section 4.2), Technology Evaluation (section 4.3), and Field Testing (section 4.4).

4.1 EVALUATION METHODOLOGY

After the identification of the major factors which can benefit from automation (section 3.3), a model was developed to objectively evaluate these economic, qualitative and environmental/energy factors. This Automated Road Maintenance Evaluation (ARME) model deals with three basic phases of automation:

- Needs Assessment phase,
- Technology Evaluation phase, and
- Field Testing phase.

In the needs assessment phase, the model identifies the maintenance activities feasible for automation, and then these maintenance activities are relatively ranked in terms of their feasibility for automation. In the technology evaluation phase, the model determines the potential feasibility of Automated Road Maintenance (ARM) systems, which are available in the market; and then relatively ranks the evaluated ARM systems. In the field testing phase, the model evaluates the field results of an ARM system selected from the technology evaluation phase. The relationship between these three phases is shown in the decision flowchart of the model (figure 4.1). This flowchart is from a public agency's perspective, and it shows the different transition stages between the three phases of the model.

The analysis procedures used for evaluating the economic, qualitative and environmental/energy factors are not the same in the three phases as shown in table 4.1. These

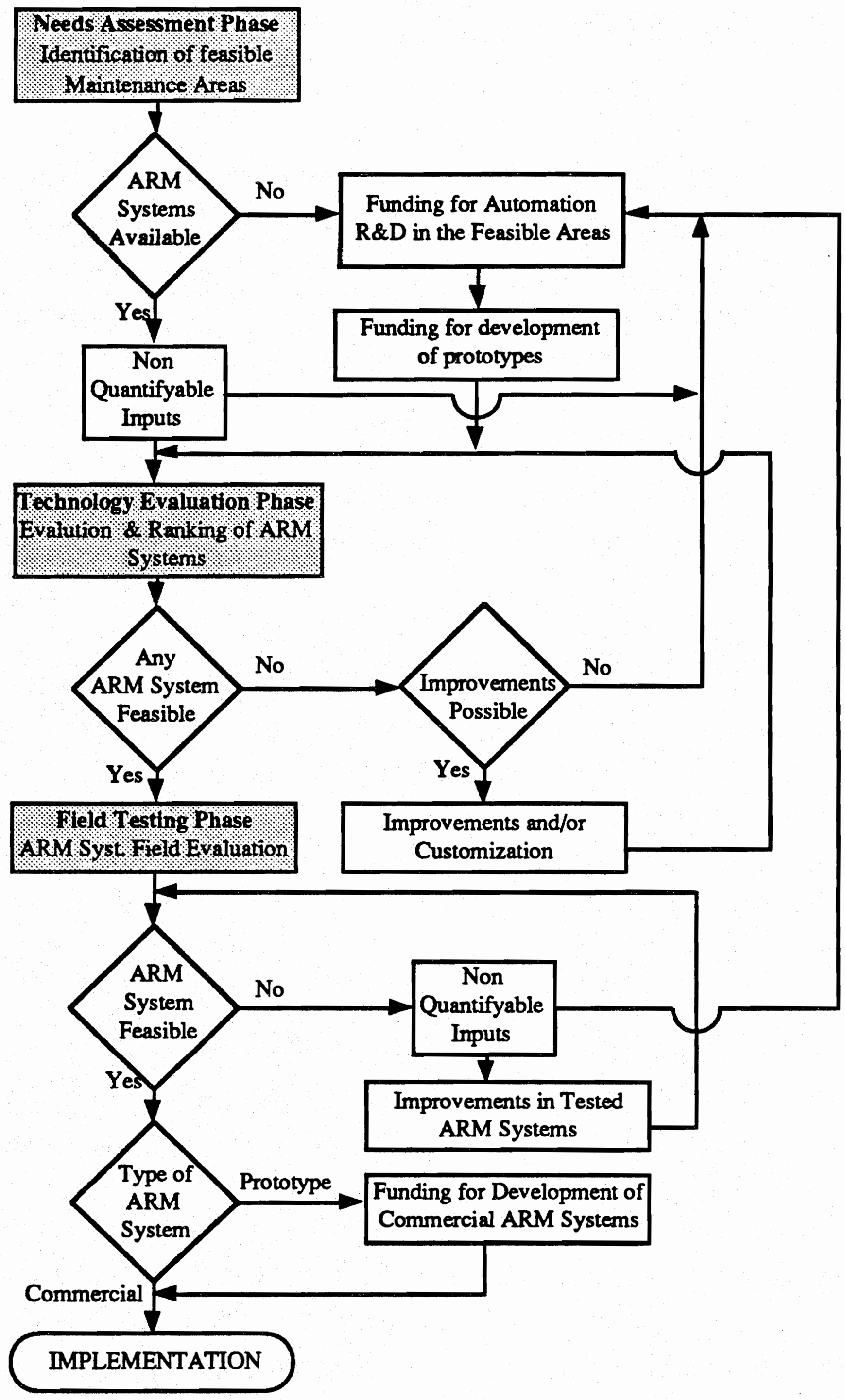


Figure 4.1 Different Phases of Automated Road Maintenance Evaluation (ARME) Model

TABLE 4.1 ANALYSIS PROCEDURES FOR THE DIFFERENT PHASES OF THE ARME MODEL.

	Economic Analysis	Qualitative Analysis	Environmental/ Energy Analysis
Needs Assessment Phase	Cost Impact analysis of maint. activities	Weighted Rating method	Weighted Rating method
Technology Evaluation Phase	Life Cycle Cost analysis of ARM systems	Weighted Rating method	QUEWZ-E
Field Evaluation Phase	Life Cycle Cost analysis of ARM systems	N/A	N/A

analysis procedures vary as detailed economic and environmental/energy analysis for every maintenance activity in the needs assessment phase is not practically possible. However, when a prototype or commercial ARM system is evaluated in the technology evaluation phase, detailed economic and environmental/energy analysis can be practically performed due to the availability of the performance data of the ARM system.

For the qualitative analyses of the model, surveys were also performed to develop the relative weights for the different "qualitative factors" or "concerns." The people surveyed for this purpose included TxDOT maintenance personnel and the University of Texas faculty members having vast experience in the maintenance area.

A computer software called QUEWZ-E was also used to determine the additional user-costs, emissions and energy (fuel/oil) consumption values, due to road closures, for typical maintenance-operation scenarios. A factorial, which encompasses most of these scenarios, was tested on QUEWZ-E to develop easy-to-use tables for determining the additional user-costs, emissions and energy consumption values.

The description of each phase of the model, along with the results of the relative weight surveys, is discussed in detail in the following sections.

4.2 ARME MODEL - NEEDS ASSESSMENT PHASE

In the needs assessment phase, the ARME model identifies the maintenance activities feasible for automation, and then these maintenance activities are relatively ranked in terms of their feasibility. The analysis procedures used in this phase are the following:

4.2.1 Economic Analysis

For the needs assessment phase, a detailed economic analysis for evaluating the benefits of automation for all of the maintenance activities performed by the public agencies (e.g. TxDOT) is not practical because of two major reasons:

- the economic savings for a maintenance activity can vary significantly based on the design and capabilities of an ARM system, and
- the number of maintenance activities performed by the public agencies is very large. For example, TxDOT routine maintenance is composed of 139 maintenance activities.

The cost-impact or expenditures/year for these activities also vary significantly. For example, approximately 75% of TxDOT routine maintenance budget is spent on twenty-five major activities out of the 139 activities they perform. Based on these characteristics of the maintenance activities, the cost-impact data alone can identify the maintenance activities which can be economically feasible for automation as most of the money is spent on only a few activities. These economically feasible activities, because of their huge cost-impact, can then be analyzed through qualitative analysis (which includes the environmental/energy factors) to determine their feasibility for automation from all perspectives.

Some of the maintenance operations, requiring road closures, cause traffic congestion and hence result in additional costs to the road users in terms of higher fuel consumption, oil consumption, vehicle operating costs, etc. Besides these higher user-costs, additional emissions from cars and trucks also occur due to these road closures. These additional values of user-costs, emissions and energy consumption can be estimated using some of the computer software packages available in the market.

However, in the needs assessment phase, the maintenance operations which result in high values for user-costs, emissions and energy consumption are only considered in the qualitative analysis; and the user-costs are not explicitly analyzed in the economic analysis . In the technology evaluation and field evaluation phases of the model, user-costs are estimated in detail in the economic analysis.

Based on this analysis methodology, a needs assessment study was performed for the TxDOT which is explained in chapter 5.

4.2.2 Qualitative Analysis

In the qualitative analysis, the subjective preferences and opinions on the non-economic (or difficult to quantify) benefits of automation are converted into numeric values to evaluate these factors more systematically. As discussed in chapter 3, there are several qualitative concerns which can benefit from automation. These concerns are grouped into seven major concern areas for the needs assessment phase: productivity, quality, safety, socio-political, technology feasibility, working environment, and user-costs/ emissions. All these concerns are evaluated systematically in the qualitative analysis.

Each of the major maintenance activities (25 for TxDOT), identified from the economic analysis, is given an Overall Concern Rating (OCR) using a weighted rating method in this analysis. This OCR for a maintenance activity is calculated by evaluating the activity for each of the concerns, converting the evaluation responses into rating numbers, multiplying the rating number for each concern by the relative weight of that concern, and then summing these weighted-ratings to arrive at the OCR which can vary between 0 and 10. The higher the OCR, the more the maintenance activity is feasible for automation. The rating structure is developed in such a way that the OCR of 5 is the cut-off point between feasible and non-feasible maintenance activities.

A sample questionnaire for evaluating a maintenance activity (sealing cracks/joints) is shown is figure 4.2. This questionnaire can easily be answered by a person with experience in crack sealing. As can be seen from the sample questionnaire, each of the concems is first checked for either a positive, intermediate or negative response. A positive or "Yes" response is equivalent to a "10 rating", an "intermediate" response is equivalent to a "5 rating", and a negative or "No" response is equivalent to a "0 rating". The intermediate response represents the conditions between yes or no (e.g. sometimes, partly true, etc.). After assigning a rating number to the response, these ratings are multiplied by the relative weight of that concern and then added together to an OCR number which can vary from 0 to 10.

The relative weights for each of the concerns were developed through a relative weight survey performed in September 1993. The people surveyed included five engineers from TxDOT

Name: **Institution:** **Position:**

Automation Needs Assessment Questionnaire for SEALING CRACKS/JOINTS (Code 220)				
How much do you know about this maintenance area (please circle one)? Little Some Considerable				
For each of the following Concerns, please mark your Response in either Yes, No or Intermediate columns (Don't mark in the shaded areas). For Concern No. 5 (Technology Feasibility), the responses have already been marked.				
CONCERNS	**RESPONSE***			**RATING**
	Yes	**Intermediate****	**No**	
1. Productivity & Other				
01. Highly labor intensive area				
02. Low income level of work crew/operators				
03. Significant materials wastage				
04. More productivity required (large work demand)				
05. Work involves repetitive/cyclic tasks				
06. Work involves time consuming tasks				
07. Work involves environment-dependent tasks				
2. Quality				
01. Consistency in work required				
02. Accuracy in work required				
03. Other quality concerns (aesthetics, visual, etc.) also important				
3. Safety				
01. Work physically dangerous to the work crew/operators				
02. Work hazardous to the health of the work crew/operators				
03. Work physically dangerous to the passing by road users				
04. Work hazardous to the health of the passing by road users				
4. Socio-Political				
01. Workers are not expected to resist to automation				
02. Workers' motivation to change expected (same workers can be used with additional training/increased salary, etc.)				
5. Technology Feasibility				
01. Existing Automation R&D in this maintenance area	X			
02. Automated systems commercially available***		X		
6. Working Environment				
01. Noisy conditions in the work area				
02. Vibrations in the work area				
03. Dirty conditions in the work area				
04. Work involve heavy/high lifts				
05. Meticulous work (great detail/carefulness required)				
06. Exhaustive work				
7. User-Costs & Emissions				
Higher user-costs and emissions due to the following: 01. Road closures required				
02. Long closure times required for setup & removal				
03. Night time operations are not currently performed				
OVERALL CONCERN RATING (OCR)				

* For non-applicable concerns or unknown answer, no entry should be made.
** Intermediate represents conditions between yes or no. For example sometimes, partly true, etc.
*** Mark Intermediate column if Prototype systems are available.

Figure 4.2 A sample questionnaire for the Needs Assessment survey

division of maintenance & operations, and TxDOT district 14; and five faculty/staff members from the University of Texas at Austin. All the people surveyed had vast experience in the highway maintenance area.

The people surveyed were asked to first rate all the concerns, for each of the seven concern areas including productivity, on a relative importance scale by marking a line anywhere on the scale (figure 4.3A). Then at the end, they were asked to rate the concern areas (figure 4.3B). The rating scale was then converted into a numeric scale as shown in figure 4.3C. This type of scale was used for the relative weight development survey because a similar rating scale has already been used very successfully in the pavement management area [Hudson 1993]. After converting all the responses into numeric ratings (with a range of 0 to 5), the rating for each individual concern was divided by the sum of the all the concern ratings, of that area, to calculate the relative weight of that concern. Similarly, the rating of each concern area was divided by the sum of ratings for all the concerns areas to calculate the relative weights for these areas.

Due to the huge data processing requirements, several user-friendly computer spreadsheets were developed to analyze the data. These spreadsheets not only analyzed the whole data set and reported the summary, but several checks/protections were also developed to monitor and control the data input errors.

For the results of this relative weight survey, each of the concern areas (e.g. productivity, quality, etc.) are reported as relative percentages of the OCR, whereas each of the concerns (e.g. consistency and accuracy for the concern area Quality) are reported as relative percentages of that concern areaas shown in table 4.2. These results are shown graphically in figure 4.4. The effects of the small sample size (10), due to the resource and time restrictions, can be seen from the large standard deviations present. However, the mean values from both the TxDOT engineers and the University of Texas faculty/ staff members came out to be quite similar.

4.2.3 Environmental/Energy Analysis

Some of the maintenance activities, requiring road closures, cause traffic congestion; and hence result in additional emissions (carbon monoxide, hydrocarbons, and oxides of nitrogen) and fuel/oil consumption from cars and trucks. These additional values for emissions and energy consumption can be estimated using some of the computer software packages available in the market.

CONCERNS	RATING SCALE				
1. PRODUCTIVITY Concerns for Present Maintenance Practices					
	Least Important	Slightly Important	Important	Very Important	Extremely Important
1.01 Highly labor intensive area					
1.02 Low income level of work crew/operators					
1.03 Significant materials wastage					
1.04 More productivity required (large work demand)					
1.05 Work involves repetitive/cyclic tasks					
1.06 Work involves time consuming tasks					
1.07 Work involves environment-dependent tasks					

Figure 4.3A Sample form for the development of relative weights for Qualitative Concerns, ARME-Needs Assessment phase

OVERALL RATING

CONCERN AREAS	RATING SCALE				
1. PRODUCTIVITY	Least Important	Slightly Important	Important	Very Important	Extremely Important
2. WORKING ENVIRONMENT	Least Important	Slightly Important	Important	Very Important	Extremely Important
3. SAFETY	Least Important	Slightly Important	Important	Very Important	Extremely Important
4. QUALITY	Least Important	Slightly Important	Important	Very Important	Extremely Important
5. USER-COSTS & EMISSIONS	Least Important	Slightly Important	Important	Very Important	Extremely Important
6. SOCIO-POLITICAL	Least Important	Slightly Important	Important	Very Important	Extremely Important
7. TECHNOLOGY FEASIBILITY	Least Important	Slightly Important	Important	Very Important	Extremely Important

Figure 4.3B Sample form for the development of relative weights for Qualitative Concerns, ARME-Needs Assessment phase

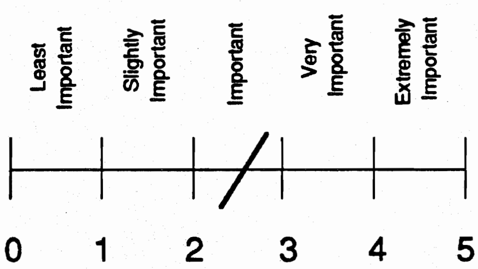


Figure 4.3C Conversion of subjective rating scale into the numeric scale for the Qualitative Analysis of ARME model

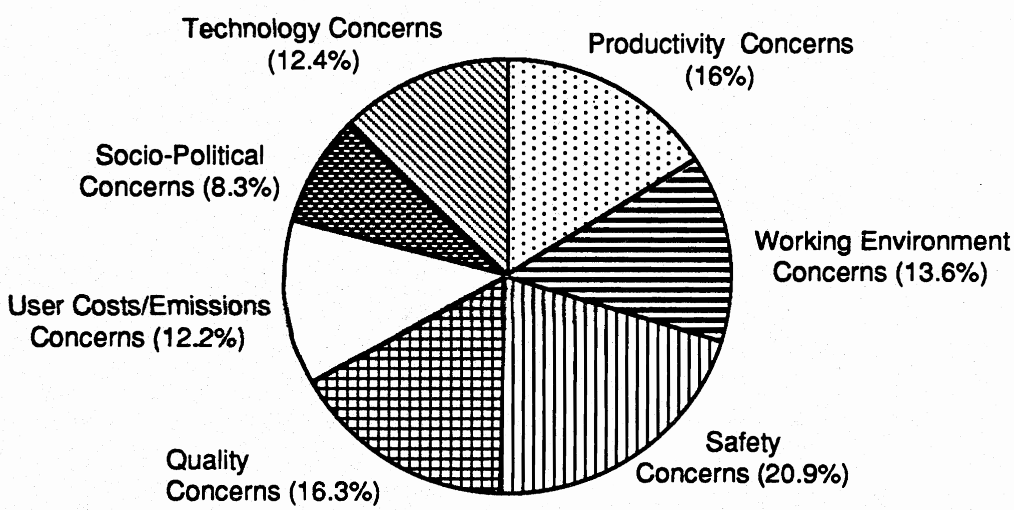


Figure 4.4 Results of relative weight survey, ARME-Needs Assessment phase

Table 4.2 Results of relative weight survey, Needs Assessment phase

CONCERNS	RELATIVE IMPORTANCE WEIGHTS					
	TxDOT*		Univ. of Texas*		Average*	
	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean
1. Productivity Concerns (PRD)	1.4	14.8 % OCR	4.9	17.6 % OCR	3.7	16.2 % OCR
01 Highly labor intensive activity	3.6	18.6 %PRD	5.6	20.0 %PRD	4.5	19.3 %PRD
02 Low income level of work crew/operators	2.8	12.7 %PRD	2.1	6.1 %PRD	4.2	9.4 %PRD
03 Significant materials wastage	3.2	19.0 %PRD	2.6	14.1 %PRD	3.8	16.5 %PRD
04 More productivity reqd. (large work demand)	7.0	14.8 %PRD	2.1	16.6 %PRD	4.9	15.7 %PRD
05 Work involve repetitive/cyclic tasks	3.9	10.0 %PRD	5.2	16.5 %PRD	5.5	13.2 %PRD
06 Work involve time consuming tasks	6.1	13.9 %PRD	0.9	15.6 %PRD	4.2	14.8 %PRD
07 Work involve environment-dependent tasks	4.9	11.1 %PRD	5.3	11.1 %PRD	4.8	11.1 %PRD
2. Working Environment Concerns (WOR)	2.9	13.8 % OCR	4.5	13.5 % OCR	3.6	13.6 % OCR
01 Noisy conditions in the work area	5.8	15.5 %WOR	3.0	16.5 %WOR	4.4	16.0 %WOR
02 Vibrations in the work area	5.4	11.2 %WOR	2.6	12.9 %WOR	4.1	12.1 %WOR
03 Dirty conditions in the work area	5.7	14.8 %WOR	2.0	14.6 %WOR	4.0	14.7 %WOR
04 Work involves heavy/high lifts	8.2	21.1 %WOR	4.6	21.6 %WOR	6.3	21.4 %WOR
05 Meticulous work	7.0	19.3 %WOR	3.0	16.7 %WOR	5.3	18.0 %WOR
06 Exhaustive work	1.9	18.1 %WOR	3.3	17.7 %WOR	2.6	17.9 %WOR
3. Safety Concerns (SAF)	3.2	23.8 % OCR	1.8	18.0 % OCR	3.9	20.9 % OCR
01 Work physically dangerous to the work crew/ operators	3.4	26.2 % SAF	3.6	28.8 % SAF	3.6	27.5 % SAF
02 Work hazardous to the health of the work crew/ operators	3.4	26.2 % SAF	5.4	26.7 % SAF	4.2	26.4 % SAF
03 Work physically dangerous to the passing by road users	0.6	25.3 % SAF	5.1	25.9 % SAF	3.4	25.6 % SAF
04 Work hazardous to the health of the passing by road users	6.6	22.4 % SAF	5.7	18.7 % SAF	6.1	20.6 % SAF
4. Quality Concerns (QLT)	2.6	18.6 % OCR	3.2	14.1 % OCR	3.6	16.3 % OCR
01 Consistency in work	2.3	35.0 %QLT	5.0	37.6 %QLT	3.9	36.3 %QLT
02 Accuracy in work	3.9	36.9 %QLT	5.0	37.4 %QLT	4.2	37.1 %QLT
03 Other qual. concerns (aesthetics, visual, etc.)	4.9	28.1 %QLT	10.0	25.0 %QLT	7.6	26.6 %QLT
5. User-Costs & Emissions Concerns (U/E)	6.2	11.0 % OCR	3.6	13.3 % OCR	4.9	12.2 % OCR
01 Road closures required	9.2	21.9 % U/E	7.2	33.7 % U/E	10.0	27.8 % U/E
02 Long closure times reqd. for setup/removal	12.5	41.0 % U/E	2.7	34.8 % U/E	9.1	37.9 % U/E
03 Night time operations	10.2	37.1 % U/E	5.8	31.5 % U/E	8.4	34.3 % U/E
6. Socio-Political Concerns (S/P)	3.7	7.6 % OCR	2.5	9.0 % OCR	3.0	8.3 % OCR
01 Workers' resistance for automation	21.8	44.3 % S/P	13.6	42.6 % S/P	17.1	43.5 % S/P
02 Workers' motivation to change	21.8	55.7 % S/P	13.6	57.4 % S/P	17.1	56.5 % S/P
7. Technology Feasibility Concerns (TEC)	1.7	10.3 % OCR	1.3	14.5 % OCR	2.8	12.4 % OCR
01 Existing level of R&D in Automation	7.5	46.7 %TEC	4.9	54.6 %TEC	7.3	50.6 %TEC
02 Automated systems commercially available	7.5	53.3 %TEC	4.9	45.4 %TEC	7.3	49.4 %TEC

*Total Number of Responses=10, Responses from TxDOT=5, Responses from University of Texas=5

However, in the needs assessment phase, the maintenance activities which require road closures are only considered in the qualitative analysis under the user-costs/emissions concern area (section 4.2.2); and no explicit environmental/energy analysis is recommended for this phase. However, in the technology evaluation and field testing phases of the model, these additional emissions and energy consumption values were estimated in detail using the QUEWZ-E model as discussed in section 4.3.4.

4.2.4 Overall Ranking of maintenance activities

Using the results of the economic and qualitative analyses, the maintenance activities can be ranked independently for these two perspectives. However, a cost-concern matrix can also be used to show the effects of both the economic and qualitative analysis (figure 4.5). The conceptual idea of this matrix was derived from the work done for automation needs analysis in the construction area [Tucker 1992A].

On this cost-concern matrix, the maintenance activities can fall into either of the following two feasibility regions:

- Feasible region, and
- Non-feasible region.

On the Y-axis of the figure, OCR value of 5 is the cut-off point between the feasible and non-feasible regions. The X-axis of the cost-concern matrix is based on the TxDOT yearly maintenance expenditures, and this scale can vary from one public agency to another.

4.3 ARME MODEL - TECHNOLOGY EVALUATION PHASE

In the technology evaluation phase, the model determines the potential feasibility of ARM systems, which are available in the market; and then relatively ranks the evaluated ARM systems. The analysis procedures used in this phase are the following:

4.3.1 Economic Analysis

In the technology evaluation phase, detailed economic analysis for an ARM system can be performed using life cycle costs/savings method. In this method, all the costs and savings of the ARM system, occurring throughout the working life of the system, are converted into *dollars at a certain point in time* to estimate the savings (or extra expenditures) to a public agency due to

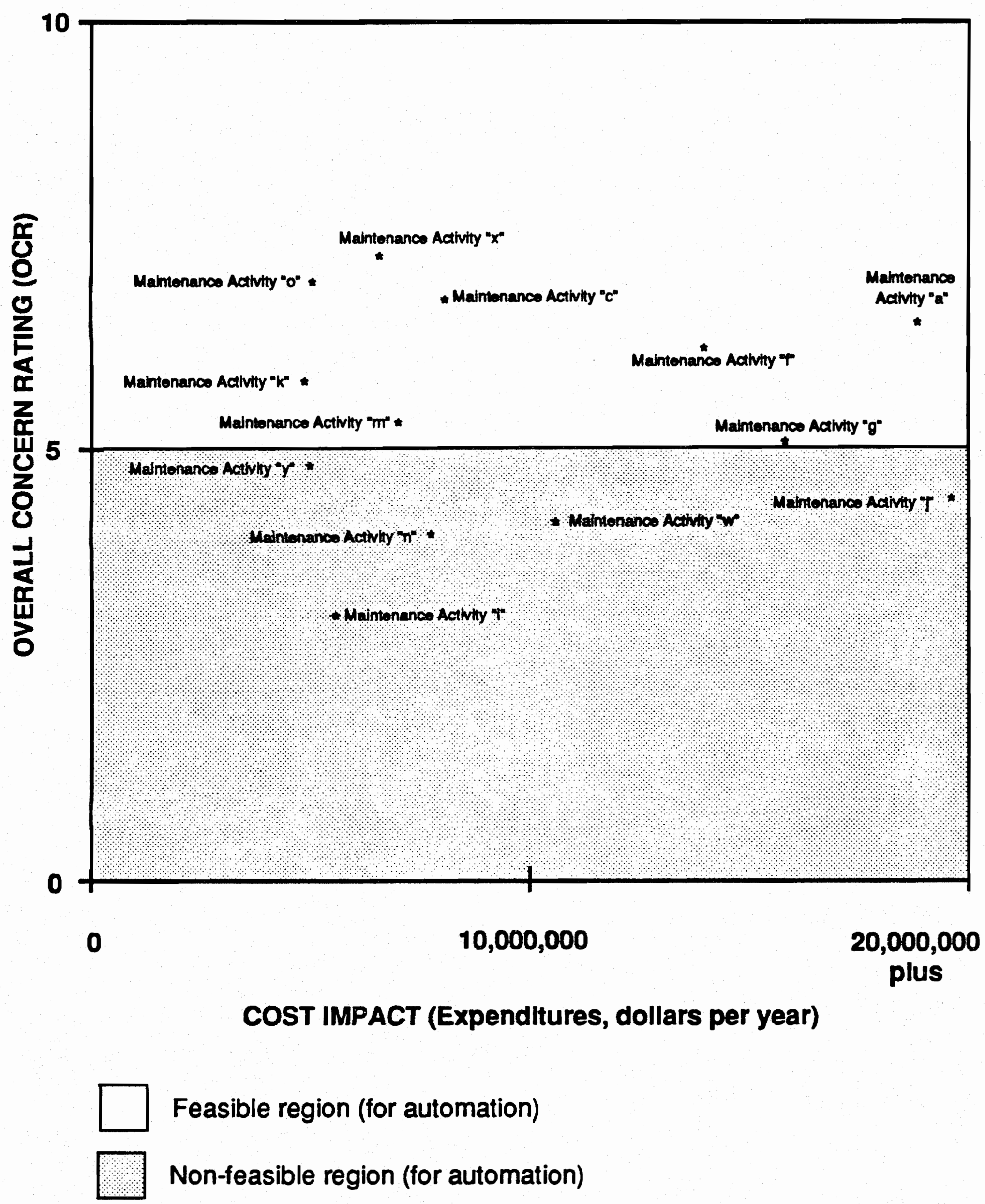


Figure 4.5 Overall Ranking of Maintenance Activities

the ARM system. All the economic factors to be considered in this analysis are identified in section 3.3.

The costs of any ARM system can be divided into four major categories: initial, maintenance, operational, and overhead. The savings of an ARM system can be divided into two major groups: direct maintenance cost savings and user-cost savings. The direct maintenance cost savings can result from labor reduction, improved productivity, and reduced material wastage. The user-cost savings mostly result from reduction in lane closure times due to expedited operation of ARM system. Besides the costs and savings of ARM system, other economic factors to be considered in the life cycle analysis are the cost impact (expenditures per year), the unit costs for current practices and the division of current maintenance expenditures into labor, material, equipment (rentals), overheads, etc.

For the life cycle economic analysis, a user-friendly computer spreadsheet was developed. The economic analysis performed by the spreadsheet includes the estimation of both the direct (pubic agency) and indirect (users) cost savings. After the input of the required data which includes the costs of ARM system, number of typical crew members to be reduced by ARM system, and the public agency's (TxDOT) expenditure data; the spreadsheet automatically converts all these costs and savings into net present worth (NPW) values to compute the life cycle savings (or extra expenditures) of the ARM system, from the public agency's perspective. The spreadsheet can either be used to evaluate three different scenarios for a particular ARM system by varying the interest rates, working efficiencies, etc. (figure 4.6A); or it can be used to evaluate three different ARM systems for a particular interest rate and analysis period (figure 4.6B). Several checks and protections are built-in the spreadsheets to avoid data input errors. Due to the open architecture of the spreadsheet, an ARM system developer can also use it to test infinite scenarios to determine the optimum development costs of his/her prototype system.

After the computation of the direct maintenance cost savings for the life cycle of the ARM system, the spreadsheet then performs case studies to determine the user-cost savings. The user-costs are estimated at the project level as they can vary significantly from the maintenance operations performed on a busy urban expressway to a low volume rural farm-to-market road. For example, an economically unfeasible ARM system (from public agencies perspective) can become feasible if used on a urban expressway because of the high user-cost savings.

ECONOMIC ANALYSIS OF "XYZ" ARM SYSTEM (DIFFERENT INTEREST SCENARIOS)			
GENERAL DATA	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**
WORK UNITS OF THE ARM SYSTEM	Square Yds.	Square Yds.	Square Yds.
ESTIMATED WORK CAPACITY OF THE ARM SYSTEM (UNITS/YEAR)	150,000	150,000	150,000
ESTIMATED YEARLY EFFICIENCY OF THE ARM SYSTEM	80%	80%	80%
ANALYSIS PERIOD OR LIFE OF THE ARM SYSTEM (YEARS)	10	10	10
INTEREST RATE	2.00%	6.00%	10.00%
INITIAL COST OF ARM SYSTEM (PRESENT $)	$100,000	$100,000	$100,000
OPERATING COSTS OF ARM SYSTEM (ANNUAL $)	$5,000	$5,000	$5,000
MAINTENANCE COSTS OF ARM SYSTEM (ANNUAL $)	$10,000	$10,000	$10,000
OVERHEADS OF ARM SYSTEM (ANNUAL $)	$5,000	$5,000	$5,000
SALVAGE VALUE OF ARM SYSTEM (FUTURE $)	$25,000	$25,000	$25,000
LIFE CYCLE COST/UNIT-WORK OF 1 ARM SYSTEM ($/UNIT)	**$0.22**	**$0.19**	**$0.18**
CURRENT TXDOT COSTS/UNIT WORK ($ /UNIT)	$2.25	$2.25	$2.25
" " YEARLY EXPENDITURES FOR THIS ACTIVITY ($/YEAR)	$8,000,000	$8,000,000	$8,000,000
" " EXPENDITURES ON LABOR FOR THIS ACTIVITY (%)	40.00%	40.00%	40.00%
" " TYPICAL CREW SIZE FOR THIS MAINTENANCE ACTIVITY	10	10	10
NUMBER OF CREW MEMBERS TO BE REDUCED BY THE ARM SYSTEM	3	3	3
YEARLY UNIT WORK DONE BY TXDOT (UNITS)	**3,555,556**	**3,555,556**	**3,555,556**
% WORK PERFORMED BY 1 ARM SYSTEM	**4.22%**	**4.22%**	**4.22%**
LIFE CYCLE LABOR SAVING/UNIT-WORK OF1 ARM SYSTEM	**$0.30**	**$0.25**	**$0.21**
TXDOT LIFE-CYCLE SAVINGS (1 ARM SYSTEM)	**$104,652**	**$64,842**	**$35,602**
TXDOT LIFE-CYCLE SAVINGS (ALL WORK BY ARM SYSTEMS)	**$2,406,989**	**$1,491,358**	**$818,851**

Note: Output in bold format

Figure 4.6A Economic Analysis for 3 different interest scenarios, Technology Evaluation phase

ECONOMIC ANALYSIS OF "XYZ" ARM SYSTEM (DIFFERENT INTEREST SCENARIOS)			
CASE STUDY	SCENARIO 1	SCENARIO 2	SCENARIO 3
PROJECT	INTERSTATE I-35, AUSTIN-SAN ANTONIO (50 mile segment)		
ESTIMATED TOTAL UNIT WORK TO BE PERFORMED	10,400	10,400	10,400
NO. OF LANES EACH DIRECTION	4	4	4
ADT EACH DIRECTION	30,000	30,000	30,000
ESTIMATED LENGTH OF ROAD CLOSURE, MILES (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF LANES CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF DAYS CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
ESTIMATED REDUCTION IN CLOSURE TIME (FROM CONV. TO ARM)*	10%	10%	10%
USER COSTS PER OPERATION, CONV. METHODS *	38,259	38,259	38,259
USER COSTS PER OPERATION, ARM SYSTEM *	36,250	36,250	36,250
NO. OF THESE TYPICAL OPERATIONS PER YEAR	13	13	13
TOTAL USER COSTS, CONVENTIONAL METHODS *	**$4,467,641**	**$3,660,664**	**$3,056,105**
TOTAL USER COSTS, ARM SYSTEM *	**$4,233,043**	**$3,468,441**	**$2,895,627**
UNIT COST (USER-COSTS) FROM CONV. SYSTEM ($/UNIT)	**$429.58**	**$351.99**	**$293.86**
UNIT COST (USER-COSTS) FROM ARM SYSTEM ($/UNIT)	**$407.02**	**$333.50**	**$278.43**
TOTAL UNIT COST BY CONV. METHODS (TXDOT+USER COSTS)	**$431.83**	**$354.24**	**$296.11**
TOTAL UNIT COST BY ARM SYSTEM (TXDOT+USER COSTS)	**$409.19**	**$335.70**	**$280.65**
TOTAL TXDOT SAVINGS ON CASE STUDY 1 (PRESENT $)	**$907**	**$562**	**$309**
TOTAL USER-COST SAVINGS ON CASE STUDY 1 (PRESENT $)	**$234,598**	**$192,223**	**$160,478**
TOTAL SAVINGS ON CASE STUDY 1 (1 ARM SYSTEM)	**$235,505**	**$192,785**	**$160,786**

Note: Output in bold format

Figure 4.6A Economic Analysis for 3 different interest scenarios, Technology Evaluation phase (Cont.)

ECONOMIC ANALYSIS OF X1, X2 & X3 ARM SYSTEMS			
GENERAL DATA	**X1 SYSTEM**	**X2 SYSTEM**	**X3 SYSTEM**
WORK UNITS OF THE ARM SYSTEM	Square Yds.	Square Yds.	Square Yds.
ESTIMATED WORK CAPACITY OF THE ARM SYSTEM (UNITS/YEAR)	150,000	200,000	225,000
ESTIMATED YEARLY EFFICIENCY OF THE ARM SYSTEM	80%	80%	80%
ANALYSIS PERIOD OR LIFE OF THE ARM SYSTEM (YEARS)	8	8	8
INTEREST RATE	2.00%	2.00%	2.00%
INITIAL COST OF ARM SYSTEM (PRESENT $)	$100,000	$150,000	$185,000
OPERATING COSTS OF ARM SYSTEM (ANNUAL $)	$5,000	$6,000	$20,000
MAINTENANCE COSTS OF ARM SYSTEM (ANNUAL $)	$10,000	$10,000	$10,000
OVERHEADS OF ARM SYSTEM (ANNUAL $)	$5,000	$7,500	$10,000
SALVAGE VALUE OF ARM SYSTEM (FUTURE $)	$20,000	$25,000	$25,000
LIFE CYCLE COST/UNIT-WORK OF 1 ARM SYSTEM ($/UNIT)	**$0.24**	**$0.24**	**$0.32**
CURRENT TXDOT COSTS/UNIT WORK ($ /UNIT)	$2.25	$2.25	$2.25
" " YEARLY EXPENDITURES FOR THIS ACTIVITY ($/YEAR)	$8,000,000	$8,000,000	$8,000,000
" " EXPENDITURES ON LABOR FOR THIS ACTIVITY (%)	40.00%	40.00%	40.00%
" " TYPICAL CREW SIZE FOR THIS MAINTENANCE ACTIVITY	10	10	10
NUMBER OF CREW MEMBERS TO BE REDUCED BY THE ARM SYSTEM	3	3	4
YEARLY UNIT WORK DONE BY TXDOT (UNITS)	**3,555,556**	**3,555,556**	**3,555,556**
% WORK PERFORMED BY 1 ARM SYSTEM	**4.22%**	**5.63%**	**6.33%**
LIFE CYCLE LABOR SAVING/UNIT-WORK OF1 ARM SYSTEM	**$0.31**	**$0.31**	**$0.41**
TXDOT LIFE-CYCLE SAVINGS (1 ARM SYSTEM)	**$67,242**	**$94,764**	**$136,682**
TXDOT LIFE-CYCLE SAVINGS (ALL WORK BY ARM SYSTEMS)	**$1,546,570**	**$1,610,996**	**$2,050,230**

Note: Output in bold format

Figure 4.6B Economic Analysis of 3 competing ARM systems, Technology Evaluation phase

ECONOMIC ANALYSIS OF X1, X2 & X3 ARM SYSTEMS			
CASE STUDY	X1 SYSTEM	X2 SYSTEM	X3 SYSTEM
PROJECT	INTERSTATE I-35, AUSTIN-SAN ANTONIO (50 mile segment)		
ESTIMATED TOTAL UNIT WORK TO BE PERFORMED	10,400	10,400	10,400
NO. OF LANES EACH DIRECTION	4	4	4
ADT EACH DIRECTION	30,000	30,000	30,000
ESTIMATED LENGTH OF ROAD CLOSURE, MILES (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF LANES CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF DAYS CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
ESTIMATED REDUCTION IN CLOSURE TIME (FROM CONV. TO ARM)*	30%	60%	10%
USER COSTS PER OPERATION, CONV. METHODS *	38,259	38,259	38,259
USER COSTS PER OPERATION, ARM SYSTEM *	31,260	21,250	35,160
NO. OF THESE TYPICAL OPERATIONS PER YEAR	13	13	13
TOTAL USER COSTS, CONVENTIONAL METHODS *	**$3,643,453**	**$3,643,453**	**$3,643,453**
TOTAL USER COSTS, ARM SYSTEM *	**$2,976,929**	**$2,023,664**	**$3,348,331**
UNIT COST (USER-COSTS) FROM CONV. SYSTEM ($/UNIT)	**$350.33**	**$350.33**	**$350.33**
UNIT COST (USER-COSTS) FROM ARM SYSTEM ($/UNIT)	**$286.24**	**$194.58**	**$321.95**
TOTAL UNIT COST BY CONV. METHODS (TXDOT+USER COSTS)	**$352.58**	**$352.58**	**$352.58**
TOTAL UNIT COST BY ARM SYSTEM (TXDOT+USER COSTS)	**$288.42**	**$196.76**	**$324.11**
TOTAL TXDOT SAVINGS ON CASE STUDY 1 (PRESENT $)	**$728**	**$770**	**$987**
TOTAL USER-COST SAVINGS ON CASE STUDY 1 (PRESENT $)	**$666,524**	**$1,619,788**	**$295,122**
TOTAL SAVINGS ON CASE STUDY 1 (1 ARM SYSTEM)	**$667,252**	**$1,620,558**	**$296,109**

Note: Output in bold format

Figure 4.6B Economic Analysis of 3 competing ARM systems, Technology Evaluation phase (Cont.)

The user-costs, used in the spreadsheet, for both the conventional and ARM operations are determined from the user-cost charts. The charts are developed by testing a factorial, encompassing most typical maintenance operation scenarios, on the QUEWZ-E model. Complete details on the scope of these user-cost charts are given in the next section.

4.3.2 Estimation of User-Costs

Lane closures due to maintenance work on highways reduce the capacity of the highway, and hence result in additional fuel consumption, delays, harmful emissions, and higher operating/other costs of the vehicles. The increases in fuel consumption, operating costs, and delays are costs directly borne by the highway user; whereas emissions of Carbon monoxide (CO), Hydrocarbon (HC) & Oxides of Nitrogen (NOx) are not only harmful to the environment but are also dangerous for the highway users & residents of abutting areas.

Several models are available for estimating the additional user costs for maintenance operations on the highways and freeways. One of these models is Queue and User Cost Evaluation of Work Zones (QUEWZ) which calculates the additional user costs due to closures [Memmot 1982].

QUEWZ was selected to perform the user-costs analysis due to the higher capabilities of this model. A relative comparison of QUEWZ with other work-zone computer based evaluation models is shown in Table 4.3 [Solminihac 1992]. Also, QUEWZ has recently been updated to

TABLE 4.3 COMPARISON OF WORK-ZONE COMPUTER BASED EVALUATION MODELS

CAPABILITIES	DELAY	FREWAY	QUEWZ	FREQ10PC
Evaluated alternate lane closure configurations	Yes	Yes	Yes	Yes
Estimate amount of traffic diverting from freeway	No	No	Limited	Limited
Identify acceptable lane closure schedules	Not Directly	Not Directly	Yes	Not Directly
Estimate queue lengths and delays	Yes	Yes	Yes	Yes
Estimate additional road user costs	No	No	Yes	No
Evaluate multiple freeway links and ramp effects.	No	No	Not Directly	Yes

include the user-costs resulting from additional fuel and oil consumption and to report the emission of air-pollutants including carbon-monoxide, hydrocarbons, and oxides of nitrogen. This newer version, which is a PC based software, is called QUEWZ-E and was developed at the University of Texas at Austin [Seshadri 1993].

Several variables which have impacts on user-costs, during highway maintenance operations, were tested using this QUEWZ-E model. These variables are listed as following:

- Number of total lanes each direction and number of lanes closed,
- Length of closure,
- Time of closure,
- Traffic volumes (ADT), and
- Traffic mix (%s of autos & trucks in the traffic stream).

All of these variables can be tested in QUEWZ for a wide range of values. Hence, to test these variables for typical situations during highway maintenance operations, a factorial was developed (figure 4.7). The range/values of these input variables which were tested are given below:

<u>Number of total lanes each direction and number of lanes closed:</u> Two cases were considered for the number of lanes in each direction:

- typical four lane rural highways (two lanes each direction), and
- typical eight lane urban freeways (four lanes each direction).

For both the cases the closures of one and two lanes were tested. For the two lane closure case on the four lane highway, a crossover strategy was used (figure 4.8).

<u>Length of closure:</u> Two closure lengths, which are typical of highway maintenance operations, were tested. These closure lengths were 0.5 mile and 1 mile.

<u>Time of closure:</u> A typical day-time closure was tested. The times used were the following:

- Hours of restricted capacity
  - Beginning at 8:00 A.M.
  - Ending at 4 P.M.
- Hours of Work-zone activity
  - Beginning at 9:00 A.M.

			1 Lane closed		2 Lanes closed	
	ADT	Trucks	0.5 mi. closed	1 mi. closed	0.5 mi. closed	1 mi. closed
2 LANE HIGHWAYS	10,000	10%	Run No. 1	Run No. 34	Run No. 67	Run No. 100
		20%	Run No. 2	Run No. 35	Run No. 68	Run No. 101
		30%	Run No. 3	Run No. 36	Run No. 69	Run No. 102
	15,000	10%	Run No. 4	Run No. 37	Run No. 70	Run No. 103
		20%	Run No. 5	Run No. 38	Run No. 71	Run No. 104
		30%	Run No. 6	Run No. 39	Run No. 72	Run No. 105
	20,000	10%	Run No. 7	Run No. 40	Run No. 73	Run No. 106
		20%	Run No. 8	Run No. 41	Run No. 74	Run No. 107
		30%	Run No. 9	Run No. 42	Run No. 75	Run No. 108
	25,000	10%	Run No. 10	Run No. 43	Run No. 76	Run No. 109
		20%	Run No. 11	Run No. 44	Run No. 77	Run No. 110
		30%	Run No. 12	Run No. 45	Run No. 78	Run No. 111
	30,000	10%	Run No. 13	Run No. 46	Run No. 79	Run No. 112
		20%	Run No. 14	Run No. 47	Run No. 80	Run No. 113
		30%	Run No. 15	Run No. 48	Run No. 81	Run No. 114
	35,000	10%	Run No. 16	Run No. 49	Run No. 82	Run No. 115
		20%	Run No. 17	Run No. 50	Run No. 83	Run No. 116
		30%	Run No. 18	Run No. 51	Run No. 84	Run No. 117
	40,000	10%	Run No. 19	Run No. 52	Run No. 85	Run No. 118
		20%	Run No. 20	Run No. 53	Run No. 86	Run No. 119
		30%	Run No. 21	Run No. 54	Run No. 87	Run No. 120
4 LANE HWYS.	45,000	10%	Run No. 22	Run No. 55	Run No. 88	Run No. 121
		20%	Run No. 23	Run No. 56	Run No. 89	Run No. 122
		30%	Run No. 24	Run No. 57	Run No. 90	Run No. 123
	50,000	10%	Run No. 25	Run No. 58	Run No. 91	Run No. 124
		20%	Run No. 26	Run No. 59	Run No. 92	Run No. 125
		30%	Run No. 27	Run No. 60	Run No. 93	Run No. 126
	55,000	10%	Run No. 28	Run No. 61	Run No. 94	Run No. 127
		20%	Run No. 29	Run No. 62	Run No. 95	Run No. 128
		30%	Run No. 30	Run No. 63	Run No. 96	Run No. 129
	60,000	10%	Run No. 31	Run No. 64	Run No. 97	Run No. 130
		20%	Run No. 32	Run No. 65	Run No. 98	Run No. 131
		30%	Run No. 33	Run No. 66	Run No. 99	Run No. 132

Figure 4.7 Design factorial tested on the QUEWZ-E Model

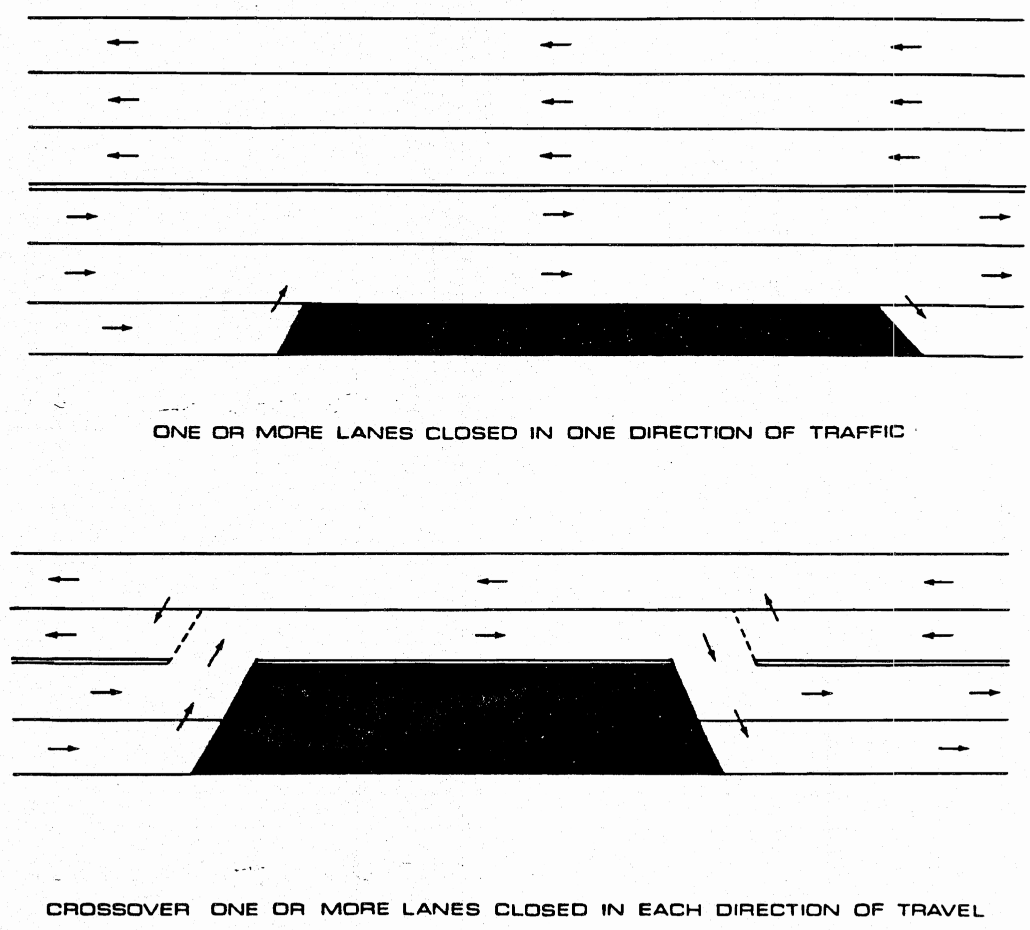


Figure 4.8 Lane closure strategies through a work zone [Memmot 1982]

Ending at 3 P.M.

One extra hour of restricted capacity before/after the beginning/ending of actual maintenance operation was used for the setup and removal times of the equipment and safety devises.

Traffic Volumes: Several different traffic volumes (ADTs) were tested. As shown in figure 4.7, for four-lane highways, an ADT range (in each direction) of 10,000 to 40,000 was selected whereas for the eight-lane highways / freeways, an ADT range (in each direction) of 45,000 to 60,000 was used. The selection of these ADTs was based on the capacity and typical usage of these highways and freeways. The lower ADTs (under 45,000) were not tested for the eight lane highways / freeways due to the negligible effects of lane closures at these ADTs. A typical ADT distribution was used which is shown in figure 4.9.

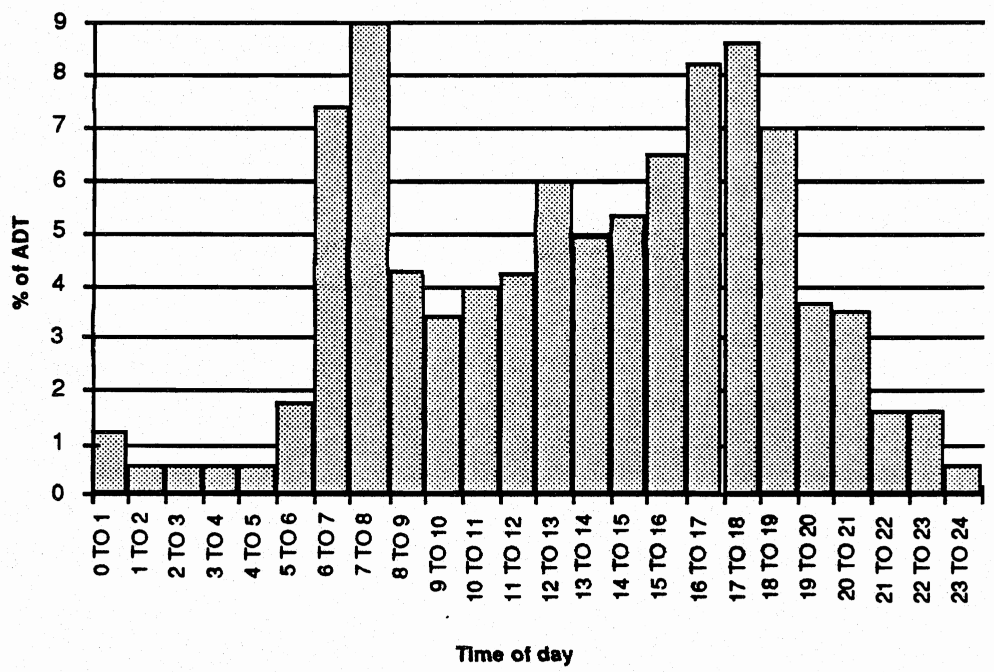


Figure 4.9 Typical distribution of ADT during a day

Traffic Mix: To analyze the effects of different car and truck combinations in the traffic stream, the traffic mix was divided into three major categories as following:

- 90% Autos & 10% Trucks
- 80% Autos & 20% Trucks
- 70% Autos & 30% Trucks

This range was selected as per the typical traffic mix values on the highways and freeways [Asphalt Ins. 1970].

Other Inputs: As the base year used in the QUEWZ-E model is 1981, an inflation rate correction is required to get the values for today. An average inflation rate of 6% was used from 1981 to 1993, and by applying the compound amount factor, a correction factor of 200% was selected for 1993.

The test results for total additional user-costs ($) are summarized in table 4.4. The user-costs in most cases increased by a factor of 2 or more for each increment of 5,000 in the ADTs. For the four lane highways, the user-costs increased by a factor of 2 to 3 except that there was a sudden jump between the ADTs of 25,000 and 30,000 each direction as the hourly peaks, 8% to 9% of ADT, exceeded the available reduced capacity resulting in long queues. Due to the higher capacities of the eight lane highways, the closures on 1 of the 4 lanes caused the user-costs to increase by a factor of about 1.3 for each increments of 5000 in the ADT. However, the user-costs increased almost exponentially for closures on 2 of the 4 lanes for each increment of 5000 in the ADT.

The user-costs were directly proportional to the percentage of trucks in the traffic stream and the closure length. For the increase in closure length from 0.5 mile to 1 mile (all truck cases), the user-costs slightly increased by a factor of 1.0 to 1.2. For the four lane highways, the user-costs doubled when two lanes were closed instead of one. For the eight lane highways, the user-costs increased by a factor of 2.5 to 16 (higher factor for higher volumes) when two lanes were closed instead of one.

4.3.3 Qualitative Analysis

As discussed in chapter 3, there are several qualitative concerns which can benefit from an ARM system. These concerns are grouped into six major concern areas for the technology

TABLE 4.4 TEST RESULTS FOR ADDITIONAL USER-COSTS ($/DAY) FROM THE QUEWZ-E MODEL

			1 Lane closed		2 Lanes closed	
	ADT	Trucks	0.5 mi. closed	1 mi. closed	0.5 mi. closed	1 mi. closed
2 LANE HIGHWAYS	10,000	10%	208	225	416	450
		20%	264	282	528	564
		30%	319	339	638	678
	15,000	10%	560	632	1,120	1,264
		20%	693	772	1,386	1,544
		30%	825	912	1,650	1,824
	20,000	10%	1,256	1,465	2,512	2,930
		20%	1,516	1,745	3,032	3,490
		30%	1,776	2,025	3,552	4,050
	25,000	10%	2,982	3,557	5,964	7,114
		20%	3,470	4,099	6,940	8,198
		30%	3,957	4,642	7,914	9,284
	30,000	10%	35,793	37,368	71,586	74,736
		20%	37,013	38,741	74,026	77,482
		30%	38,259	40,141	76,518	80,282
	35,000	10%	112,990	116,077	225,980	232,154
		20%	115,622	119,010	231,244	238,020
		30%	118,352	122,042	236,704	244,084
	40,000	10%	303,795	308,655	607,590	617,310
		20%	309,348	314,684	618,696	629,368
		30%	315,203	321,014	630,406	642,028
4 LANE HWYS.	45,000	10%	1,417	1,576	3,583	4,219
		20%	1,746	1,920	4,275	4,973
		30%	2,075	2,265	4,967	5,727
	50,000	10%	1,899	2,133	5,965	7,113
		20%	2,320	2,577	6,939	8,199
		30%	2,741	3,021	7,914	9,285
	55,000	10%	2,509	2,843	17,317	19,549
		20%	3,039	3,406	18,801	21,250
		30%	3,569	3,968	20,290	22,957
	60,000	10%	3,277	3,742	71,586	74,736
		20%	3,936	4,446	74,027	77,483
		30%	4,594	5,149	76,518	80,281

evaluation phase. These major concern areas are technology, quality, safety, socio-political, working environment, and worker utilization.

Using a similar method as in the needs assessment phase, every evaluated ARM system is given an Overall Concern Rating (OCR) using the weighted rating method. The procedure for determining this OCR is the same as in the needs assessment phase (section 4.2.2), and the only difference is that the set of possible concerns for the two phases are not the same. Similarly the OCR of 5 is the cut-off point between feasible and non-feasible ARM systems.

A sample questionnaire for evaluating an ARM systems is shown is figure 4.10. The relative weights for each of the concerns were developed through a relative weight survey, performed along-with the relative weight survey for the needs assessment phase, in September 1993. Two pages of this survey form are shown in figure 4.11A and 4.11B. The spreadsheet used to analyze the data for the needs assessment phase (relative weight) survey was expanded to also analyze the data for this phase's survey. The results of this relative weight survey is shown in table 4.5. These results are shown graphically in figure 4.12. The effects of the small sample size (10), due to the resource and time restrictions, can also be seen from the large standard deviations present. However, similar to the needs assessment phase survey, the mean values from both the TxDOT and University of Texas faculty/staff came out to be quite similar.

4.3.4 Environmental/Energy Analysis

Lane closures due to maintenance work on highways reduce the capacity of the highway, and hence result in additional fuel and oil consumption, delays, harmful emissions, and higher operating/other costs of the vehicles. The QUEWZ-E model, selected for the user-costs analysis (section 4.3.2), also report the emission of air-pollutants including carbon-monoxide, hydrocarbons, and oxides of nitrogen besides the energy consumption (fuel/oil) values. For the factorial tested for developing the user-costs charts from the QUEWZ-E model, emissions and energy consumption values were also recorded and analyzed. Complete details on the scope and limitations of the factorial are already discussed in the user-costs section, and hence only the results for emissions and energy consumption are discussed in this section.

Emissions (Carbon Monoxide, Hydrocarbons and Oxides of Nitrogen): The test results of additional emission of carbon monoxide (CO) due to the presence of work zones are given in

Qualitative Analysis of "XYZ" ARM system (Technology Evaluation phase)				
For each of the following Concerns/Benefits, please mark your Response in either Yes, No or Intermediate columns (Don't mark in the shaded areas).				
CONCERNS/BENEFITS	RESPONSE*			RATING
	Yes	Intermediate**	No	
1. Technology Concerns				
01 Commercially available system				
02 Spares/Support easily available				
03 Reliable Technology (System and/or Manufacturer)				
04 Durable Technology (System and/or Manufacturer)				
05 Low risk of failure (not unusual design/operation)				
06 Skill level to operate the system is similar to that of existing work crew				
07 Minimum additional training is reqd. for work crew				
08 New work crew/operators easily available				
09. Setup/breakdown time lower than current methods				
10 Easy transportation of the system to the work site				
11 User friendly system				
12 Less clean-up required than current methods				
13 System can perform multiple tasks				
14 System can operate in most typical situations				
2. Working Environment Benefits				
01 Improvement in noisy conditions				
02 Improvement in vibratory conditions				
03 Improvement in dirty conditions				
04 Improvement in heavy/high lift works				
05 Improvement in meticulous work				
06 Improvement in exhaustive work				
3. Safety Benefits				
01 Reduced potential for physical injuries (work crew)				
02 Reduced potential for physical injuries (road users)				
03 Reduction in health hazards (work crew)				
04 Reduction in health hazards (road users)				
4. Quality Benefits				
01 Improvement in consistency				
02 Improvement in accuracy				
03 Improvement in other quality concerns (aesthetics, visual, etc.)				
5. Socio-Political Concerns				
01 Systems acceptable to the workers				
02 Workers motivation to change expected (increased salary with additional training)				
03 System's overall acceptability in the agency expected				
6. Worker Utilization Concerns				
01 Lower number of workers/operators required				
02 Same work crew/operators can be used				
OVERALL CONCERN RATING (OCR)				

* For non-applicable concerns/benefits or unknown answers, no entry should be made

** Intermediate represents conditions between yes or no. For example, sometimes, partly true, etc.

Figure 4.10 A sample Qualitative Analysis sheet (Technology Evaluation phase)

CONCERNS	RATING SCALE
1. TECHNOLOGY Concerns for evaluating the Automated Systems	
1.01 Commercially available system	Least Important / Slightly Important / Important / Very Important / Extremely Important
1.02 Spares/Support easily available	Least Important / Slightly Important / Important / Very Important / Extremely Important
1.03 Reliable Technology (System and/or Manufacturer)	Least Important / Slightly Important / Important / Very Important / Extremely Important
1.04 Durable Technology (System and/or Manufacturer)	Least Important / Slightly Important / Important / Very Important / Extremely Important
1.05 Low risk of failure (not unusal design/operation)	Least Important / Slightly Important / Important / Very Important / Extremely Important
1.06 Skill level required to operate the System is similar to that of existing work crew/operators	Least Important / Slightly Important / Important / Very Important / Extremely Important
1.07 Minimum additional training required for the work crew/operators	Least Important / Slightly Important / Important / Very Important / Extremely Important

Figure 4.11A Sample form for the development of relative weights for Qualitative Concerns, ARME-Technology Evaluation phase

OVERALL RATING

CONCERN AREAS	RATING SCALE
1. TECHNOLOGY Concerns	Least Important / Slightly Important / Important / Very Important / Extremely Important
2. WORKING ENVIRONMENT Benefits	Least Important / Slightly Important / Important / Very Important / Extremely Important
3. SAFETY Benefits	Least Important / Slightly Important / Important / Very Important / Extremely Important
4. QUALITY Benefits	Least Important / Slightly Important / Important / Very Important / Extremely Important
5. SOCIO-POLITICAL Concerns	Least Important / Slightly Important / Important / Very Important / Extremely Important
6. WORKER UTILIZATION Concerns	Least Important / Slightly Important / Important / Very Important / Extremely Important

Figure 4.11B Sample form for the development of relative weights for Qualitative Concerns, ARME-Technology Evaluation phase

Table 4.5 Results of relative weight survey, Technology Evaluation phase

CONCERNS	RELATIVE IMPORTANCE WEIGHTS					
	TxDOT*		Univ. of Texas*		Average*	
	Std. Dev.	Mean	Std. Dev.	Mean	Std.Dev.	Mean
1. Technology Concerns (TEC)	**3.7**	**16.5 % OCR**	**4.2**	**17.3 % OCR**	**3.8**	**16.9 % OCR**
01 Commercially available system	0.8	6.1 %TEC	1.1	6.9 %TEC	1.0	6.5 %TEC
02 Spares/Support easily available	1.5	6.7 %TEC	2.7	9.6 %TEC	2.6	8.2 %TEC
03 Reliable Technology (System and/or Manufacturer)	1.7	7.4 %TEC	3.0	11.0 %TEC	3.0	9.2 %TEC
04 Durable Technology (System and/or Manufacturer)	1.3	7.0 %TEC	3.0	11.0 %TEC	3.0	9.0 %TEC
05 Low risk of failure (not unusual design/operation)	0.8	7.8 %TEC	1.4	8.7 %TEC	1.2	8.3 %TEC
06 Skill level to operate the system is similar to that of existing work crew	0.7	7.9 %TEC	1.9	4.1 %TEC	2.4	6.0 %TEC
07 Minimum additional training for work crew	2.6	7.4 %TEC	2.3	3.1 %TEC	3.3	5.2 %TEC
08 New work crew/operators easily available	1.6	5.8 %TEC	2.2	3.5 %TEC	2.2	4.6 %TEC
09. Setup/breakdown time lower than current methods	1.7	6.6 %TEC	2.9	6.5 %TEC	2.2	6.6 %TEC
10 Easy transportation of the system to the work site	1.5	7.2 %TEC	0.7	8.1 %TEC	1.2	7.7 %TEC
11 User friendly system	0.9	8.8 %TEC	0.8	9.7 %TEC	0.9	9.3 %TEC
12 Less clean-up required than current methods	1.6	6.1 %TEC	1.7	4.5 %TEC	1.8	5.3 %TEC
13 System can perform multiple tasks	0.8	6.9 %TEC	2.1	3.4 %TEC	2.4	5.2 %TEC
14 System can operate in most typical situations	0.8	8.2 %TEC	2.7	9.9 %TEC	2.1	9.0 %TEC
2. Working Environment Benefits (WOR)	**6.7**	**13.1 % OCR**	**5.4**	**16.0 % OCR**	**5.9**	**14.6 % OCR**
01 Improvement in noisy conditions	5.4	17.4 %WOR	5.3	15.3 %WOR	5.2	16.3 %WOR
02 Improvement in vibratory conditions	2.7	12.4 %WOR	2.3	14.1 %WOR	2.5	13.2 %WOR
03 Improvement in dirty conditions	2.3	14.1 %WOR	3.6	13.7 %WOR	2.8	13.9 %WOR
04 Improvement in heavy/high lift works	9.6	22.5 %WOR	3.2	20.6 %WOR	6.8	21.5 %WOR
05 Improvement in meticulous work	3.0	16.3 %WOR	1.1	16.3 %WOR	2.1	16.3 %WOR
06 Improvement in exhaustive work	4.5	17.3 %WOR	5.1	20.1 %WOR	4.7	18.7 %WOR
3. Safety Benefits (SAF)	**3.9**	**22.6 % OCR**	**4.8**	**22.2 % OCR**	**4.1**	**22.4 % OCR**
01 Reduced potential for physical injuries (work crew)	1.1	24.5 % SAF	6.8	26.5 % SAF	4.7	25.5 % SAF
02 Reduced potential for physical injuries (road users)	0.4	25.2 % SAF	2.6	26.9 % SAF	2.0	26.0 % SAF
03 Reduction in health hazards (work crew)	0.4	25.2 % SAF	3.0	24.2 % SAF	2.0	24.7 % SAF
04 Reduction in health hazards (road users)	0.4	25.2 % SAF	3.8	22.4 % SAF	2.9	23.8 % SAF
4. Quality Benefits (QLT)	**3.2**	**19.4 % OCR**	**7.3**	**16.1 % OCR**	**5.6**	**17.7 % OCR**
01 Improvement in consistency	2.4	35.1 %QLT	5.0	32.8 %QLT	3.9	34.0 %QLT
02 Improvement in accuracy	2.4	35.1 %QLT	2.2	35.4 %QLT	2.2	35.2 %QLT
03 Improvement in other quality concerns (aesthetics, visual, etc.)	4.9	29.9 %QLT	5.2	31.8 %QLT	4.8	30.8 %QLT
5. Socio-Political Concerns (S/P)	**6.2**	**9.6 % OCR**	**4.4**	**12.4 % OCR**	**5.3**	**11.0 % OCR**
01 Systems acceptability by workers	4.9	32.8 % S/P	9.1	26.2 % S/P	7.7	29.5 % S/P
02 Workers' motivation to change (increased salary with additional training)	3.7	31.5 % S/P	12.3	24.2 % S/P	9.4	27.9 % S/P
03 System's overall acceptability in the organization	6.4	35.7 % S/P	17.8	49.6 % S/P	14.6	42.6 % S/P
6. Worker Utilization Concerns (W/U)	**2.0**	**18.9 % OCR**	**4.4**	**16.0 % OCR**	**3.6**	**17.5 % OCR**
01 Lower number of workers/operators required	12.2	47.8 % W/U	7.3	61.5 % W/U	11.9	54.7 % W/U
02 Same work crew/operators can be used	12.2	52.2 % W/U	7.3	38.5 % W/U	11.9	45.3 % W/U

*Total Number of Responses=10, Responses from TxDOT=5, Responses from University of Texas=5

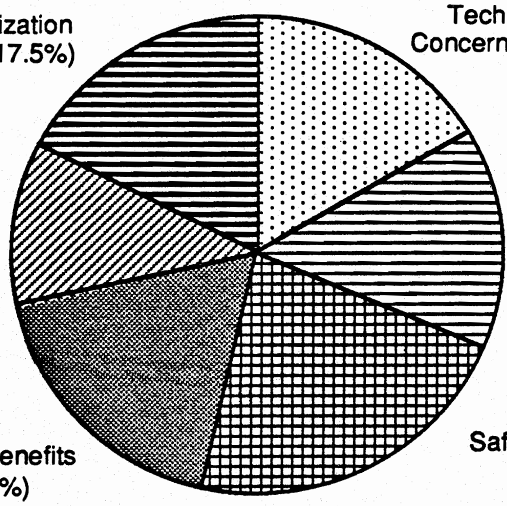


Figure 4.12 Results of relative weight survey, ARME-Technology Evaluation phase

table 4.6. The emission of CO increased, for each ADT increment of 5000, by a factor of approximately 1.7 to 16 (sixteen) for the four lane highways, and by a factor of 1.7 to 4.7 for the eight lane highways. For the four lane highways, the additional emission of CO did not change significantly when the closure length was increased from 0.5 mile to 1.0 mile, it decreased by a factor of 0.7 to 0.9 for each 10 % increase in the number of trucks, and it doubled when two lanes were closed instead of one. For the eight lane highways, the additional emission of CO did not change when the closure length was increased from 0.5 mile to 1.0 mile, it decreased by a factor of approximately 0.7 for each 10 % increase in the number of trucks, and it increased by a factor of 2 to 40 when two lanes were closed instead of one.

The test results of additional emission of Hydrocarbons (HC) and Oxides of Nitrogen (NOx) due to the presence of work zones are given in table 4.7 and table 4.8, respectively. Additional emissions of both HC and NOx were not significant for lower to medium ADT values (up to 25,000 for four lanes and 55,000 for eight lanes), and above these ADTs significant values were reported which can be seen in these tables.

TABLE 4.6 TEST RESULTS FOR ADDITIONAL EMISSIONS OF CARBON-MONOXIDE (KGS./DAY) FROM THE QUEWZ-E MODEL

			1 Lane closed		2 Lanes closed	
	ADT	Trucks	0.5 mi. closed	1 mi. closed	0.5 mi. closed	1 mi. closed
2 LANE HIGHWAYS	10,000	10%	2.4	2.4	4.8	4.8
		20%	1.9	1.8	3.8	3.6
		30%	1.4	1.3	2.8	2.6
	15,000	10%	4.4	4.3	8.8	8.6
		20%	3.4	3.3	6.8	6.6
		30%	2.4	2.3	4.8	4.6
	20,000	10%	8.2	8.1	16.4	16.2
		20%	6.4	6.4	12.8	12.8
		30%	4.7	4.7	9.4	9.4
	25,000	10%	20.1	20.7	40.2	41.4
		20%	17.1	17.8	34.2	35.6
		30%	14.1	14.8	28.2	29.6
	30,000	10%	267.8	271.5	535.6	543.0
		20%	251.3	255.0	502.6	510.0
		30%	231.6	235.4	463.2	470.8
	35,000	10%	803.1	812.3	1606.2	1624.6
		20%	755.6	765.0	1511.2	1530.0
		30%	698.0	707.4	1396.0	1414.8
	40,000	10%	1906.4	1922.6	3812.8	3845.2
		20%	1783.7	1799.9	3567.4	3599.8
		30%	1634.5	1650.7	3269.0	3301.4
4 LANE HWYS.	45,000	10%	10.5	10.3	22.8	22.9
		20%	8.0	7.9	18.4	18.6
		30%	5.6	5.5	14.1	14.3
	50,000	10%	13.0	12.8	40.2	41.5
		20%	10.0	9.9	34.3	35.6
		30%	7.0	7.0	28.3	29.7
	55,000	10%	16.3	16.2	121.0	125.2
		20%	12.7	12.7	110.4	114.8
		30%	9.1	9.1	99.1	103.6
	60,000	10%	20.7	20.8	535.7	543.0
		20%	16.4	16.6	502.5	510.0
		30%	12.2	12.4	463.3	470.9

TABLE 4.7 TEST RESULTS FOR ADDITIONAL EMISSIONS OF HYDROCARBONS (KGS./DAY) FROM THE QUEWZ-E MODEL

			1 Lane closed		2 Lanes closed	
	ADT	Trucks	0.5 mi. closed	1 mi. closed	0.5 mi. closed	1 mi. closed
2 LANE HIGHWAYS	10,000	10%	0.0	0.0	0.0	0.0
		20%	0.0	0.0	0.0	0.0
		30%	0.0	0.0	0.0	0.0
	15,000	10%	0.1	0.2	0.2	0.4
		20%	0.0	0.1	0.0	0.2
		30%	0.0	0.1	0.0	0.2
	20,000	10%	0.3	0.5	0.6	1.0
		20%	0.2	0.5	0.4	1.0
		30%	0.2	0.5	0.4	1.0
	25,000	10%	1.0	1.7	2.0	3.4
		20%	1.0	1.6	2.0	3.2
		30%	1.0	1.6	2.0	3.2
	30,000	10%	23.2	24.9	46.4	49.8
		20%	23.7	25.4	47.4	50.8
		30%	24.2	25.8	48.4	51.6
	35,000	10%	70.9	74.1	141.8	148.2
		20%	72.7	75.8	145.4	151.6
		30%	74.3	77.3	148.6	154.6
	40,000	10%	168.0	172.9	336.0	345.8
		20%	172.3	177.1	344.6	354.2
		30%	175.9	180.7	351.8	361.4
4 LANE HWYS.	45,000	10%	0.1	0.3	0.8	1.6
		20%	0.0	0.2	0.8	1.5
		30%	0.0	0.2	0.7	1.4
	50,000	10%	0.2	0.5	2.1	3.4
		20%	0.1	0.4	2.0	3.2
		30%	0.1	0.3	1.9	3.1
	55,000	10%	0.3	0.7	9.2	11.6
		20%	0.2	0.6	9.2	11.6
		30%	0.2	0.5	9.3	11.5
	60,000	10%	0.5	1.0	46.4	49.7
		20%	0.4	0.9	47.5	50.7
		30%	0.3	0.8	48.4	51.5

TABLE 4.8 TEST RESULTS FOR ADDITIONAL EMISSIONS OF OXIDES OF NITROGEN (KGS./DAY) FROM THE QUEWZ-E MODEL

			1 Lane closed		2 Lanes closed	
	ADT	Trucks	0.5 mi. closed	1 mi. closed	0.5 mi. closed	1 mi. closed
2 LANE HIGHWAYS	10,000	10%	0.0	0.0	0.0	0.0
		20%	0.0	0.0	0.0	0.0
		30%	0.0	0.0	0.0	0.0
	15,000	10%	0.0	0.0	0.0	0.0
		20%	0.0	0.0	0.0	0.0
		30%	0.0	0.0	0.0	0.0
	20,000	10%	0.0	0.1	0.0	0.2
		20%	0.0	0.1	0.0	0.2
		30%	0.0	0.1	0.0	0.2
	25,000	10%	0.2	0.3	0.4	0.6
		20%	0.2	0.4	0.4	0.8
		30%	0.3	0.5	0.6	1.0
	30,000	10%	4.6	5.0	9.2	10.0
		20%	6.8	7.3	13.6	14.6
		30%	9.2	9.8	18.4	19.6
	35,000	10%	14.2	14.9	28.4	29.8
		20%	21.0	21.9	42.0	43.8
		30%	28.4	29.6	56.8	59.2
	40,000	10%	33.7	34.7	67.4	69.4
		20%	49.5	51.1	99.0	102.2
		30%	67.0	69.0	134.0	138.0
4 LANE HWYS.	45,000	10%	0.0	0.0	0.1	0.3
		20%	0.0	0.0	0.1	0.3
		30%	0.0	0.0	0.1	0.4
	50,000	10%	0.0	0.1	0.3	0.6
		20%	0.0	0.1	0.4	0.8
		30%	0.0	0.1	0.5	1.0
	55,000	10%	0.0	0.1	1.7	2.2
		20%	0.0	0.1	2.5	3.2
		30%	0.0	0.1	3.3	4.2
	60,000	10%	0.0	0.1	9.2	9.9
		20%	0.0	0.2	13.6	14.6
		30%	0.0	0.2	18.3	19.6

Energy Consumption (Fuel and Oil): The test results of additional fuel consumption due to the presence of work zones are given in table 4.9. The fuel consumption increased, for each ADT increment of 5000, by a factor of approximately 1.3 to 1.6 for the four lane highways, and by a factor of approximately 1.1 for the eight lane highways. For the four lane highways, the additional fuel consumption doubled when the closure length was increased from 0.5 mile to 1.0 mile, it increased by a factor of 1.2 to 1.3 for each 10 % increase in the number of trucks, and it doubled when two lanes were closed instead of one. For the eight lane highways, the additional fuel consumption doubled when the closure length was increased from 0.5 mile to 1.0 mile, it increased by a factor of 1.2 to 1.3 for each 10 % increase in the number of trucks, and it increased by a factor of 1.1 to 1.8 (higher factor for higher volumes) when two lanes were closed instead of one.

The test results of additional oil consumption due to the presence of work zones are given in table 4.10. The oil consumption increased, for each ADT increment of 5000, by a factor of approximately 1.3 to 1.8 for the four lane highways, and by a factor of approximately 1.1 for the eight lane highways. For the four lane highways, the additional oil consumption doubled when the closure length was increased from 0.5 mile to 1.0 mile, it increased by a factor of approximately 1.2 for each 10 % increase in the number of trucks, and it doubled when two lanes were closed instead of one. For the eight lane highways, the additional oil consumption doubled when the closure length was increased from 0.5 mile to 1.0 mile, it increased by a factor of approximately 1.2 for each 10 % increase in the number of trucks, and it increased by a factor of approximately 1.1 when two lanes were closed instead of one.

4.3.5 Overall Ranking

Most ARM systems can be relatively ranked from the ARME model, regardless of their function, level of automation, differences in design and performance, etc. Even ARM systems for different maintenance activities (e.g. an automated crack sealer verses an automated pothole system) can also be relatively ranked.

Using the results of the economic, qualitative and environmental/ energy analysis; the ARM systems can be ranked independently for these three perspectives. The effects of the both the economic savings and qualitative benefits can also be shown together using the cost-concern matrix concept (figure 4.13). The emissions or energy consumption reductions can also be added, to the cost-concern matrix, as a third dimension.

TABLE 4.9 TEST RESULTS FOR ADDITIONAL FUEL CONSUMPTION (GALLONS/DAY) FROM THE QUEWZ-E MODEL

			1 Lane closed		2 Lanes closed	
	ADT	Trucks	0.5 mi. closed	1 mi. closed	0.5 mi. closed	1 mi. closed
2 LANE HIGHWAYS	10,000	10%	134	268	268	536
		20%	171	343	343	685
		30%	209	417	417	834
	15,000	10%	208	416	416	831
		20%	270	540	540	1,081
		30%	333	665	665	1,330
	20,000	10%	289	578	578	1,156
		20%	381	762	762	1,524
		30%	473	946	946	1,892
	25,000	10%	434	868	868	1,736
		20%	582	1,163	1,163	2,327
		30%	729	1,459	1,459	2,917
	30,000	10%	697	1,395	1,395	2,789
		20%	942	1,884	1,884	3,767
		30%	1,186	2,373	2,373	4,746
	35,000	10%	939	1,878	1,878	3,756
		20%	1,270	2,540	2,540	5,080
		30%	1,601	3,202	3,202	6,404
	40,000	10%	1,306	2,611	2,611	5,222
		20%	1,767	3,534	3,534	7,069
		30%	2,229	4,458	4,458	8,916
4 LANE HWYS.	45,000	10%	602	1,204	665	1,329
		20%	780	1,559	881	1,762
		30%	957	1,913	1,098	2,195
	50,000	10%	676	1,352	868	1,736
		20%	879	1,759	1,163	2,327
		30%	1,083	2,165	1,459	2,917
	55,000	10%	752	1,505	1,041	2,082
		20%	983	1,966	1,404	2,808
		30%	1,214	2,428	1,767	3,534
	60,000	10%	831	1,662	1,395	2,789
		20%	1,090	2,180	1,884	3,767
		30%	1,350	2,699	2,373	4,745

TABLE 4.10 TEST RESULTS FOR ADDITIONAL OIL CONSUMPTION (QUARTS/DAY) FROM THE QUEWZ-E MODEL

			1 Lane closed		2 Lanes closed	
	ADT	Trucks	0.5 mi. closed	1 mi. closed	0.5 mi. closed	1 mi. closed
2 LANE HIGHWAYS	10,000	10%	3.3	6.6	6.6	13.2
		20%	4.1	8.2	8.2	16.4
		30%	4.9	9.8	9.8	19.6
	15,000	10%	4.9	9.8	9.8	19.6
		20%	6.2	12.4	12.4	24.8
		30%	7.5	15.0	15.0	30.0
	20,000	10%	6.6	13.2	13.2	26.4
		20%	8.4	16.8	16.8	33.6
		30%	10.1	20.2	20.2	40.4
	25,000	10%	12.0	24.0	24.0	48.0
		20%	15.2	30.4	30.4	60.8
		30%	18.4	36.8	36.8	73.6
	30,000	10%	21.0	42.0	42.0	84.0
		20%	26.9	53.8	53.8	107.6
		30%	32.6	65.2	65.2	130.4
	35,000	10%	27.6	55.2	55.2	110.4
		20%	35.3	70.6	70.6	141.2
		30%	43.1	86.2	86.2	172.4
	40,000	10%	39.9	79.8	79.8	159.6
		20%	51.1	102.2	102.2	204.4
		30%	62.2	124.4	124.4	248.8
4 LANE HWYS.	45,000	10%	14.8	29.6	15.2	30.4
		20%	18.6	37.2	19.2	38.4
		30%	22.3	44.6	23.3	46.6
	50,000	10%	16.5	33.0	24.0	48.0
		20%	20.6	41.2	30.5	61.0
		30%	24.9	49.8	37.0	74.0
	55,000	10%	18.2	36.4	30.4	60.8
		20%	22.8	45.6	38.7	77.4
		30%	27.6	55.2	47.0	94.0
	60,000	10%	19.9	39.8	42.1	84.2
		20%	25.1	50.2	53.6	107.2
		30%	30.4	60.8	65.3	130.6

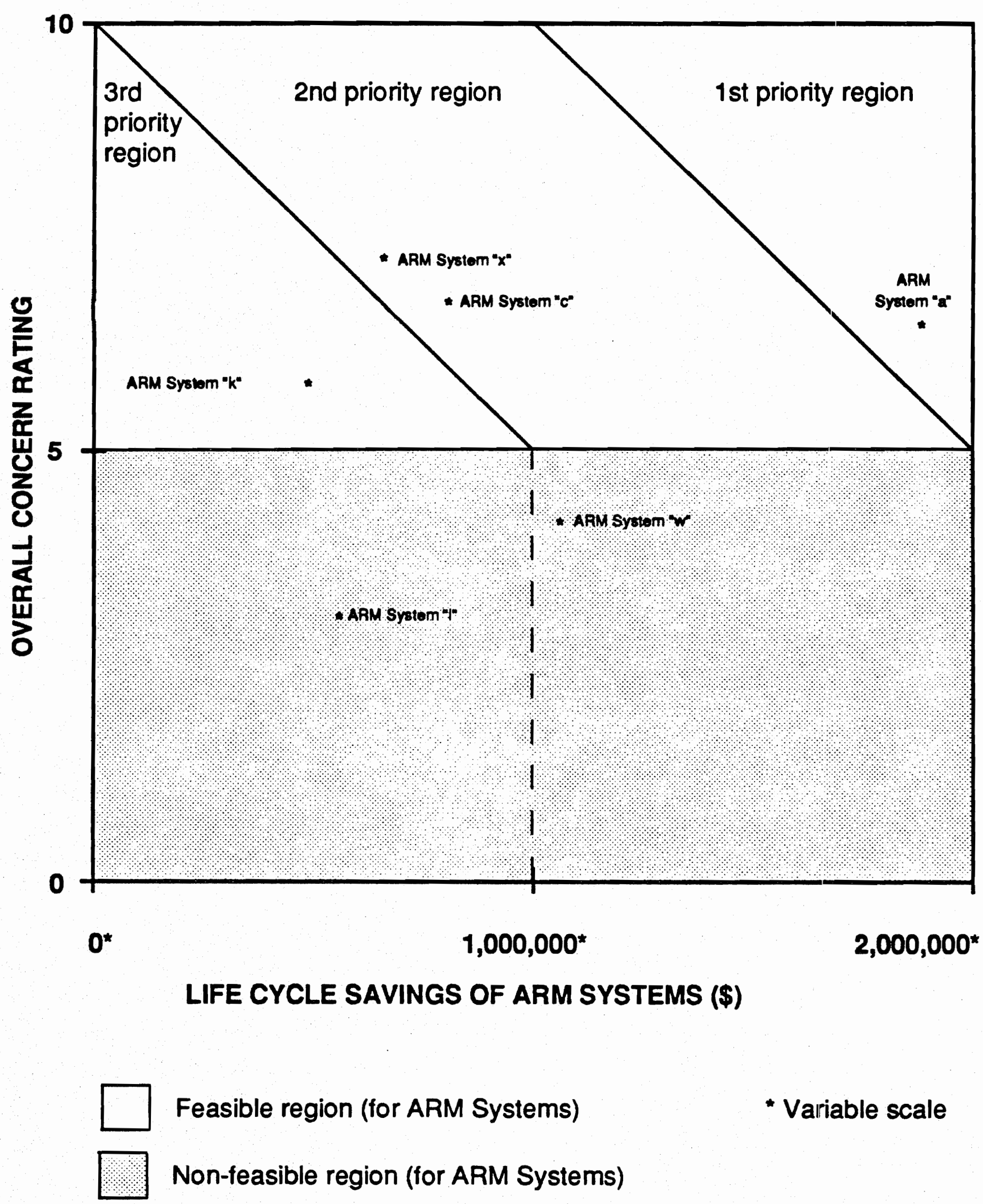


Figure 4.13 Overall Ranking of ARM Systems

4.4 ARME MODEL - FIELD TESTING PHASE

The field testing of an ARM system, before an agency purchases several ARM systems to fully automate a specific maintenance activity, is essential because most of the ARM systems available today are either prototype systems or are based on unproved technologies. Also, field testing of a promising ARM system can provide invaluable information including technical problems/shortfalls of the system, operational problems, socio-political problems, and most important of all the actual economic savings.

The duration of the actual field testing of an ARM system depends on the engineering judgment of the engineer in-charge of the field testing project. However, a typical field testing duration of 1 year has been used to evaluate automated systems for construction industry [Tucker 1990B].

In the field testing phase, the model evaluates the field results of an ARM system selected from the technology evaluation phase. Only economic analysis is performed in this phase which is explained as following:

4.4.1 Economic Analysis

In the field testing phase, the model evaluates the actual field data of an ARM system by comparing it with the life cycle economic analysis data from the technology evaluation phase. A computer spreadsheet is developed for this purpose which reports the differences, between the data from the two phases, in either positive (better performance than expected) or negative (poorer performance than expected) percentages. A printout for a sample economic analysis is shown in figure 4.14.

With this spreadsheet, the effects of the variables having an impact on the economic savings can easily be identified for modifications/ improvements in the ARM system, if required. For example, the effects of higher capacity/ efficiency of an ARM system (285,500 sqyds/year @80% verses expected capacity of 275,000 sqyds./year @70%) can be seen in the sample analysis. Although, all the costs of the ARM system are higher than estimated, still due to the higher capacity and efficiency, the life cycle savings are much higher than expected.

Although this spreadsheet is quite simple in terms of the analysis, it can easily be expanded. The expansions might include further quantification of the input variables identified in

ECONOMIC ANALYSIS OF XYZ ARM SYSTEM (ARME - FIELD TESTING PHASE)			
GENERAL DATA	Technology Evaluation Results	Field Testing Results	Difference
WORK UNITS OF THE ARM SYSTEM	Sqyds.	Sqyds.	**N/A**
ESTIMATED WORK CAPACITY OF THE ARM SYSTEM (UNITS/YEAR)	275,000	285,500	**3.82%**
ESTIMATED YEARLY EFFICIENCY OF THE ARM SYSTEM	70%	80%	**10.00%**
ANALYSIS PERIOD OR LIFE OF THE ARM SYSTEM (YEARS)	6	6	**0.00%**
INTEREST RATE	4.00%	4.00%	**0.00%**
INITIAL COST OF ARM SYSTEM (PRESENT $)	$75,000	$78,000	**-4.00%**
OPERATING COSTS OF ARM SYSTEM (ANNUAL $)	$4,000	$4,200	**-5.00%**
MAINTENANCE COSTS OF ARM SYSTEM (ANNUAL $)	$6,000	$6,350	**-5.83%**
OVERHEADS OF ARM SYSTEM (ANNUAL $)	$5,000	$5,250	**-5.00%**
SALVAGE VALUE OF ARM SYSTEM (FUTURE $)	$7,500	$7,500	**0.00%**
LIFE CYCLE COST/UNIT-WORK OF 1 ARM SYSTEM ($/UNIT)	**$0.13**	**$0.11**	11.61%
CURRENT TXDOT COSTS/UNIT WORK ($ /UNIT)	$0.71	$0.71	**0.00%**
" " YEARLY EXPENDITURES FOR THIS ACTIVITY ($/YEAR)	$6,532,000	$6,532,000	**0.00%**
" " EXPENDITURES ON LABOR FOR THIS ACTIVITY (%)	44.75%	22.00%	**N/A**
" " TYPICAL CREW SIZE FOR THIS MAINTENANCE ACTIVITY	7	4	**N/A**
NUMBER OF CREW MEMBERS TO BE REDUCED BY THE ARM SYSTEM	3	0	**N/A**
YEARLY UNIT WORK DONE BY TXDOT (UNITS)	9,200,000	9,200,000	**0.00%**
% WORK PERFORMED BY 1 ARM SYSTEM	**2.99%**	**3.10%**	**3.82%**
LIFE CYCLE LABOR SAVING/UNIT-WORK OF1 ARM SYSTEM	**$0.17**	**$0.18**	**3.79%**
TXDOT LIFE-CYCLE SAVINGS (1 ARM SYSTEM)	**$48,593**	**$86,845**	**78.72%**

Note: Output in bold format

Figure 4.14 Economic Analysis for ARME - Field Testing phase

ECONOMIC ANALYSIS OF XYZ ARM SYSTEM (ARME - FIELD TESTING PHASE)			
CASE STUDY	Technology Evaluation Results	Field Testing Results	Difference
PROJECT	INTERSTATE I-35, AUSTIN-SAN ANTONIO (50 mile segment)		
ESTIMATED TOTAL UNIT WORK TO BE PERFORMED	10,400	11,200	**7.69%**
NO. OF LANES EACH DIRECTION	4	4	**N/A**
ADT EACH DIRECTION	30,000	30000	**N/A**
ESTIMATED LENGTH OF ROAD CLOSURE, MILES (CONV., ARM)	(1,1)	(1,1)	**N/A**
NO. OF LANES CLOSED (CONV., ARM)	(1,1)	(1,1)	**N/A**
NO. OF DAYS CLOSED (CONV., ARM)	(1,1)	(1,1)	**N/A**
ESTIMATED REDUCTION IN CLOSURE TIME (FROM CONV. TO ARM)	50%	42%	**-16.00%**
USER COSTS PER OPERATION, CONV. METHODS	38,259	38,259	**0.00%**
USER COSTS PER OPERATION, ARM SYSTEM	19,129	16,221	**-15.20%**
NO. OF THESE TYPICAL OPERATIONS PER YEAR	13	13	**0.00%**
TOTAL USER COSTS, CONVENTIONAL METHODS	**$2,607,266**	**$2,607,266**	**0.00%**
TOTAL USER COSTS, ARM SYSTEM	**$1,303,599**	**$1,105,425**	**-15.20%**
UNIT COST (USER-COSTS) FROM CONV. SYSTEM ($/UNIT)	**$250.70**	**$232.79**	**-7.14%**
UNIT COST (USER-COSTS) FROM ARM SYSTEM ($/UNIT)	**$125.35**	**$98.70**	**-21.26%**
TOTAL UNIT COST BY CONV. METHODS (TXDOT+USER COSTS)	**$251.41**	**$233.50**	**-7.12%**
TOTAL UNIT COST BY ARM SYSTEM (TXDOT+USER COSTS)	**$126.01**	**$99.35**	**-21.16%**
TOTAL TXDOT SAVINGS ON CASE STUDY 1 (PRESENT $)	**$438**	**$710**	**62.21%**
TOTAL USER-COST SAVINGS ON CASE STUDY 1 (PRESENT $)	**$1,303,667**	**$1,501,841**	**15.20%**
TOTAL LIFE-CYCLE SAVINGS ON CASE STUDY 1 (1 ARM SYSTEM)	**$1,304,105**	**$1,502,551**	**15.22%**

Note: Output in bold format

Figure 4.14 Economic Analysis for ARME - Field Testing phase (Cont.)

the spreadsheet or addition of more variables which might be missing in the spreadsheet. However, the basic idea behind the development of this spreadsheet is to emphasize the importance of comparison between the actual and expected/promised performance of an ARM system before a system is selected for full-scale implementation in a public or private enterprise.

The analysis tools of the ARME model were later used to evaluate the feasibility of TxDOT maintenance activities (chapter 5), and to evaluate the feasibility of an automated crack sealer for the Texas environment (chapter 6).

CHAPTER 5. AUTOMATION NEEDS ASSESSMENT OF TXDOT MAINTENANCE ACTIVITIES

This chapter discusses the results of an automation needs assessment study performed for the TxDOT. The tools developed from the ARME model were used to carry out this study. The first section of this chapter outlines the criteria used for the selection of maintenance activities in the study (section 5.1). This is followed by the details of the needs assessment survey (section 5.2), and finally the results including the overall ranking of maintenance activities are discussed (section 5.3).

5.1 SELECTION OF MAINTENANCE ACTIVITIES FOR THE STUDY

As discussed in section 4.2.1, only a few major activities of the TxDOT constitute most of the routine maintenance expenditures. This trend can be seen from table 5.1 in which all the major maintenance activities of the TxDOT are identified and ranked in terms of their economic impact. These top 25 maintenance activities consume approximately 75% of the routine maintenance funds of TxDOT, and hence were selected for the automation needs assessment study because of their huge cost impact.

5.2 DETAILS OF THE AUTOMATION NEEDS ASSESSMENT SURVEY

After the selection of the maintenance activities, survey questionnaire packets were sent to several TxDOT maintenance sections. These packets consisted of survey forms for the twenty-five selected maintenance activities of TxDOT with instructions, project background and brief definitions of each of the activities. A sample survey form is shown in figure 4.2 in section 4.2.2. Brief descriptions of each of these major maintenance activities are given in table 5.2.

The personnel surveyed were the maintenance supervisors and engineers who had sufficient experience in these maintenance activities. However, to account for the different levels-of-experience a person can have for different maintenance activities; the surveyed person was also asked for his/her experience level for each maintenance activities. The possible replies for this question were little (1), some (2), and considerable (3) experience. The numbers in the brackets are the relative-experience numbers given to a respondent when analyzing the data. The average rating number for a concern (AR_i) was determined as following:

TABLE 5.1 MAJOR MAINTENANCE ACTIVITIES OF TXDOT FOR 1992

No.	Maintenance Activities (TxDOT code)	1992 Expenditures	% of Total
1	Leveling or overlay w/ maintainer (212)	34,911,237	10.33%
2	Mowing (511)	29,404,289	8.70%
3	Paint & Bead Striping (711)	18,722,575	5.54%
4	Install or Re-install Signs (732)	15,628,941	4.62%
5	Base Removal & Replacement (110)	13,825,508	4.09%
6	Leveling or overlay w/ laydown machine (211)	10,948,608	3.24%
7	Signal Maintenance (741)	10,484,608	3.10%
8	Litter Removal (521)	9,134,339	2.70%
9	Pothole Repairs (240)	7,959,761	2.35%
10	Illumination (742)	7,722,911	2.28%
11	Street Sweeping (522)	7,584,105	2.24%
12	Strip or spot seal (232)	7,070,662	2.09%
13	Assistance to Traffic (810)	7,018,613	2.08%
14	Guard Fences (722)	6,902,209	2.04%
15	Misc. Sign Maintenance (734)	6,597,754	1.95%
16	Culvert Maintenance (570)	6,484,928	1.92%
17	Aggregate Seal coat (231)	6,379,703	1.89%
18	Misc. Roadside Maintenance (592)	6,045,162	1.79%
19	Ditch Maintenance (561)	5,583,094	1.65%
20	Rest Area Maintenance (532)	5,328,191	1.58%
21	Picnic Area Maintenance (531)	4,963,245	1.47%
22	Sealing cracks & joints (220)	4,888,241	1.45%
23	Side Road Approaches & Crossovers (470)	4,821,823	1.43%
24	Reshaping Ditches & slopes (560)	4,750,698	1.41%
25	Driveway Maintenance (594)	4,580,472	1.35%
	Sub-total for major maintenance activities	**247,741,677**	**73.27%**
	Other maintenance activities	90,380,566	26.73%
	Total for all maintenance activities	**338,122,243**	**100.00%**
	Administrative expenditures	79,550,398	*****
	Grand Total	**417,672,641**	*****

TABLE 5.2 DESCRIPTION OF THE TXDOT MAJOR MAINTENANCE ACTIVITIES

Code	Description of Maintenance Activity
110	**Base & Subgrade Removal & Replacement:** The removal of base and/or subgrade materials from distressed or failed areas and replacement with suitable material (includes surfacing).
211	**Leveling or Overlay with Laydown Machine:** The application of asphaltic tack coat and placing asphaltic concrete material to improve the ride qualities or level up low spots.
212	**Leveling or Overlay with a Maintainer, Drag Box, or similar Equipment:** The application of asphaltic tack coat and placing layers of asphaltic concrete material.
220	**Sealing Cracks and Joints:** Cleaning, filling, and sealing joints and cracks in the pavement using asphaltic rubber or other materials.
231	**Aggregate Seal Coat (Full Width):** Application of a single layer of asphaltic material followed by the application of a single layer of aggregate over the full width of the travel lane or shoulder.
232	**Strip or Spot Seal:** Application of a single layer of asphaltic material followed by the application of a single layer of aggregate over areas that are not the full width of the travel lane or shoulder.
240	**Potholes Repairs:** The repair of holes with an area less than or equal to one square yard (if more than one square yard then charge to leveling by hand, code 213).
470	**Side Road Approaches and Crossovers:** The installation or maintenance of side road approaches or crossovers.
511	**Mowing:** Mowing of the right-of-way.
521	**Litter Removal:** Removal and disposal of litter from the entire right-of-way, excluding picnic and rest areas.
522	**Street Sweeping:** Routine street sweeping.
531	**Picnic Area Maintenance (Without Restrooms):** Work performed in maintaining picnic areas, including mowing, litter pickup, emptying litter barrels, paved areas, maintenance of plantings, graffiti removal, etc.
532	**Rest Area Maintenance (With Restrooms):** Work performed in janitorial and grounds maintenance including mowing, litter pickup, emptying litter barrels, maintenance of plantings, cleaning rest rooms, cleaning arbors, graffiti removal, minor painting, etc.

TABLE 5.2 DESCRIPTION OF THE TXDOT MAJOR MAINTENANCE ACTIVITIES (CONTINUED)

Code	Description of Maintenance Activity
560	**Reshaping Ditches and Slopes:** Reshaping ditches and slopes using maintainer and/or grader, etc. Not to be used for work at culverts and bridges.
561	**Ditch Maintenance:** Removal and hauling of silt, drift, and/or filing eroded areas. Not to be used for work at culverts and bridges.
570	**Culvert and Storm Drain Maintenance:** The repair and maintenance of culverts up to bridge classification (20' measured along centerline of roadway). This work includes silt and debris removal, inlet or storm drain cleaning and other maintenance items related to culverts and storm drains.
592	**Miscellaneous Roadside Maintenance:** This includes blading or fireguards, insect and rodent control, maintenance of ROW fences, cattle guards, and any other roadside maintenance that is not covered by other 500 series codes.
594	**Driveway Maintenance:** All works associated with maintaining driveways in accordance with the driveway policy.
711	**Paint and Bead Striping:** Striping lane lines, center lines, and edgelines using paint and beads. (including all make ready operations such as spotting, etc.)
722	**Guard Fences:** Erection and maintenance of guard fences including post, metal beams, etc.
732	**Install or Reinstall Signs:** The initial installation of posts and signs, the installation of an old sign on a new post or the installation of a new sign on an existing post.
734	**Miscellaneous Sign Maintenance:** Maintenance and removal of signs including straightening of posts.
741	**Signal Maintenance:** Maintenance and operation of traffic signals other than freeway and advanced systems.
742	**Illumination:** Installation, maintenance, and operation of illumination systems including continuous lighting, safety lighting, and sign illumination.
810	**Assistance to Traffic (Natural Disasters):** Provide assistance to traffic caused by natural disasters.(excluding for snow and ice)

$$AR_i = \frac{\sum_{i=1}^{n}(R_i \times E_i)}{\sum_{i=1}^{n} E_i}$$

where,

AR_i ~ averaged rating for a concern

R_i ~ individual ratings for a concern by surveyed personnel

Ei ~ relative experiences of the surveyed personnel

The overall concern rating was then calculated by multiplying the averaged ratings of each concern (AR_i) by their relative weights in the overall rating as following:

$OCR = AR_i \times w_i$

where,

OCR ~ overall concern rating for a maintenance activity

w_i ~ relative weight of a concern in the overall rating

The number of responses for each of the maintenance activities were not the same, and varied from 3 to 7. Most of the respondents were maintenance supervisors from TxDOT district 14 while a couple of responses were also received from the engineers at the TxDOT maintenance section in Austin.

A user-friendly computer spreadsheet was developed to analyze the data of this needs assessment survey. This spreadsheet was linked with the spreadsheets developed earlier for determining the relative weights of different concerns, and it automatically analyzed all the input data to report the final overall concern rating (OCR) numbers for each of the twenty-five maintenance activities. The analysis performed by the spreadsheet included computation of an average rating number for each of the concerns, multiplication of these average rating numbers by their relative weights in the overall rating to determine the final OCR for each maintenance activity, and reporting of the results in detailed and summarized formats. The results reported by the spreadsheet in the summarized format are shown in table 5.3 whereas detailed results are given in table A.1 in appendix A. Based on this survey, the maintenance activities were ranked for their qualitative feasibility for automation as discussed previously in section 4.2.2. This qualitative concern ranking is shown in table 5.4.

TABLE 5.3 SUMMARY OF NEEDS ASSESSMENT SURVEY

CONCERNS	RELATIVE WEIGHT %	Base Remov./Replac.(110)	Level. w/Laydwn. Mach.(211)	Leveling w/Maintainer(212)	Sealing Cracks/Joints(220)	Aggregate Seal Coat(231)	Strip or Spot Seal(232)	Potholes Repairs(240)	Side Road Appr./Cros.(470)	Mowing(511)	Litter Removal(521)	Street Sweeping(522)	Picnic Area Mnt.(531)	Rest Area Mnt.(532)	Reshp. Ditches/Slopes(560)	Ditch Maintenance(561)	Culvert Mnt.(570)	Misc. Roadside Mnt.(592)	Driveway Mnt.(594)	Paint/Bead Striping(711)	Guard Fences(722)	Install/Reinstall Signs(732)	Misc. Sign Mnt.(734)	Signal Maintenance(741)	Illumination(742)	Assistance to Traffic(810)
Number of Responses		6	6	6	7	6	7	7	6	6	6	5	5	5	6	5	5	5	5	5	4	4	4	3	3	4
1. Productivity & Other (PRD)	**16.2% of OCR**																									
01. Highly labor intensive area	19.3% of PRD	7.0	5.8	7.2	10.0	8.2	9.1	9.1	5.0	4.6	6.7	1.7	5.0	7.8	2.8	3.2	6.5	5.4	5.4	5.5	10.0	10.0	6.8	9.2	9.2	6.0
02. Low income level of work crew/operators	9.4% of PRD	6.3	5.8	6.6	7.5	6.1	7.5	10.0	6.8	8.2	7.3	2.9	8.6	6.7	3.4	3.9	5.0	5.0	5.0	2.5	6.5	7.3	7.3	0.8	0.8	6.5
03. Significant materials wastage	16.5% of PRD	2.7	1.5	0.6	5.0	5.7	5.6	2.9	1.1	0.0	0.0	0.0	0.0	3.3	1.9	0.0	0.0	0.0	0.4	4.5	0.0	0.0	1.4	1.7	0.0	2.0
04. More productivity required (large work demand)	15.7% of PRD	8.3	6.9	8.1	8.3	7.5	6.6	4.7	3.2	7.1	8.0	8.8	4.1	1.7	7.5	6.8	5.8	5.8	5.8	7.5	5.0	3.6	3.6	4.2	4.2	2.0
05. Work involves repetitive/cyclic tasks	13.2% of PRD	5.3	5.4	7.2	7.2	6.8	6.6	6.2	7.9	7.9	8.0	7.5	8.2	7.8	6.9	6.8	9.2	8.1	9.6	8.5	6.5	7.3	7.3	4.2	4.2	5.5
06. Work involves time consuming tasks	14.8% of PRD	8.0	6.9	8.1	9.2	9.3	8.8	9.4	7.5	7.5	7.7	9.6	5.5	5.0	7.5	6.1	8.5	6.2	9.2	7.5	9.5	10.0	10.0	6.7	6.7	7.5
07. Work involves environment-dependent tasks	11.1% of PRD	8.3	8.8	8.4	9.2	9.3	10.0	7.6	6.1	4.3	3.3	8.8	4.1	2.8	7.5	6.1	5.4	6.5	5.0	5.5	3.0	0.0	1.4	0.0	0.0	5.0
Rating Number for PRD	OK*	**6.5**	**5.7**	**6.5**	**8.1**	**7.6**	**7.7**	**7.0**	**5.1**	**5.4**	**5.8**	**5.3**	**4.8**	**5.0**	**5.2**	**4.5**	**5.7**	**5.1**	**5.7**	**6.1**	**5.9**	**5.6**	**5.4**	**4.3**	**4.0**	**4.8**
2. Quality (QLT)	**16.3% of OCR**																									
01. Consistency in work required	36.3% of QLT	10.0	10.0	10.0	9.2	10.0	9.4	9.4	10.0	7.5	6.0	8.3	8.2	8.3	9.4	9.3	7.3	3.8	9.2	9.5	8.0	8.6	8.6	9.2	9.2	4.5
02. Accuracy in work required	37.1% of QLT	9.0	8.8	9.4	8.1	9.3	9.4	6.8	8.2	4.6	4.3	6.7	5.5	5.0	9.4	9.3	6.2	6.2	7.9	9.5	8.0	8.6	8.6	9.2	9.2	8.5
03. Other qual. concerns (aesthetics, visual, etc.) also imp.	26.6% of QLT	4.0	6.2	5.6	4.4	8.9	7.5	4.1	6.1	8.2	6.3	9.6	7.7	7.8	8.4	8.2	6.2	7.3	6.3	10.0	8.0	7.3	7.3	4.2	4.2	6.0
Rating Number for QLT	OK*	**8.0**	**8.5**	**8.6**	**7.5**	**9.4**	**8.9**	**7.0**	**8.3**	**6.6**	**5.5**	**8.0**	**7.0**	**6.9**	**9.1**	**9.0**	**6.6**	**5.6**	**7.9**	**9.6**	**8.0**	**8.3**	**8.3**	**7.8**	**7.8**	**6.4**
3. Safety (SAF)	**20.9% of OCR**																									
01. Work physically dangerous to the work crew	27.5% of SAF	7.2	8.1	7.5	7.9	8.8	9.0	10.0	6.9	6.3	5.5	4.2	1.0	1.0	7.5	5.0	4.3	5.0	5.8	8.8	6.3	7.5	7.5	10.0	8.8	10.0
02. Work hazardous to the health of the work crew	26.4% of SAF	4.4	3.8	5.0	4.6	7.5	5.0	6.8	0.6	2.5	3.0	1.7	1.0	1.0	4.0	1.9	2.9	3.6	1.7	5.6	2.5	5.0	5.0	2.5	1.3	4.0
03. Work physically dangerous to the road users	25.6% of SAF	7.2	6.9	7.5	5.4	8.8	5.0	9.1	6.9	4.4	1.0	7.5	0.0	0.0	6.5	5.0	2.9	5.0	5.8	8.8	6.3	5.0	5.0	2.5	1.3	10.0
04. Work hazardous to the health of the road users	20.6% of SAF	2.2	2.5	2.0	0.0	5.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0
Rating Number for SAF	OK*	**5.5**	**5.5**	**5.7**	**4.8**	**7.6**	**6.1**	**6.9**	**3.8**	**3.5**	**2.6**	**3.5**	**0.5**	**0.5**	**4.8**	**3.1**	**2.7**	**4.0**	**3.5**	**6.5**	**4.0**	**4.7**	**4.7**	**4.0**	**3.1**	**6.4**
4. Socio-Political (S/P)	**8.3% of OCR**																									
01. Workers' not expected to resist to automation	43.5% of S/P	8.3	5.4	5.0	5.0	4.6	4.7	4.4	4.6	3.9	5.3	5.0	5.5	4.4	5.6	5.7	6.2	5.0	5.4	7.0	7.5	5.9	5.9	4.2	4.2	7.0
02. Workers' motivation to change expected (same workers can be used with additional training/increased salary, etc.)	56.5% of S/P	6.0	4.6	5.3	8.6	6.4	6.3	5.9	6.4	5.7	4.7	6.3	4.5	5.0	6.9	7.1	5.8	6.9	6.7	4.0	5.5	5.9	5.9	5.8	5.8	6.0
Rating Number for S/P	OK*	**7.0**	**4.9**	**5.2**	**7.0**	**5.7**	**5.6**	**5.2**	**5.7**	**4.9**	**5.0**	**5.7**	**4.9**	**4.8**	**6.3**	**6.5**	**5.9**	**6.1**	**6.1**	**5.3**	**6.4**	**5.9**	**5.9**	**5.1**	**5.1**	**6.4**
5. Technology Feasibility (TEC)	**12.4% of OCR**																									
01. Existing Automation R&D in this maintenance area	50.6% of TEC	5.0	5.0	5.0	10.0	5.0	5.0	10.0	0.0	5.0	10.0	0.0	0.0	0.0	5.0	5.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	10.0
02. Automated systems commercially available	49.4% of TEC	5.0	5.0	5.0	5.0	5.0	5.0	10.0	0.0	5.0	5.0	0.0	0.0	0.0	5.0	5.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	10.0
Rating Number for TEC	OK*	**5.0**	**5.0**	**5.0**	**7.5**	**5.0**	**5.0**	**10.0**	**0.0**	**5.0**	**7.5**	**0.0**	**0.0**	**0.0**	**5.0**	**5.0**	**0.0**	**0.0**	**0.0**	**7.5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**10.0**
6. Working Environment (WOR)	**13.6% of OCR**																									
01. Noisy conditions in the work area	16.0% of WOR	8.7	9.2	9.4	8.6	8.6	8.1	4.7	8.6	8.9	2.7	5.8	0.0	0.0	8.4	9.3	8.1	4.6	7.9	8.5	6.5	4.1	4.1	3.3	3.3	5.5
02. Vibrations in the work area	12.1% of WOR	5.3	6.2	4.4	1.7	3.2	3.1	2.6	1.8	7.1	0.0	4.6	0.0	0.0	4.1	1.1	2.3	0.0	1.3	3.5	0.0	0.0	0.0	0.0	0.0	1.0
03. Dirty conditions in the work area	14.7% of WOR	9.3	9.2	8.8	7.2	9.3	9.4	7.9	10.0	9.3	8.3	5.8	8.2	7.8	9.4	9.3	8.1	6.2	7.5	4.5	6.5	3.6	2.7	0.8	2.5	6.0
04. Work involve heavy/high lifts	21.4% of WOR	0.7	2.7	0.9	3.9	2.1	1.6	5.0	1.1	0.0	5.7	0.0	5.9	3.3	0.6	1.1	4.6	3.5	3.8	5.5	10.0	8.6	5.9	3.3	3.3	6.5
05. Meticulous work (great detail/carefulness required)	18.0% of WOR	5.3	5.8	7.8	7.5	8.9	7.5	4.7	7.9	3.6	1.0	4.2	5.9	4.4	5.6	5.4	4.2	1.9	5.4	9.5	8.0	8.6	7.3	9.2	8.3	5.0
06. Exhaustive work	17.9% of WOR	3.7	8.5	6.9	7.8	6.1	5.9	7.1	5.4	5.7	7.0	3.8	4.5	3.3	4.4	4.3	6.2	4.2	5.4	4.0	8.5	7.3	5.9	5.0	5.0	7.5
Rating Number for WOR	OK*	**5.2**	**6.7**	**6.1**	**6.2**	**6.3**	**5.8**	**5.4**	**5.7**	**5.3**	**4.3**	**3.8**	**4.3**	**3.3**	**5.1**	**4.9**	**5.6**	**3.5**	**5.3**	**6.0**	**7.1**	**5.9**	**4.7**	**3.9**	**4.0**	**5.5**
7. User-Costs & Emissions (U/E)	**12.2% of OCR**																									
Higher user-costs and emissions due to the following: 01. Road closures required	27.8% of U/E	7.3	7.3	6.3	7.8	6.4	7.2	5.0	2.5	0.0	0.0	2.5	0.0	0.0	3.1	1.8	1.5	2.7	2.5	4.5	3.5	1.4	1.4	2.5	2.5	10.0
02. Long closure times required for setup & removal	37.9% of U/E	7.7	5.8	6.6	7.5	6.1	6.6	2.6	1.8	0.0	0.0	1.3	0.0	0.0	2.5	1.1	0.8	1.9	1.7	1.5	3.5	1.4	0.0	2.5	2.5	9.0
03. Night time operations are not performed	34.3% of U/E	2.7	8.5	10.0	9.4	9.3	8.1	7.9	10.0	8.6	10.0	5.0	9.1	3.9	8.8	10.0	10.0	8.8	10.0	2.0	10.0	10.0	8.6	3.3	5.0	3.0
Rating Number for U/E	OK*	**5.9**	**7.1**	**7.7**	**8.2**	**7.3**	**7.3**	**5.1**	**4.8**	**2.9**	**3.4**	**2.9**	**3.1**	**1.3**	**4.8**	**4.3**	**4.2**	**4.5**	**4.8**	**2.5**	**5.7**	**4.3**	**3.3**	**2.8**	**3.4**	**7.2**
OVERALL CONCERN RATING (OCR)	OK*	**6.1**	**6.3**	**6.5**	**6.9**	**7.2**	**6.7**	**6.8**	**4.8**	**4.8**	**4.7**	**4.3**	**3.4**	**3.1**	**5.8**	**5.2**	**4.3**	**4.1**	**4.8**	**6.4**	**5.3**	**5.1**	**4.7**	**4.1**	**4.0**	**6.6**

** Automatic check for ensuring SUM(Relative Weight Percentages)=100%*

TABLE 5.4 CONCERN RANKING OF THE MAINTENANCE ACTIVITIES

Code	Maintenance Activity	OCR
231	Aggregate Seal coat	7.2
220*	Sealing cracks & joints	6.9
240	Pothole Repairs	6.8
232	Strip or spot seal	6.7
810	Assistance to Traffic	6.6
212	Leveling or overlay with maintainer, drag-box, etc.	6.5
711	Paint & Bead Striping	6.4
211	Leveling or overlay with laydown machine	6.3
110	Base and sub-grade removal & replacement	6.1
560	Reshaping Ditches & slopes	5.8
722	Guard Fences	5.3
561	Ditch Maintenance	5.2
732	Install or Re-install Signs	5.1
470	Side Road Approaches & Crossovers	4.8
511	Mowing	4.8
594	Driveway Maintenance	4.8
734	Misc. Sign Maintenance	4.7
521	Litter Removal	4.7
570	Culvert & Storm Maintenance	4.3
522	Street Sweeping	4.3
741	Signal maintenance	4.1
592	Misc. Roadside Maintenance	4.1
742	Illumination	4.0
531	Picnic Area Maintenance	3.4
532	Rest Area Maintenance	3.1

5.3 Overall Ranking of TxDOT maintenance activities

Based on the cost and concern data, from the previous two sections, each of the maintenance activity was plotted on the cost-concern matrix as shown in figure 5.1. As can be seen from this figure, only 13 of the 25 activities surveyed exhibited a need for automation; and most of these activities (seven out of the thirteen) are related to pavements' maintenance, four are roadside maintenance activities, and two are traffic related. In chapter 6, the availability of automated systems for these 13 activities is discussed. Feasibility can be analyzed based on the availability and estimated technology performance.

One limitation of this study is that it was performed for determining the need for

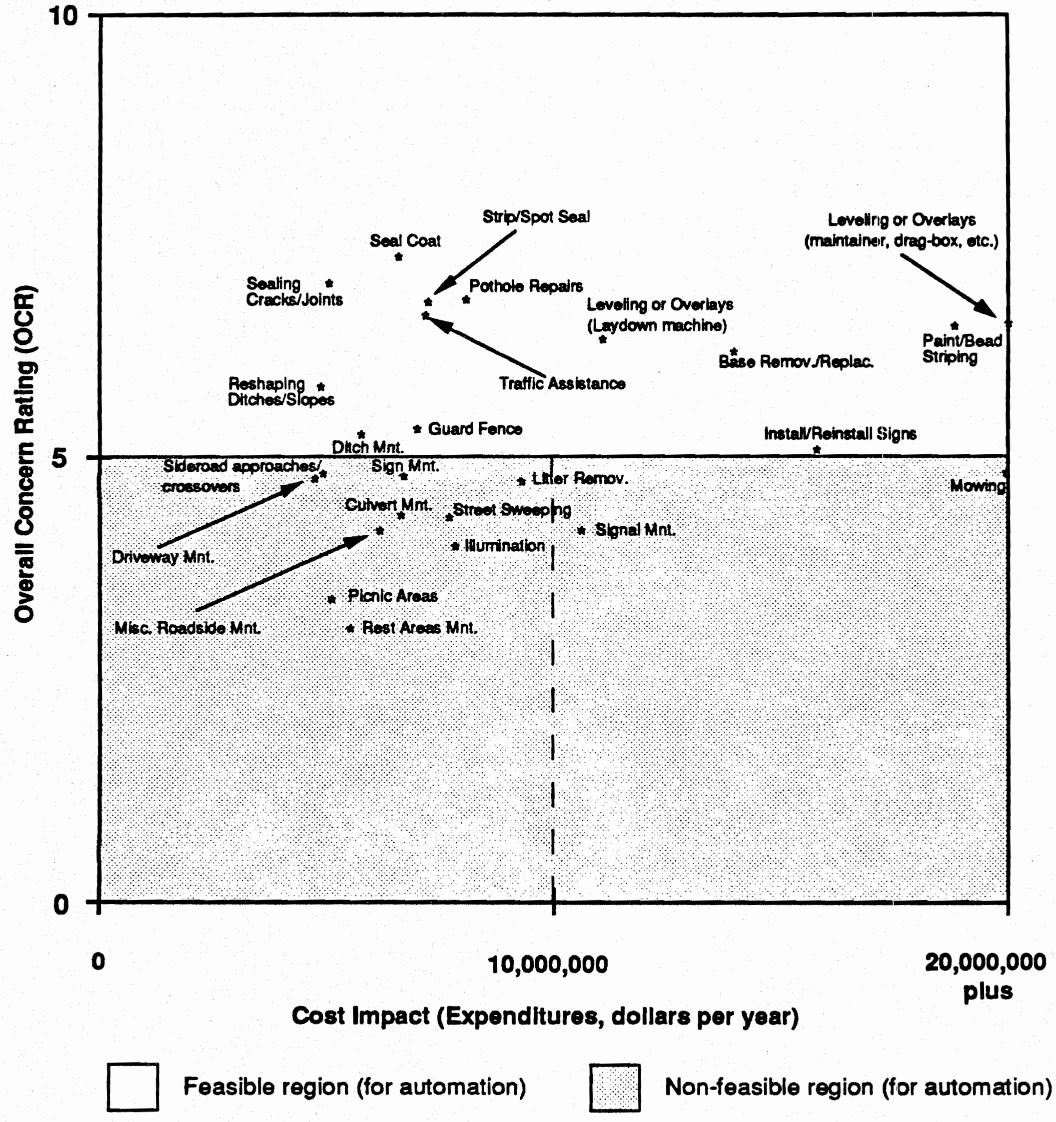


Figure 5.1 Needs Assessment Ranking of TxDOT Maintenance Activities

automation for each of the TxDOT major activities based on the cost and concern factors . But, there will be some tasks in each maintenance activity which may not be technically feasible. To determine which of the tasks in these high priority maintenance activities are technologically feasible, a separate detailed technology feasibility study is required. This technology feasibility factor was not totally ignored in the needs assessment survey as one of the concern areas in the survey dealt with this subject. However, this was a broad-based needs assessment study to identify the major maintenance activities which should be given the priority in future research .

CHAPTER 6. EVALUATION OF AUTOMATED ROAD MAINTENANCE (ARM) SYSTEMS

In this chapter, detailed evaluation of an automated system is performed, for one of the maintenance areas, to demonstrate how the ARME model can be used to evaluate automated systems. The first section of this chapter gives an inventory of ARM systems currently available, including both prototype and commercial systems (section 6.1). In the second section of this chapter, the implementation of an automated crack sealer in the state of Texas is evaluated, and this evaluation procedure in documented in detailed steps (section 6.2).

6.1 STATUS REPORT OF ARM SYSTEMS

In the first phase of this research project, several ARM systems were identified. This effort was continued in this second phase, and several new ARM systems were identified through literature searches. An inventory of these systems is presented in Table 6.1. Besides the identification of the systems and the manufacturers or developers, the maintenance areas in which these ARM systems can be used are also given. Moreover, the current development status of the system, prototype or commercial, is also shown in the table.

As can be seen from this inventory, almost two thirds of all the ARM systems are prototype systems. Also, ARM systems for some of the feasible maintenance activities for automation, determined from the needs assessment study (chapter 5), still need to be developed. These activities include installing or re-installing signs, and maintenance of guard fences. Moreover, the ARM systems which can be used for some of the most feasible activities just automate some tasks in these activities, and hence there is a large potential for further research in this area. These feasible activities, for whom the currently available ARM systems have only automated some tasks, include base removal & replacement, maintenance of ditches, reshaping of slopes & ditches, and leveling or overlays which are currently performed with the laydown machines, maintainers, drag-boxes or similar equipment.

6.2 EVALUATION OF AN AUTOMATED CRACK SEALER (ACS) SYSTEM

The need for sealing cracked pavements will remain for as long as there are paved roads. The technologies used in crack sealing have advanced slowly. New, more effective hot poured asphaltic binders are being continuously improved and significant advances are being

TABLE 6.1 A CURRENT INVENTORY OF ARM SYSTEMS

System and Manufacturer	Maintenance Area	C[1]	P[2]
Addco Cone, Addco Manufacturing Co. MN, USA [Hsieh 1992]	Traffic Control	x	
Quickchange Movable Barrier System, US Barrier Systems, Inc., California, USA [Hsieh 1992]	Traffic Control	x	
Super Quartz II Portable Traffic Signals, Horizon Signal, Pennsylvania, USA [Hsieh 1992]	Traffic Control	x	
Remote Controlled "Follower", Minnesota Department of Transportation, Minnesota, USA [Hsieh 1992]	Traffic Control		x
Dynapac Pavement Patcher, Dynapac Light Equipment, New Jersey, USA [Hsieh 1992]	Pothole Repairs	x	
SHRP Thermo-Patch Pothole Patcher, Northwestern U. & U. of California-Davis, USA [Hsieh 1992]	Pothole Repairs		x
"Puff" the Pothole Patcher, One Man Inc., New Mexico, USA [Hsieh 1992]	Pothole Repairs	x	
Automatic Crack-Filling Robot, Carnegie-Mellon U. and U. of Texas at Austin, USA [Hsieh 1992]	Sealing Cracks & Joints		x
SHRP Automated Crack/Joint Sealing Machine, Caltrans & U. of California-Davis, USA [SHRP 1993]	Sealing Cracks & Joints		x
Robot Asphalt Paver, Nippon Hodo Co. & Others, Japan [Goto 1990 and Umeda 1993]	Overlays, Base Removal/Repl.		x
Automatic Snowplow, Nichijo Manufacturing Co., Japan [Fakuda 1992]	Snowplow		x
Automatic Line Painting System, Ministry of Transportation of Ontario, Canada [Hsieh 1992]	Paint Stripe		x
Automated Paint Striping System, Caltrans & U. of California-Davis, USA [UC-Davis 1993]	Paint Stripe		x
Automated Raised Marker Placement System, Caltrans & U. of California-Davis, USA [UC-Davis 1993]	Pavement Markers		x
Multipurpose Traveling Vehicle, Societe Nicholas of France [Skibniewski 1990]	Mowing, etc.		x
Regional Irrigation Management System, Caltrans & U. of California-Davis, USA [UC-Davis 1993]	Irrigation		x
Automated Litter Removal Machine, Caltrans & U. of California-Davis, USA [UC-Davis 1993]	Litter Removal		x
Autonomous Dump Truck System, Technical Research Ins., U. of Tsukuba & Tokyo Aircraft Ins. Co., Japan [Sugiura 1993]	Earthwork (Base Remov./Repl., etc.)		x
Macropaver w/ Automated controller & monitor, Valley Slurry Seal Company, California, USA [Valley 1992]	Fog/Slurry Seal Microsurfacing	x	
Blade-Pro Motorgrader Control System, Spectra-Physics Laserplane Inc., Dayton, Ohio, USA [Spectra 1992]	Base Removal/ Replacement, Ditch Maintenance, etc.	x	
Integrated Surface Patcher (ISP), Seemar Company, France [Skibniewski 1990]	Surface Sealing		x
SHRP Robot Shadow Vehicle, ENSCO, Inc., USA [SHRP 1993]	Traffic Control		x

[1] C = Commercial System [2] P = Prototype System in R&D Phase

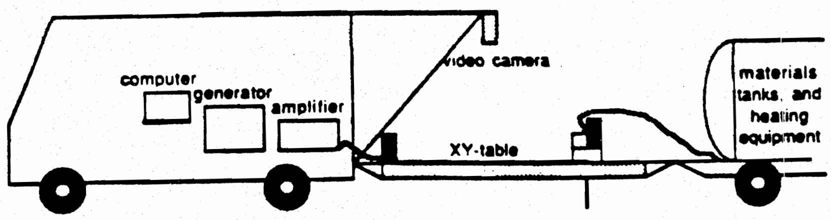
made in cold poured materials. The application techniques, however, have remained much the same over the last 15 years. Crack sealing crews are typically composed of 7 personnel, 3-4 of which are involved in identifying, cleaning, or sealing cracks [McNeil 1992]. A prototype automated system that will drastically reduce these labor requirement is evaluated from TxDOT, private contractors', and road-users' perspectives in this study.

Crack sealing operations are a significant component of a typical road maintenance budget. It is estimated that approximately $188 million per year are spent on crack sealing by all the public agencies in the United States excluding expenditures by private organizations, airports and the military [Hsieh 1992]. The TxDOT spends approximately 7 million dollars every year on crack sealing which is approximately 1.5% of their total routine maintenance budget [TxDOT 1993C]. The most significant fact concerning these expenditures is the percentage that is spent on labor which ranges from 40 to 60% of the total as discussed in detail later in this chapter. Through automation, these labor expenditures can be reduced drastically.

There are many motivators for developing an automated crack sealing (ACS) system. In addition to the quantifiable categories of labor-costs and user-costs savings, the system can have positive impacts in the areas of worker safety, job quality, and working environment. The most important of these concerns is safety, and the best way to improve worker safety in a highway environment is to remove the worker from danger. A survey of public agencies throughout the United States and Canada show that there were 3681 injury accidents related to road maintenance activities in 1991 [Deng 1992]. An ACS system that minimizes the requirement for on-road labor will certainly reduce these statistics significantly if implemented nationwide.

6.2.1 Description of ACS System

Current crack sealing operations are generally performed by using an equipment train setup. A lead vehicle such as a pickup truck tows the sealant tank and carries the worker tools. The automated system would utilize a similar setup, adding an X-Y table to the equipment train. The X-Y table is a welded steel frame structure which is drawn on 4 rubber tired double wheels. The drive system is comprised of rack and pinion transmissions for the gantry and cart driven by two stationary servo-motors. Each motor is powered by a single axis motor controller box [Haas 1992]. Figure 6.1 shows a schematic of an early version of the system.



A Schematic Illustration of the Crack Sealing Robot System

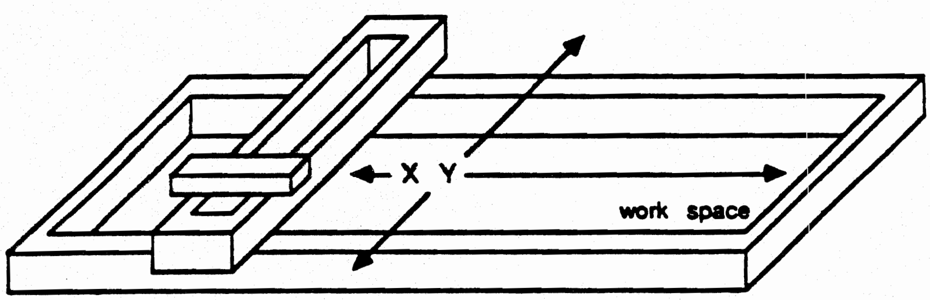


Table Conceptual Design

Figure 6.1 Prototype Design of Automated Crack Sealer (Acs) System

The concept has been modified slightly so that instead of the computer selecting and filling/sealing the crack automatically, now the operator will select the cracks to be filled by watching them on a monitor. By tracing over cracks with a light pen, the driver can identify the work to be carried out by the XY table manipulator. The controller software translates the traced images into commands for cleaning and sealing the cracks. A roving supervisor could monitor the work for quality control purposes. The follower vehicle would be required to provide a safe environment for the roving supervisor. This vehicle could also be equipped with backup systems and additional sealant to allow uninterrupted work. Hence, the sealing crew will consist of three people: a driver/operator, a supervisor, and a follower vehicle driver. This modification in the concept was required as the image-analysis time of the computer to select actual cracks on the road is unpractical as compared to a human response.

All the components required in the ACS system are shown in table 6.2 with prices and specifications. These components can either be mounted in the bed of the pickup truck or on the X-Y table frame.

6.2.2 Economic Analysis

Although the study area for this evaluation is the state of Texas, the implications of automated crack sealing have nation-wide applications. Figure 6.2 shows that most crack sealing in the United States is performed by in-house maintenance crews. Some states utilize contract work to supplement their capabilities.

The automation needs assessment survey for the TxDOT maintenance activities has shown that crack sealing is a very desirable candidate for automation (chapter 5). Automated crack sealing operations throughout the state would require approximately 26 units based upon current expenditures. Of these 26 units, 10 would be required by the TxDOT and the other units would be required by the private contractors working for TxDOT. This estimate is based upon current contracting trends as discussed in detail later in this section.

The costs of the ACS system can be divided into four major categories: initial (discussed in detail in section 6.2.1), maintenance, operational, and overheads. The savings of the ACS system can be divided into two major groups: direct maintenance cost savings and user-cost savings. The direct maintenance cost savings can result from labor reduction, improved productivity, and reduced material wastage. The user-cost savings mostly result from reduction in

TABLE 6.2 COST BREAKDOWN OF THE AUTOMATED CRACK SEALER

Components	Estimated Price	Manufacturer/ Supplier	Product / Specifications / Contact	Phone #
X-Y Table	$30,000	C&D Robotics	12' x 5' (c/o Jimmy Fitzpatrick)	(409) 832-4991
Video Camera (2 @ $2000)	$ 4,000	N/A	Specifications not yet determined	N/A
Video Frame Grabber (2 @ $2000)	$ 4,000	Rapier	Rapier XTV with Rapier 24; 24 bit true color video at 1152 x 882 resolution	(800) 578-5644
Image Processing Software	$ 2,000	In-house development work at UT	Unavailable	N/A
Power Generator	$ 1,200	Grainger, Inc.	See Appendix	(512) 837-7440
UPS	$ 4,300	General Signal, Inc.	See Appendix	
Air Compressor	$ 400	Grainger, Inc.	See Appendix	(512) 837-7440
PC with Intel 486/66mhz processor	$ 2,500	Gateway 2000	16mb RAM, 424mb Hard Drive, local bus, graphics accelerator card with 2mb RAM, mouse, 124 key keyboard, etc.	(800) 846-2024
PC-17" Monitor	$ 1,000	Midwest Micro	MAG 17" monitor with 1280x1024 resolution, .26 dot pitch, Horiz scan 30/68 kHz	(800) 972-8822
Total Component Costs	$49,400			
Miscellaneous Costs*	$ 600			
Assembly Labor	$20,000			
Total**	**$70,000**			

* The miscellaneous costs account for variations in the estimated costs of the video cameras, image processing software and other components.

** The system above does not include the costs of a sealant tank, as this is inherent to any crack sealing operation.

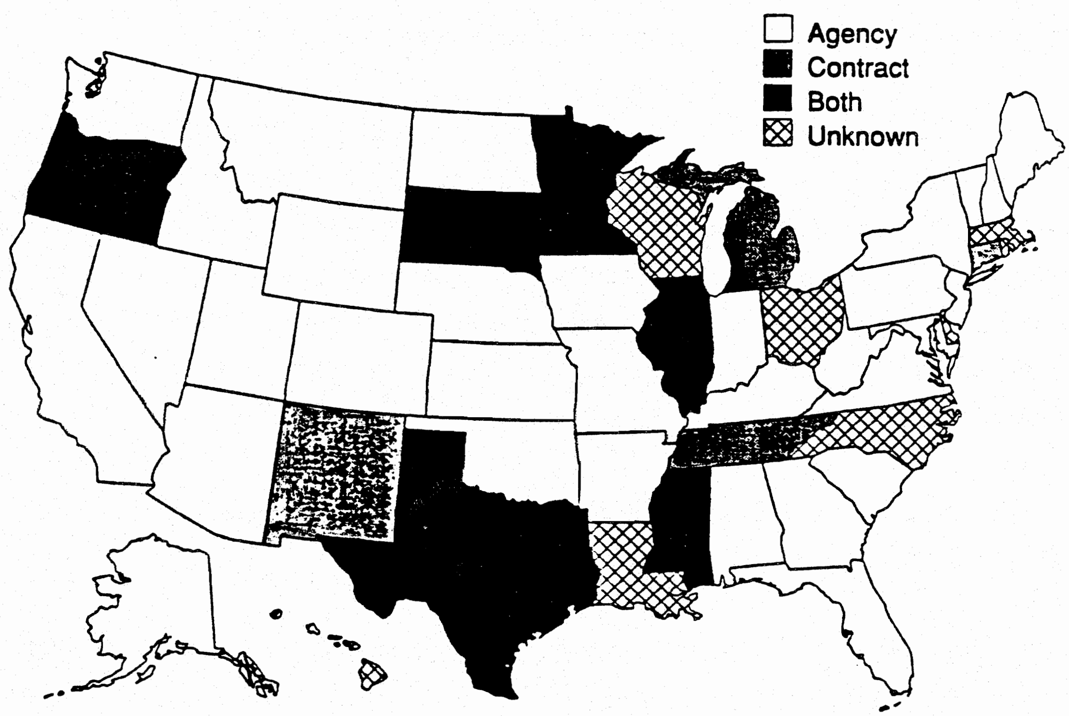


Figure 6.2 Crack sealing practices in the United States

lane closure times due to expedited operation of the ACS system. Besides the costs and savings of the ACS system, other economic factors to be considered in the life cycle analysis are the cost impact (expenditures per year), the unit costs for current practices and the division of current maintenance expenditures into labor, material, equipment (rentals), overheads, etc.

For the life cycle economic analysis, the computer spreadsheet from the ARME model was used. The economic analysis performed by the spreadsheet includes the estimation of both the direct (TxDOT or private contractors) and indirect (users) cost savings. The input data included the costs of the ACS system, number of typical crew members to be reduced by the ACS system, and the TxDOT or private contractors' expenditure data. The spreadsheet then automatically converted all these costs and savings into net present worth (NPW) values to compute the life cycle savings (or extra expenditures) of the ACS system, from the TxDOT or private contractors' perspective. Three different minimum attractive rate of return (MARR) scenarios for the both the TxDOT and the private contractors were tested.

After the computation of the direct maintenance cost savings for the life cycle of the ACS system, a case study on a 20 mile long Interstate 35 section was also performed to determine the user-cost savings. The user-costs are estimated at the project level as they can vary significantly from the maintenance operations performed on a busy urban expressway to a low volume rural farm-to-market road. Hence, an economically unfeasible ACS system from TxDOT or private contractors' perspective can be very feasible from users' perspective if used on a urban expressway because of the high user-cost savings.

All the economic analysis parameters of the ACS system are discussed in detail as following:

<u>Costs & working life of the ACS system:</u> The initial cost of the system is estimated to be $70,000 as shown in table 6.2. Other annual costs of the system are operating costs ($4,500), maintenance costs ($3,000), and overheads ($3,750). The working life of the system is expected to be six years [McNeil 1992B].

<u>Units of Measurement:</u> The unit of measurement used, by the different districts of TxDOT, for crack sealing vary from pounds (lbs.) and gallons to square yards, linear foot, or lane-miles. However, all the districts are required to convert this data in either pounds (for asphaltic

rubber materials) or gallons (for all other materials) when reporting this data to the maintenance division in Austin. This data is recorded and maintained under code 221 (asphaltic rubber materials, in pounds) or code 222 (all other materials, in gallons) by the maintenance division. All crack sealing done using asphaltic rubber materials (code 221) is hot poured while most crack sealing done using other materials (code 222) is cold poured. As the productivity rates for both these methods are different, besides the change in equipment requirements, the economic analysis performed is divided into either hot pour or cold pour crack sealing throughout this report. Hence, hot pouring refer to code 221 and is reported in pounds (lbs.) whereas cold pouring refer to code 222 and is reported in gallons.

The crack sealing operations can be further divided into two major categories: in-house work by TxDOT and contracted work. The TxDOT maintenance division also keep track of both the in-house and contracted expenditures and the unit-costs. Hence, for this analysis, the crack sealing operations in Texas were divided into the following four categories:

- In-house crack sealing using hot pouring,
- Contracted crack sealing using hot pouring,
- In-house crack sealing using cold pouring, and
- Contracted crack sealing using cold pouring.

TxDOT annual expenditures on crack sealing: The annual expenditure data, from the TxDOT maintenance division in Austin, was only available for the first nine months of 1993 when this evaluation study was performed. Also, this is the first year that TxDOT is tracking detailed cost data on crack sealing. The total expenditures on crack sealing are estimated to be $7 million in 1993, and the expenditure trend from the first nine-months of 1993 was used to estimate the annual expenditures for the whole year as shown in table 6.3 [TxDOT 1993B and 1993C].

Unit-Costs and Unit-work performed in Texas: The unit-costs for both hot pour and cold pour crack sealing (for both in-house and contracted work) were available from TxDOT and shown in tables 2.6 and 2.7 in chapter 2. These unit-costs were used with the expenditure data to determine the annual work performed in pounds or gallons. However, to see the relativity between these two units of work, both of these were also converted into lane-miles by utilizing the results of an earlier research study conducted by TxDOT [Malek 1993]. The basic findings of this study were that approximately 800 lbs. of hot pour materials (Crafco Road Saver #523) or 55 gallons of cold pour materials (Kengo) are required to seal a typical lane-mile of a road section.

TABLE 6.3 TXDOT ANNUAL EXPENDITURES ON CRACK SEALING

Crack Sealing Category	Expenditure trend from the first nine months of 1993	Estimated Annual expenditures in 1993
In-house expenditures (hot pour)	24.08%	$1,685,600
Contracted expenditures (hot pour)	61.72%	$4,320,400
In-house expenditures (cold pour)	9.84%	$688,800
Contracted expenditures (cold pour)	4.36%	$305,200
Total	**100.00%**	**$7,000,000**

Also, the productivity rates were 2 lane-miles/day (or 1600 lbs./day) for hot pour crack sealing and 3 lane-miles/day (or 1600 lbs./day) for cold pour crack sealing.

These unit-costs and annual units of work for Texas are given below:

In-house hot pour crack sealing:

Unit-costs = $0.73/lbs.

$$\text{Annual unit-work performed} = \frac{(\$1,685,600)}{(\$0.73/\text{lbs.})} = 2,309,041 \text{ lbs.}$$

$$\text{Annual unit-work performed} = \frac{(2,309,041 \text{ lbs.})}{(800 \text{ lbs./lane-mile})} = 2886 \text{ lane-miles}$$

Contracted hot pour crack sealing:

Unit-costs = $0.70/lbs.

$$\text{Annual unit-work performed} = \frac{(\$4,320,400)}{(\$0.70/\text{lbs.})} = 6,172,000 \text{ lbs.}$$

$$\text{Annual unit-work performed} = \frac{(6,172,000 \text{ lbs.})}{(800 \text{ lbs./lane-mile})} = 7715 \text{ lane-miles}$$

In-house cold pour crack sealing:

Unit-costs = $4.76/gallons

$$\text{Annual unit-work performed} = \frac{(\$688,800)}{(\$4.76/\text{gallons})} = 144,706 \text{ gallons}$$

$$\text{Annual unit-work performed} = \frac{(144,706 \text{ gal.})}{(55 \text{ gal./lane-mile})} = 2631 \text{ lane-miles}$$

Contracted cold pour crack sealing:

Unit-costs = $8.40/gallons

Annual unit-work performed, gallons = $\frac{(\$305,200)}{(\$8.40/\text{gallons})}$ = 36,333 gallons, or

Annual unit-work performed = $\frac{(36,333 \text{ gal.})}{(55 \text{ gal./lane-mile})}$ = 661 lane-miles

Percentage of Labor: The percentage of expenditures spent on labor were also computed using the statewide summary report of TxDOT expenditures [TxDOT 1993C]. These percentages are only for the in-house work but due to the absence of any data from private contractors, these were also used for the private contractor scenarios in the economic analysis. The data from TxDOT divides the total expenditures into labor, equipment, material, overheads, and contract; and the percentage of labor expenditures were computed as following:

$$\% \text{ expenditures on labor} = \frac{\text{labor expenditures} + 50\% \text{ overheads}}{\text{total expenditures - contract expenditures}}$$

Based on the above formula and the data available from the TxDOT for the first nine months of 1993, the following labor expenditure percentages were obtained:

$$\% \text{ expenditures on labor, in-house hot pouring} = \frac{(\$830,528 + 50\% \times \$1,703,777)}{(\$5,657,247 - \$2,010,818)} = 46.14\%$$

$$\% \text{ expenditures on labor, in-house cold pouring} = \frac{(\$333,052 + 50\% \times \$242,580)}{(\$970,504 - \$221,970)} = 60.70\%$$

Working capacity of ACS Systems: To estimate the working capacity of the ACS system, first the current productivity rate for the hot pouring and cold pouring cases was determined for a typical crew. It was assumed for this study that the productivity rates for both the in-house and contracted work are not significantly different. The current annual productivity rates in pounds or gallons were determined using the results of the TxDOT research study, discussed before, as following:

Productivity rate, hot pour crack sealing (both in-house & contracted)

$$\frac{2 \text{ lane-miles}}{\text{day}} \times \frac{800 \text{ lbs.}}{\text{lane-mile}} \times \frac{250 \text{ workdays}}{\text{year}} = \frac{(400,000 \text{ lbs.})}{\text{year}}$$

Productivity rate, cold pour crack sealing (both in-house & contracted)

$$\frac{\text{3 lane-miles}}{\text{day}} \times \frac{\text{55 gallons}}{\text{lane-mile}} \times \frac{\text{250 workdays}}{\text{year}} = \frac{\text{(41,250 gallons)}}{\text{year}}$$

It is estimated that an ACS system can enhance the current productivity by 20% due to faster effective operating speed and reduced setup/removal times between widely spaced cracks on long road sections. Also, a 90% efficiency rate was used to account for the unexpected breakdowns for 10% of the time. Hence, the rated capacity of the automated crack sealer was estimated as following:

ACS productivity rate, hot pour crack sealing (both in-house & contracted)

$$\frac{\text{(400,000 lbs.)}}{\text{year}} \times 1.20 \times 0.90 = \frac{\text{(432,000 lbs.)}}{\text{year}}$$

ACS productivity rate, cold pour crack sealing (both in-house & contracted)

$$\frac{\text{(41,250 gallons)}}{\text{year}} \times 1.20 \times 0.90 = \frac{\text{(44,450 gallons)}}{\text{year}}$$

Number of Automated Crack Sealers required for Texas: The total number of ACS systems required for Texas were determined for the four basic cases as following:

ACS systems required for in-house work with hot pour materials

$$\frac{\text{(2,309,041 lbs.)}}{\text{(432,000 lbs.)}} = \text{5.3 or 6 systems}$$

ACS systems required for contracted work with hot pour materials

$$\frac{\text{(6,172,000 lbs.)}}{\text{(432,000 lbs.)}} = \text{14.3 or 15 systems}$$

ACS systems required for in-house work with cold pour materials

$$\frac{\text{(144,706 gallons)}}{\text{(44,550 gallons)}} = \text{3.2 or 4 systems}$$

ACS systems required for contracted work with cold pour materials

$$\frac{\text{(36,333 gallons)}}{\text{(44,550 gallons)}} = 0.8 \text{ or } 1 \text{ systems}$$

Total number of ACS systems required for Texas = 24 to 26 systems

Sensitivity Analysis : The following Minimum Attractive Rate of Return (MARR) scenarios were used for the sensitivity analysis:

In-house scenarios, MARR range = 4%, 6% and 8%

Contracted scenarios, MARR range = 20%, 25% and 30%

User-Costs: Lane closures due to crack sealing work on highways reduce the capacity of the highway, and hence result in additional fuel consumption, delays, harmful emissions, and higher operating/other costs of the vehicles. For determining the user-cost savings for typical crack sealing operations, a case study was performed for the 20 mile segment of Interstate 35 between the cities of San Marcos and New Braunfels. This is a four lane segment with a consistent ADT of approximately 55,000 throughout the section length. The percentage of trucks on this segment is estimated to be 20% due to the inter-city nature of the highway.

A typical one lane closure was considered for both the conventional and automated operation. The user-costs for a conventional crack sealing operation from 8 AM to 4 PM, including an hour both in the morning and evening as setup and removal time, were found out to be $10,625 from the QUEWZ-E model. With a 20% estimated reduction in the closure time or 1 hour due to the expedited ACS operation (8 AM to 3 PM), the user-costs came out to be $8,368. To determine the number of crack sealing operations on this section, an "operation" was defined as one-lane mile of crack sealing. Using this definition, the annual number of these operations on this segment were estimated as following:

$$\frac{\text{(20 x 4 lane-miles)}}{\text{(183,550 Texas lane-miles)}} \times \frac{\text{(13,893 operations)}}{\text{year}} = \frac{\text{6 operations}}{\text{year}}$$

This data was then entered into the spreadsheet to determine the life-cycle savings from the users and TxDOT or private contractors perspectives, for this project.

Results of Economic Analysis: The detailed output of the economic analysis, from the computer spreadsheet, are given in appendix B. Figures B.1a & B.1b provides results for in-house hot pour crack sealing, figures B.2a & B.2b for contracted hot pouring, figures B.3a & B.3b for contracted hot pouring, and figures B.4a & B.4b for contracted cold pouring.

These results are summarized in table 6.4. As can be seen from the table, the ACS offer significant savings for both TxDOT and private contractors (with much higher MARR than TxDOT) for the cold pour than the hot pour crack sealing. The basic reason behind this is that the most significant savings of the ACS system are from the reduction in labor, and the cold pouring has a much higher share of labor in the total expenditures (60.70% for cold pour verses 46.14% for hot pour).

Another major finding of this research is the amount of user-cost savings which can result from the ACS system. As can be seen from the table 6.4, crack sealing by the ACS on a small segment of Interstate-35 alone (0.04% of all the crack sealing operations in Texas, 6/13,893) can result in so significant user-costs savings that even an ACS system with no direct maintenance cost savings is also feasible.

6.2.3 Qualitative Analysis

There are many intangible or qualitative benefits of the ACS system. These include improvements in concerns including safety, quality, working environment, etc. The working environment will see improvements by reducing noisy, dirty conditions and limiting meticulous, exhaustive activities. Improvements in safety are numerous especially the reduction in health hazards and the potential for physical injuries for the work crew. The improvement in project quality is also expected.

A qualitative analysis of the benefits of ACS system was also performed using the tools developed from the ARME model (section 4.3.3). The ACS system scored a high OCR number of 8.4 on a 0 to 10 scale as shown in figure 6.3. Hence, it can be safely concluded that this system is very desirable from the qualitative perspective in addition to the economic perspective.

6.2.4 Environmental/Energy Analysis

The estimated reduction in the emissions and fuel/oil consumption on the case study

TABLE 6.4 LIFE-CYCLE SAVINGS OF THE AUTOMATED CRACK SEALER (ACS) SYSTEM

	Direct Savings* (1 ACS System)	Direct Savings* (All work by ACS)	User-Cost Savings (case study)
In-house hot pour crack sealing			
(MARR = 4%)	$322,680	$1,613,399	$70,989
(MARR = 6%)	$297,803	$1,489,014	$66,590
(MARR = 8%)	$275,290	$1,376,452	$62,603
Contracted hot pour crack sealing			
(MARR = 20%)	$165,248	$2,313,476	$45,034
(MARR = 25%)	$138,259	$1,935,626	$39,968
(MARR = 30%)	$116,065	$1,624,906	$35,788
In-house cold pour crack sealing			
(MARR = 4%)	$272,392	$817,175	$70,989
(MARR = 6%)	$250,631	$751,892	$66,590
(MARR = 8%)	$230,943	$692,828	$62,603
Contracted cold pour crack sealing			
(MARR = 20%)	$331,760	$331,760	$45,034
(MARR = 25%)	$286,040	$286,040	$39,968
(MARR = 30%)	$248,390	$248,390	$35,788

* Savings to either the TxDOT or private contractors

Qualitative Analysis of Automated Crack Sealer (Univ. of Texas at Austin)				
For each of the following Concerns/Benefits, please mark your Response in either Yes, No or Intermediate columns (Don't mark in the shaded areas).				
CONCERNS/BENEFITS	**RESPONSE**			**RATING**
	Yes	**Intermediate***	**No**	
1. Technology Concerns				**7.0**
01 Commercially available system			X	0
02 Spares/Support easily available		X		5
03 Reliable Technology (System and/or Manufacturer)		X		5
04 Durable Technology (System and/or Manufacturer)		X		5
05 Low risk of failure (not unusual design/operation)		X		5
06 Skill level to operate the system is similar to that of existing work crew	X			10
07 Minimum additional training is reqd. for work crew	X			10
08 New work crew/operators easily available	X			10
09. Setup/breakdown time lower than current methods		X		5
10 Easy transportation of the system to the work site	X			10
11 User friendly system	X			10
12 Less clean-up required than current methods		X		5
13 System can perform multiple tasks	X			10
14 System can operate in most typical situations	X			10
2. Working Environment Benefits				**8.3**
01 Improvement in noisy conditions	X			10
02 Improvement in vibratory conditions		X		5
03 Improvement in dirty conditions	X			10
04 Improvement in heavy/high lift works		X		5
05 Improvement in meticulous work	X			10
06 Improvement in exhaustive work	X			10
3. Safety Benefits				**10.0**
01 Reduced potential for physical injuries (work crew)	X			10
02 Reduced potential for physical injuries (road users)	X			10
03 Reduction in health hazards (work crew)	X			10
04 Reduction in health hazards (road users)	X			10
4. Quality Benefits				**6.9**
01 Improvement in consistency	X			10
02 Improvement in accuracy	X			10
03 Improvement in other quality concerns (aesthetics, visual, etc.)			X	0
5. Socio-Political Concerns				**5.0**
01 Systems acceptable to the workers		X		5
02 Workers motivation to change expected (increased salary with additional training)		X		5
03 System's overall acceptability in the agency expected		X		5
6. Worker Utilization Concerns				**10.0**
01 Lower number of workers/operators required	X			10
02 Same work crew/operators can be used	X			10
OVERALL CONCERN RATING (OCR)			**8.2**	

* Intermediate represents conditions between yes or no. For example, sometimes, partly true, etc.

Figure 6.3 Qualitative Analysis of the Automated Crack Sealer (ACS) System

were also reported by QUEWZ-E model. These results are shown in table 6.5. As can be seen from this table, the emissions and fuel/oil consumption decreased between 15% to 23%; and hence it is estimated that very significant reductions in these variables will result if the ACS system is implemented on the state level.

Several scenarios for the implementation of the ACS system, from both the TxDOT and private contractors' perspectives were analyzed in this evaluation study. In every scenario of the economic analysis, the system proves to be very feasible. Also, the user-cost savings of this system are tremendous as can be seen from the case study for typical crack sealing operations on an interstate highway. Moreover, in both the qualitative and environmental/ energy analysis, the ACS system came out to be very feasible.

If the ACS systems are implemented at the statewide level, the direct savings are estimated to be $2.43 million for the TxDOT (4% MARR) and $2.64 million for the private contractors (20% MARR). The total user-cost savings are estimated to be $11.0 million for the 3229 miles of the interstate highways in Texas. Also, the actual user-cost savings would be much higher as the savings on urban freeways, farm-to-market roads, and secondary roads, etc. are not included in this $11.0 million estimate.

The analysis is, however, limited in scope due to the development stage of this ACS system. But, automation of crack sealing is inevitable: the economic benefits are numerous besides the very significant improvements in qualitative, environmental and energy concerns.

TABLE 6.5 REDUCTION IN ENVIRONMENTAL AND ENERGY FACTORS FOR THE CASE STUDY

	Conventional Operation	Automated Operation	Reduction (%)
Carbon-monoxide, CO (Kgs.)	57.4	48.2	19.1
Hydrocarbon, HC (Kgs.)	5.8	4.8	20.8
Oxides of Nitrogen, NOx (Kgs.)	1.6	1.3	23.1
Fuel Consumption (Gallons)	1404.1	1179.9	19.0
Oil Consumption (Gallons)	38.7	33.6	15.1

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

The major objectives of this research were to develop a systematic methodology to evaluate the benefits of automated road maintenance, to identify the maintenance activities which are feasible for automation, and to evaluate the feasibility of specific automated systems.

These objectives were achieved by the development of a comprehensive Automated Road Maintenance Evaluation (ARME) model. The ARME model provides a methodology through which a maintenance activity or an automated system can be evaluated from economic, qualitative, environmental and energy perspectives. Using the model as analysis tool, the other two objectives of the research were met. The feasibility of automation of the major maintenance activities of the TxDOT was evaluated using the ARME model's needs assessment phase. The feasibility of implementing an Automated Crack Sealer (ACS) system in Texas was evaluated using the ARME model's technology evaluation phase.

Based on the results of these two analyses, needs assessment of maintenance activities and technology evaluation of ACS system, the following conclusions and recommendations were developed:

7.1 FEASIBILITY OF MAINTENANCE ACTIVITIES FOR AUTOMATION

For the identification of feasible maintenance activities, detailed analysis was performed for the major maintenance activities of the TxDOT from the economic, qualitative, environmental and energy perspectives. Of the 25 maintenance activities evaluated, only 13 were found out to be feasible for automation. Most of these activities (7 out of the 13) are pavement related, four are roadside maintenance activities, and two are traffic related. These maintenance activities are listed as following:

Pavements related maintenance activities

- Base removal and replacement
- Crack and joint sealing
- Leveling or Overlays (currently done with maintainer, drag-box, etc.)
- Leveling or Overlays (currently done with laydown machines)
- Pothole repairs
- Strip and spot seal

- Seal coat

Roadside maintenance activities

- Ditch maintenance
- Reshaping ditches and slopes
- Guard fence maintenance
- Installing and re-installing signs

Traffic related maintenance activities

- Traffic assistance
- Paint and bead striping

One limitation of this evaluation approach is that there will be some sub-activities or tasks in each of the above maintenance activities which may not be technically feasible to automate. However, this was a broad-based needs assessment study in which all the major maintenance activities of the TxDOT were evaluated to identify the ones which should be given priority in future research and development. Also, this technology feasibility factor was not entirely ignored in the needs assessment study as one of the concerns areas in the study dealt with the subject.

It is recommended that a detailed technology feasibility study be conducted for each of the maintenance activities identified through this research. The major objective of this proposed study would be to identify the sub-activities or tasks which are technically feasible to automate. Technology feasibility studies have already being done for some of the maintenance activities including crack sealing and pothole repairs but a comprehensive and extensive effort is required. The combined results of the needs assessment study and the proposed technology feasibility study would then greatly help the R&D personnel, from both the university and the industry, in developing new and innovative automated systems for the road and highway maintenance activities.

7.2 FEASIBILITY OF AUTOMATED CRACK SEALER (ACS) SYSTEM

In evaluating the feasibility of an ACS system; estimated maintenance cost savings, user-cost savings, reduction in emissions/energy consumption, and the improvements in the qualitative factors (safety, quality, working environment, etc.) were determined. Several scenarios, from both the TxDOT and private contractors' perspectives, were analyzed; and in every scenario the system proved to be feasible for all the analysis parameters (economic, qualitative, environmental and energy).

If the ACS systems are implemented at the statewide level, the total life-cycle direct savings are estimated to be $5 million with $2.43 million for the TxDOT and $2.64 million for the private contractors. The life-cycle user-cost savings are estimated to be $11.0 million for the 3229 miles of the interstate highways in Texas, and the total user-cost savings would be much higher as the savings on urban freeways, farm-to-market roads, and secondary roads, etc. are not included in this estimate. The analysis is, however, limited in scope due to the development stage of this ACS system. It is recommended that research funding be made available to develop a field prototype of the ACS system with the proposed improvements.

In conclusion, the ARME model gives a systematic methodology to evaluate the benefits of automation from several different perspectives including economic, qualitative, environmental and energy. The practicality of this methodology was demonstrated by using it to evaluate the feasibility of maintenance activities for automation and the feasibility of an automated crack sealer system for implementation in Texas. Based on the simplicity and practicality of this methodology, it can have many other applications. These applications include testing and evaluation of new and innovative materials, equipment and systems in roads and building construction/maintenance besides other engineering and manufacturing areas.

APPENDIX A

Detailed results of the Needs Assessment Survey

Table A.1 Detailed results of the needs assessment survey

	Base Rem./Repl.(110)							Level. w/Laydown(211)							Level. w/Maint.(212)							Sealing Cracks(220)								Agg. Seal Coat(231)						
Number of Responses	6						Average	6						Average	6						Average	7							Average	6						Average
Level of Experience (little=1, some=2, considerable=3)	2	3	2	2	3	3		2	3	2	1	3	2		2	3	2	3	3	3		2	3	3	2	2	3	3		2	3	2	1	3	3	
CONCERNS	RESPONSE*							RESPONSE*							RESPONSE*							RESPONSE*								RESPONSE*						
1. Productivity & Other (PRD)																																				
01. Highly labor intensive area	5	5	10	0	10	10	7.0	0	5	0	10	10	10	5.8	0	5	5	10	10	10	7.2	10	10	10	10	10	10	10	10.0	5	5	10	10	10	10	8.2
02. Low income level of work crew/operators	5	5	10	10	10	0	6.3	5	5	10	10	0	10	5.8	5	5	10	10	0	10	6.6	10	5	10	10	10	0	10	7.5	5	5	10	10	0	10	6.1
03. Significant materials wastage	10	0	5	5	0	0	2.7	0	0	0	5	5	0	1.5	5	0	0	0	0	0	0.6	10	10	5	5	0	0	5	5.0	10	5	0	0	5	10	5.7
04. More productivity required (large work demand)	5	10	10	10	10	5	8.3	5	10	0	0	10	10	6.9	5	10	0	10	10	10	8.1	10	5	10	10	10	5	10	8.3	10	10	0	10	5	10	7.5
05. Work involves repetitive/cyclic tasks	0	10	10	0	10	0	5.3	0	10	0	5	5	10	5.4	0	10	5	10	5	10	7.2	10	5	10	10	0	5	10	7.2	5	10	10	5	0	10	6.8
06. Work involves time consuming tasks	5	10	10	0	10	10	8.0	0	10	0	10	10	10	6.9	0	10	5	10	10	10	8.1	10	5	10	10	10	10	10	9.2	5	10	10	10	10	10	9.3
07. Work involves environment-dependent tasks	5	5	10	10	10	10	8.3	10	5	10	10	10	10	8.8	5	5	10	10	10	10	8.4	10	10	10	10	10	5	10	9.2	5	10	10	10	10	10	9.3
2. Quality (QLT)																																				
01. Consistency in work required	10	10	10	10	10	10	10.0	10	10	10	10	10	10	10.0	10	10	10	10	10	10	10.0	10	5	10	10	10	10	10	9.2	10	10	10	10	10	10	10.0
02. Accuracy in work required	10	5	10	10	10	10	9.0	10	5	10	10	10	10	8.8	5	10	10	10	10	10	9.4	10	10	5	0	10	10	10	8.1	5	10	10	10	10	10	9.3
03. Other quality concerns (aesthetics, visual, etc.) also important	0	0	0	0	10	10	4.0	5	0	10	0	10	10	6.2	5	0	10	0	10	10	5.6	10	0	0	0	0	10	10	4.4	5	10	10	5	10	10	8.9
3. Safety (SAF)																																				
01. Work physically dangerous to the work crew/operators	5	5	10	10			7.2	10	5	10	10			8.1	5	5	10	10			7.5	5	10	5	10	10			7.9	5	10	10	10			8.8
02. Work hazardous to the health of the work crew/operators	0	0	10	10			4.4	0	0	10	10			3.8	0	0	10	10			5.0	0	5	0	10	10			4.6	0	10	10	10			7.5
03. Work physically dangerous to the passing by road users	5	5	10	10			7.2	5	5	10	10			6.9	5	5	10	10			7.5	5	0	5	10	10			5.4	5	10	10	10			8.8
04. Work hazardous to the health of the passing by road users	0	0	0	10			2.2	0	0	10	0			2.5	0	0	10	0			2.0	0	0	0	0	0			0.0	0	10	5	0			5.0
4. Socio-Political (S/P)																																				
01. Workers' not expected to resist in automating this maint. area	10	10	10	5	5	10	8.3	10	10	5	0	0	5	5.4	5	10	5	0	0	10	5.0	10	10	5	5	0	0	5	5.0	5	5	5	0	0	10	4.6
02. Workers' motivation to change expected (same workers can be used with additional training/increased salary, etc.)	0	5	10	5	10	5	6.0	0	5	5	0	5	10	4.6	0	0	5	10	5	10	5.3	10	10	5	5	10	10	10	8.6	5	5	5	10	5	10	6.4
5. Technology Feasibility (TEC)																																				
01. Existing Automation R&D in this maintenance area	5	5	5	5	5	5	5.0	5	5	5	5	5	5	5.0	5	5	5	5	5	5	5.0	10	10	10	10	10	10	10	10.0	5	5	5	5	5	5	5.0
02. Automated systems commercially available	5	5	5	5	5	5	5.0	5	5	5	5	5	5	5.0	5	5	5	5	5	5	5.0	5	5	5	5	5	5	5	5.0	5	5	5	5	5	5	5.0
6. Working Environment (WOR)																																				
01. Noisy conditions in the work area	5	10	10	5	10	10	8.7	5	10	10	10	10	10	9.2	5	10	10	10	10	10	9.4	5	5	10	10	10	10	10	8.6	0	10	10	10	10	10	8.6
02. Vibrations in the work area	5	5	0	5	10	5	5.3	5	5	10	0	5	10	6.2	5	5	0	0	5	10	4.4	0	0	0	0	0	0	10	1.7	0	5	0	0	0	10	3.2
03. Dirty conditions in the work area	5	10	10	10	10	10	9.3	5	10	10	10	10	10	9.2	5	10	5	10	10	10	8.8	0	10	5	10	10	5	10	7.2	5	10	10	10	10	10	9.3
04. Work involve heavy/high lifts	5	0	0	0	0	0	0.7	0	5	0	0	0	10	2.7	0	5	0	0	0	0	0.9	5	0	5	0	0	5	10	3.9	0	5	0	0	0	5	2.1
05. Meticulous work (great detail/carefulness required)	0	0	0	10	10	10	5.3	5	5	0	0	10	10	5.8	0	5	10	10	10	10	7.8	10	10	5	0	5	10	10	7.5	5	10	10	5	10	10	8.9
06. Exhaustive work	0	0	5	0	10	5	3.7	5	10	5	10	10	10	8.5	0	5	10	10	5	10	6.9	5	10	5	10	10	5	10	7.8	5	5	10	10	0	10	6.1
7. User-Costs & Emissions (U/E)																																				
Higher user-costs and emissions due to the following: 01. Road closures required	10	5	10	5	10	5	7.3	10	5	0	10	10	10	7.3	5	5	0	10	5	10	6.3	10	10	5	5	10	5	10	7.8	5	5	5	10	5	10	6.4
02. Long closure times required for setup & removal	5	5	10	5	10	10	7.7	0	5	0	10	10	10	5.8	0	5	0	10	10	10	6.6	5	10	5	0	10	10	10	7.5	0	5	0	10	10	10	6.1
03. Night time operations are not performed	5	10	0	0	0	0	2.7	0	10	10	10	10	10	8.5	10	10	10	10	10	10	10.0	5	10	10	10	10	10	10	9.4	5	10	10	10	10	10	9.3
OVERALL CONCERN RATING (OCR)	4.8	5.4	7.1	5.9	8.1	6.5	6.1	4.5	6.1	5.9	6.4	7.5	9.0	6.3	3.8	5.9	6.3	7.5	6.9	8.8	6.5	7.1	6.8	6.3	6.6	7.1	6.7	9.4	6.9	4.5	7.9	7.1	7.3	6.3	9.4	7.2

Table A.1 Detailed results of the need s assessment survey (continued)

	Strip/Spot Seal(232)								Potholes Repairs(240)								Side Road Appr.(470)							Mowing(511)						
Number of Responses	7							Average	7							Average	6						Average	6						Average
Level of Experience (little=1, some=2, considerable=3)	2	2	3	2	1	3	3		2	2	3	2	2	3	3		2	3	2	1	3	3		2	2	3	1	3	3	
CONCERNS	**RESPONSE***								**RESPONSE***								**RESPONSE***							**RESPONSE***						
1. Productivity & Other (PRD)																														
01. Highly labor intensive area	10	10	5	10	10	10	10	9.1	10	10	10	10	10	5	10	9.1	5	5	5	5	5	5	5.0	5	0	10	10	5	0	4.6
02. Low income level of work crew/operators	10	5	5	10	10	5	10	7.5	10	10	10	10	10	10	10	10.0	5	5	10	5	5	10	6.8	5	5	10	5	10	10	8.2
03. Significant materials wastage	5	5	5	5	0	5	10	5.6	5	10	0	10	0	0	0	2.9	5	0	0	5	0	0	1.1	0	0	0	0	0	0	0.0
04. More productivity required (large work demand)	5	5	10	0	10	5	10	6.6	5	10	0	5	5	5	5	4.7	0	0	0	0	5	10	3.2	5	5	10	5	5	10	7.1
05. Work involves repetitive/cyclic tasks	10	0	10	10	5	0	10	6.6	5	0	10	10	0	5	10	6.2	5	10	5	0	10	10	7.9	5	5	10	0	10	10	7.9
06. Work involves time consuming tasks	10	10	10	0	10	10	10	8.8	5	10	10	10	10	10	10	9.4	0	10	5	5	10	10	7.5	10	5	5	0	10	10	7.5
07. Work involves environment-dependent tasks	10	10	10	10	10	10	10	10.0	10	10	5	10	5	5	10	7.6	10	5	0	5	5	10	6.1	5	10	0	0	0	10	4.3
2. Quality (QLT)																														
01. Consistency in work required	10	5	10	10	10	10	10	9.4	10	5	10	10	10	10	10	9.4	10	10	10	10	10	10	10.0	0	5	10	5	10	10	7.5
02. Accuracy in work required	10	5	10	10	10	10	10	9.4	5	5	5	0	10	10	10	6.8	5	5	10	10	10	10	8.2	0	0	0	5	10	10	4.6
03. Other quality concerns (aesthetics, visual, etc.) also important	5	0	10	10	0	10	10	7.5	5	0	0	0	0	10	10	4.1		0	10	5	10	10	6.1	0	10	10	5	10	10	8.2
3. Safety (SAF)																														
01. Work physically dangerous to the work crew/operators	5	10	10	10	10			9.0	10	10	10	10	10			10.0	5	5	10	10			6.9	5	0	10	10			6.3
02. Work hazardous to the health of the work crew/operators	0	5	10	10	10			7.0	0	10	5	10	10			6.8	0	0	0	5			0.6	0	5	0	10			2.5
03. Work physically dangerous to the passing by road users	5	5	10	10	10			8.0	10	5	10	10	10			9.1	5	5	10	10			6.9	5	0	5	10			4.4
04. Work hazardous to the health of the passing by road users	0	0	10	0	0			3.0	0	0	0	0	0			0.0	0	0	0	0			0.0	0	0	0	0			0.0
4. Socio-Political (S/P)																														
01. Workers' not expected to resist in automating this maint. area	5	5	5	5	0	0	10	4.7	0	10	5	5	0	0	10	4.4	5	5	5	0	0	10	4.6	0	5	5	0	0	10	3.9
02. Workers' motivation to change expected (same workers can be used with additional training/increased salary, etc.)	5	0	5	10	10	5	10	6.3	5	0	5	5	10	5	10	5.9	5	5	5	10	5	10	6.4	0	5	5	10	5	10	5.7
5. Technology Feasibility (TEC)																														
01. Existing Automation R&D in this maintenance area	5	5	5	5	5	5	5	5.0	10	10	10	10	10	10	10	10.0	0	0	0	0	0	0	0.0	5	5	5	5	5	5	5.0
02. Automated systems commercially available	5	5	5	5	5	5	5	5.0	10	10	10	10	10	10	10	10.0	0	0	0	0	0	0	0.0	5	5	5	5	5	5	5.0
6. Working Environment (WOR)																														
01. Noisy conditions in the work area	0	5	10	10	10	10	10	8.1	5	10	10	0	10	0	0	4.7	0	10	10	10	10	10	8.6	10	10	10	10	5	10	8.9
02. Vibrations in the work area	0	10	5	0	0	0	5	3.1	5	10	5	0	0	0	0	2.6	5	5	0	0	0	0	1.8	10	10	10	0	0	10	7.1
03. Dirty conditions in the work area	5	10	10	10	10	10	10	9.4	5	10	10	10	5	5	10	7.9	10	10	10	10	10	10	10.0	10	5	10	10	10	10	9.3
04. Work involve heavy/high lifts	0	5	5	0	0	0	0	1.6	5	5	10	5	5	5	0	5.0	0	5	0	0	0	0	1.1	0	0	0	0	0	0	0.0
05. Meticulous work (great detail/carefulness required)	5	0	10	10	0	10	10	7.5	5	0	5	0	5	10	5	4.7	5	5	10	5	10	10	7.9	0	0	5	5	5	5	3.6
06. Exhaustive work	0	10	5	10	10	0	10	5.9	0	10	10	10	10	5	5	7.1	0	5	10	10	0	10	5.4	0	0	10	5	5	10	5.7
7. User-Costs & Emissions (U/E)																														
Higher user-costs and emissions due to the following: 01. Road closures required	5	10	5	0	10	10	10	7.2	5	5	5	0	10	0	10	5.0	5	5	0	10	0	0	2.5	0	0	0	0	0	0	0.0
02. Long closure times required for setup & removal	5	5	5	0	10	10	10	6.6	5	0	5	0	10	0	0	2.6	0	5	0	10	0	0	1.8	0	0	0	0	0	0	0.0
03. Night time operations are not performed	5	0	10	10	10	10	10	8.1	5	5	5	10	10	10	10	7.9	10	10	10	10	10	10	10.0	10	0	10	10	10	10	8.6
OVERALL CONCERN RATING (OCR)	5.4	5.5	7.9	6.8	7.0	6.7	9.0	6.7	5.9	6.8	6.8	6.4	7.0	5.8	7.3	6.8	3.9	5.0	5.2	5.7	5.2	6.9	4.8	3.8	3.8	5.9	4.8	5.4	7.3	4.8

Table A.1 Detailed results of the needs assessment survey (continued)

	Litter Removal(521)							Street Sweeping(522)						Picnic Area Maint.(531)						Rest Area Maint.(532)						Reshp. Ditch./Slope.(560)						
Number of Responses	6						Average	5					Average	5					Average	5					Average	6						Average
Level of Experience (little=1, some=2, considerable=3)	2	2	3	3	3	2		2	3	1	3	3		1	3	1	3	3		1	3	1	3	1		2	2	3	3	3	3	
CONCERNS	RESPONSE*							RESPONSE*						RESPONSE*						RESPONSE*						RESPONSE*						
1. Productivity & Other (PRD)																																
01. Highly labor intensive area	10	10	10	5	5	0	6.7	0	0	5	5	0	1.7	10	10	0	5	0	5.0	10	10	0	10	0	7.8	0	0	0	10	5	0	2.8
02. Low income level of work crew/operators	10	5	10	0	10	10	7.3	0	0	5	0	10	2.9	5	10	0	10	10	8.6	5	10	0	5	10	6.7	5	0	5	10	0	0	3.4
03. Significant materials wastage	0	0	0	0	0	0	0.0	0	0	0	0	0	0.0	0	0	0	0	0	0.0	0	0	0	10	0	3.3	0	0	0	10	0	0	1.9
04. More productivity required (large work demand)	10	10	10	0	10	10	8.0	5	10	5	10	10	8.8	0	0	0	5	10	4.1	0	0	0	5	0	1.7	10	5	5	10	5	10	7.5
05. Work involves repetitive/cyclic tasks	10	10	10	0	10	10	8.0	0	10	0	10	10	7.5	0	10	0	10	10	8.2	0	10	0	10	10	7.8	10	0	10	10	10	0	6.9
06. Work involves time consuming tasks	10	0	10	5	10	10	7.7	10	10	5	10	10	9.6	0	0	0	10	10	5.5	0	0	5	10	10	5.0	5	10	0	10	10	10	7.5
07. Work involves environment-dependent tasks	0	0	0	0	10	10	3.3	10	10	10	5	10	8.8	0	0	0	5	10	4.1	0	0	0	5	10	2.8	5	10	5	5	10	10	7.5
2. Quality (QLT)																																
01. Consistency in work required	5	0	5	5	10	10	6.0	10	5	5	10	10	8.3	0	10	0	10	10	8.2	0	10	5	10	10	8.3	5	10	10	10	10	10	9.4
02. Accuracy in work required	5	0	0	5	10	5	4.3	0	5	5	10	10	6.7	0	0	0	10	10	5.5	0	0	5	10	10	5.0	5	10	10	10	10	10	9.4
03. Other quality concerns (aesthetics, visual, etc.) also important	0	0	5	10	10	10	6.3	10	10	5	10	10	9.6	10	5	0	10	10	7.7	10	5	5	10	10	7.8	5	10	10	5	10	10	8.4
3. Safety (SAF)																																
01. Work physically dangerous to the work crew/operators	5	0	5	10			5.5	0	5	10			4.2	0	0	5			1.0	0	0	5			1.0	5	10	5	10			7.5
02. Work hazardous to the health of the work crew/operators	0	0	0	10			3.0	0	0	10			1.7	0	0	5			1.0	0	0	5			1.0	0	5	0	10			4.0
03. Work physically dangerous to the passing by road users	5	0	0	0			1.0	10	5	10			7.5	0	0	0			0.0	0	0	0			0.0	5	5	5	10			6.5
04. Work hazardous to the health of the passing by road users	0	0	0	0			0.0	0	0	0			0.0	0	0	0			0.0	0	0	0			0.0	0	0	0	0			0.0
4. Socio-Political (S/P)																																
01. Workers' not expected to resist in automating this maint. area	10	5	10	0	0	10	5.3	0	10	0	0	10	5.0	0	10	0	0	10	5.5	0	10	0	0	10	4.4	10	5	5	0	5	10	5.6
02. Workers' motivation to change expected (same workers can be used with additional training/increased salary, etc.)	5	5	0	10	0	10	4.7	10	0	10	5	10	6.3	10	0	10	0	10	4.5	10	0	10	5	10	5.0	5	5	5	10	5	10	6.9
5. Technology Feasibility (TEC)																																
01. Existing Automation R&D in this maintenance area	10	10	10	10	10	10	10.0	0	0	0	0	0	0.0	0	0	0	0	0	0.0	0	0	0	0	0	0.0	5	5	5	5	5	5	5.0
02. Automated systems commercially available	5	5	5	5	5	5	5.0	0	0	0	0	0	0.0	0	0	0	0	0	0.0	0	0	0	0	0	0.0	5	5	5	5	5	5	5.0
6. Working Environment (WOR)																																
01. Noisy conditions in the work area	5	0	5	5	0	0	2.7	0	0	10	10	10	5.8	0	0	0	0	0	0.0	0	0	0	0	0	0.0	5	10	10	5	10	10	8.4
02. Vibrations in the work area	0	0	0	0	0	0	0.0	5	10	0	0	5	4.6	0	0	0	0	0	0.0	0	0	0	0	0	0.0	0	10	5	0	0	10	4.1
03. Dirty conditions in the work area	5	10	10	10	5	10	8.3	0	0	10	10	10	5.8	10	5	5	10	10	8.2	10	5	5	10	10	7.8	5	10	10	10	10	10	9.4
04. Work involve heavy/high lifts	0	10	5	5	5	10	5.7	0	0	0	0	0	0.0	5	0	0	10	10	5.9	5	0	0	5	10	3.3	0	5	0	0	0	0	0.6
05. Meticulous work (great detail/carefulness required)	0	0	0	0	5	0	1.0	0	5	5	10	0	4.2	0	0	5	10	10	5.9	0	0	5	10	5	4.4	0	0	5	5	10	10	5.6
06. Exhaustive work	5	0	10	5	10	10	7.0	0	5	0	0	10	3.8	5	0	0	5	10	4.5	5	0	0	5	10	3.3	0	5	5	5	0	10	4.4
7. User-Costs & Emissions (U/E)																																
Higher user-costs and emissions due to the following: 01. Road closures required	0	0	0	0	0	0	0.0	0	0	0	0	10	2.5	0	0	0	0	0	0.0	0	0	0	0	0	0.0	5	5	0	10	0	0	3.1
02. Long closure times required for setup & removal	0	0	0	0	0	0	0.0	0	0	0	0	5	1.3	0	0	0	0	0	0.0	0	0	0	0	0	0.0	0	5	0	10	0	0	2.5
03. Night time operations are not performed	10	10	10	10	10	10	10.0	0	0	0	10	10	5.0	0	10	10	10	10	9.1	0	5	10	0	10	3.9	10	0	10	10	10	10	8.8
OVERALL CONCERN RATING (OCR)	4.8	3.6	5.0	4.3	6.0	6.7	4.7	2.5	3.6	4.3	5.2	7.1	4.3	2.3	2.5	1.6	5.4	6.7	3.4	2.3	2.3	2.3	5.4	6.0	3.1	4.1	5.5	5.0	7.3	5.8	6.7	5.8

Table A.1 Detailed results of the need s assessment survey (continued)

	Ditch Maintenance(561)						Culvert Maint.(570)						M.Roadside Maint.(592)					
Number of Responses	5					Average	5					Average	5					Average
Level of Experience (little=1, some=2, considerable=3)	2	3	3	3	3		2	3	2	3	3		2	3	2	3	3	
CONCERNS	RESPONSE*						RESPONSE*						RESPONSE*					
1. Productivity & Other (PRD)																		
01. Highly labor intensive area	0	0	10	5	0	3.2	0	10	5	5	10	6.5	0	5	5	5	10	5.4
02. Low income level of work crew/operators	5	5	10	0	0	3.9	5	5	5	0	10	5.0	5	5	5	0	10	5.0
03. Significant materials wastage	0	0	0	0	0	0.0	0	0	0	0	0	0.0	0	0	0	0	0	0.0
04. More productivity required (large work demand)	10	5	5	5	10	6.8	10	0	5	5	10	5.8	10	0	5	5	10	5.8
05. Work involves repetitive/cyclic tasks	10	10	5	10	0	6.8	10	10	5	10	10	9.2	10	5	5	10	10	8.1
06. Work involves time consuming tasks	5	0	5	10	10	6.1	5	10	5	10	10	8.5	5	5	5	5	10	6.2
07. Work involves environment-dependent tasks	5	5	5	5	10	6.1	5	5	0	5	10	5.4	5	5	0	10	10	6.5
2. Quality (QLT)																		
01. Consistency in work required	5	10	10	10	10	9.3	5	5	5	10	10	7.3	5	0	5	10	0	3.8
02. Accuracy in work required	5	10	10	10	10	9.3	5	0	5	10	10	6.2	5	0	5	10	10	6.2
03. Other quality concerns (aesthetics, visual, etc.) also important	5	10	5	10	10	8.2	5	0	5	10	10	6.2	5	5	5	10	10	7.3
3. Safety (SAF)																		
01. Work physically dangerous to the work crew/operators	5	5	5			5.0	5	0	10			4.3	5	5	5			5.0
02. Work hazardous to the health of the work crew/operators	0	0	5			1.9	0	0	10			2.9	0	5	5			3.6
03. Work physically dangerous to the passing by road users	5	5	5			5.0	5	0	5			2.9	5	5	5			5.0
04. Work hazardous to the health of the passing by road users	0	0	0			0.0	0	0	0			0.0	0	5	0			2.1
4. Socio-Political (S/P)																		
01. Workers' not expected to resist in automating this maint. area	10	5	0	5	10	5.7	10	10	0	0	10	6.2	10	5	0	0	10	5.0
02. Workers' motivation to change expected (same workers can be used with additional training/increased salary, etc.)	5	5	10	5	10	7.1	5	0	10	5	10	5.8	5	5	10	5	10	6.9
5. Technology Feasibility (TEC)																		
01. Existing Automation R&D in this maintenance area	5	5	5	5	5	5.0	0	0	0	0	0	0.0	0	0	0	0	0	0.0
02. Automated systems commercially available	5	5	5	5	5	5.0	0	0	0	0	0	0.0	0	0	0	0	0	0.0
6. Working Environment (WOR)																		
01. Noisy conditions in the work area	5	10	10	10	10	9.3	5	10	10	5	10	8.1	5	0	10	0	10	4.6
02. Vibrations in the work area	0	5	0	0	0	1.1	0	0	0	0	10	2.3	0	0	0	0	0	0.0
03. Dirty conditions in the work area	5	10	10	10	10	9.3	5	10	10	5	10	8.1	5	5	5	5	10	6.2
04. Work involve heavy/high lifts	0	0	0	5	0	1.1	0	5	0	5	10	4.6	0	5	0	0	10	3.5
05. Meticulous work (great detail/carefulness required)	0	5	5	5	10	5.4	0	0	5	5	10	4.2	0	0	5	5	0	1.9
06. Exhaustive work	0	5	5	0	10	4.3	0	5	10	5	10	6.2	0	5	5	0	10	4.2
7. User-Costs & Emissions (U/E)																		
Higher user-costs and emissions due to the following: 01. Road closures required	5	0	5	0	0	1.8	5	0	5	0	0	1.5	5	5	5	0	0	2.7
02. Long closure times required for setup & removal	0	0	5	0	0	1.1	0	0	5	0	0	0.8	0	5	5	0	0	1.9
03. Night time operations are not performed	10	10	10	10	10	10.0	10	10	10	10	10	10.0	10	5	10	10	10	8.8
OVERALL CONCERN RATING (OCR)	4.1	5.0	5.7	5.6	6.3	5.2	3.8	3.8	5.0	4.8	7.9	4.3	3.8	3.4	4.3	4.2	6.7	4.1

	Driveway Maint.(594)						Paint/Bead Striping(711)						Guard Fences(722)				
Number of Responses	5					Average	5					Average	4				Average
Level of Experience (little=1, some=2, considerable=3)	2	3	1	3	3		2	2	3	1	2		3	1	3	3	
CONCERNS	RESPONSE*						RESPONSE*						RESPONSE*				
1. Productivity & Other (PRD)																	
01. Highly labor intensive area	0	5	5	5	10	5.4	5	10	0	5	10	5.5	10	10	10	10	10.0
02. Low income level of work crew/operators	5	5	5	0	10	5.0	5	5	0	5	0	2.5	10	5	0	10	6.5
03. Significant materials wastage	0	0	5	0	0	0.4	5	5	5	0	5	4.5	0	0	0	0	0.0
04. More productivity required (large work demand)	10	0	5	5	10	5.8	5	5	10	5	10	7.5	5	5	0	10	5.0
05. Work involves repetitive/cyclic tasks	10	10	5	10	10	9.6	5	10	10	5	10	8.5	5	5	5	10	6.5
06. Work involves time consuming tasks	5	10	10	10	10	9.2	5	5	10	5	10	7.5	10	5	10	10	9.5
07. Work involves environment-dependent tasks	5	5	5	0	10	5.0	5	5	5	0	10	5.5	0	0	0	10	3.0
2. Quality (QLT)																	
01. Consistency in work required	5	10	10	10	10	9.2	10	10	10	5	10	9.5	5	5	10	10	8.0
02. Accuracy in work required	5	5	10	10	10	7.9	10	10	10	5	10	9.5	5	5	10	10	8.0
03. Other quality concerns (aesthetics, visual, etc.) also important	5	0	5	10	10	6.3	10	10	10	10	10	10.0	5	5	10	10	8.0
3. Safety (SAF)																	
01. Work physically dangerous to the work crew/operators	5	5	10			5.8	5	10	10	10		8.8	5	10			6.3
02. Work hazardous to the health of the work crew/operators	0	0	10			1.7	0	10	5	10		5.6	0	10			2.5
03. Work physically dangerous to the passing by road users	5	5	10			5.8	5	10	10	10		8.8	5	10			6.3
04. Work hazardous to the health of the passing by road users	0	0	0			0.0	0	0	5	0		1.9	0	0			0.0
4. Socio-Political (S/P)																	
01. Workers' not expected to resist in automating this maint. area	10	5	0	0	10	5.4	10	5	10	0	5	7.0	10	0	5	10	7.5
02. Workers' motivation to change expected (same workers can be used with additional training/increased salary, etc.)	5	5	10	5	10	6.7	5	5	0	10	5	4.0	0	10	5	10	5.5
5. Technology Feasibility (TEC)																	
01. Existing Automation R&D in this maintenance area	0	0	0	0	0	0.0	10	10	10	10	10	10.0	0	0	0	0	0.0
02. Automated systems commercially available	0	0	0	0	0	0.0	5	5	5	5	5	5.0	0	0	0	0	0.0
6. Working Environment (WOR)																	
01. Noisy conditions in the work area	5	10	10	5	10	7.9	5	10	10	5	10	8.5	10	5	0	10	6.5
02. Vibrations in the work area	0	5	0	0	0	1.3	5	5	5	0	0	3.5	0	0	0	0	0.0
03. Dirty conditions in the work area	5	10	5	5	10	7.5	5	5	0	5	10	4.5	5	5	5	10	6.5
04. Work involve heavy/high lifts	0	5	0	0	10	3.8	5	0	10	5	5	5.5	10	10	10	10	10.0
05. Meticulous work (great detail/carefulness required)	0	5	5	5	10	5.4	10	10	10	5	10	9.5	5	5	10	10	8.0
06. Exhaustive work	0	5	5	5	10	5.4	0	5	5	5	5	4.0	5	10	10	10	8.5
7. User-Costs & Emissions (U/E)																	
Higher user-costs and emissions due to the following: 01. Road closures required	5	5	5	0	0	2.5	10	10	0	5	0	4.5	0	5	0	10	3.5
02. Long closure times required for setup & removal	0	5	5	0	0	1.7	0	5	0	5	0	1.5	0	5	0	10	3.5
03. Night time operations are not performed	10	10	10	10	10	10.0	5	0	0	10	0	2.0	10	10	10	10	10.0
OVERALL CONCERN RATING (OCR)	3.8	5.0	5.7	4.4	7.5	4.8	5.7	6.8	6.1	5.4	6.7	6.4	4.5	5.4	5.0	8.3	5.3

Table A.1 Detailed results of the need s assessment survey (continued)

	Instal. Signs(732)					M. Sign Maint.(734)					Signal Maint. (741)					Illumination(742)					Assis. to Traffic(810)				
Number of Responses	4				Average	4				Average	3				Average	3				Average	4				Average
Level of Experience (little=1, some=2, considerable=3)	3	3	3	2		3	3	3	2		3	1	2			3	1	2			3	2	2	3	
CONCERNS	RESPONSE*					RESPONSE*					RESPONSE*					RESPONSE*					RESPONSE*				
1. Productivity & Other (PRD)																									
01. Highly labor intensive area	10	10	10	10	10.0	10	10	5	0	6.8	10	5	10		9.2	10	5	10		9.2	10	5	10	0	6.0
02. Low income level of work crew/operators	10	10	0	10	7.3	10	10	0	10	7.3	0	5	0		0.8	0	5	0		0.8	5	5	5	10	6.5
03. Significant materials wastage	0	0	0	0	0.0	0	0	5	0	1.4	0	0	5		1.7	0	0	0		0.0	0	5	5	0	2.0
04. More productivity required (large work demand)	0	5	5	5	3.6	0	5	5	5	3.6	0	5	10		4.2	0	5	10		4.2	0	5	5	0	2.0
05. Work involves repetitive/cyclic tasks	5	5	10	10	7.3	5	5	10	10	7.3	0	5	10		4.2	0	5	10		4.2	5	5	0	10	5.5
06. Work involves time consuming tasks	10	10	10	10	10.0	10	10	10	10	10.0	5	5	10		6.7	5	5	10		6.7	5	10	5	10	7.5
07. Work involves environment-dependent tasks	0	0	0	0	0.0	5	0	0	0	1.4	0	0	0		0.0	0	0	0		0.0	0	0	10	10	5.0
2. Quality (QLT)																									
01. Consistency in work required	5	10	10	10	8.6	5	10	10	10	8.6	10	5	10		9.2	10	5	10		9.2	5	5	10	0	4.5
02. Accuracy in work required	5	10	10	10	8.6	5	10	10	10	8.6	10	5	10		9.2	10	5	10		9.2	5	10	10	10	8.5
03. Other quality concerns (aesthetics, visual, etc.) also important	0	10	10	10	7.3	0	10	10	10	7.3	0	5	10		4.2	0	5	10		4.2	0	5	10	10	6.0
3. Safety (SAF)																									
01. Work physically dangerous to the work crew/operators	5	10			7.5	5	10			7.5	10	10			10.0	10	5			8.8	10	10			10.0
02. Work hazardous to the health of the work crew/operators	0	10			5.0	0	10			5.0	0	10			2.5	0	5			1.3	0	10			4.0
03. Work physically dangerous to the passing by road users	0	10			5.0	0	10			5.0	0	10			2.5	0	5			1.3	10	10			10.0
04. Work hazardous to the health of the passing by road users	0	0			0.0	0	0			0.0	0	0			0.0	0	0			0.0	0	0			0.0
4. Socio-Political (S/P)																									
01. Workers' not expected to resist in automating this maint. area	10	0	5	10	5.9	10	0	5	10	5.9	5	0	5		4.2	5	0	5		4.2	10	0	5	10	7.0
02. Workers' motivation to change expected (same workers can be used with additional training/increased salary, etc.)	0	10	5	10	5.9	0	10	5	10	5.9	5	10	5		5.8	5	10	5		5.8	0	10	5	10	6.0
5. Technology Feasibility (TEC)																									
01. Existing Automation R&D in this maintenance area	0	0	0	0	0.0	0	0	0	0	0.0	0	0	0		0.0	0	0	0		0.0	10	10	10	10	10.0
02. Automated systems commercially available	0	0	0	0	0.0	0	0	0	0	0.0	0	0	0		0.0	0	0	0		0.0	10	10	10	10	10.0
6. Working Environment (WOR)																									
01. Noisy conditions in the work area	5	10	0	0	4.1	5	10	0	0	4.1	5	5	0		3.3	5	5	0		3.3	5	10	10	0	5.5
02. Vibrations in the work area	0	0	0	0	0.0	0	0	0	0	0.0	0	0	0		0.0	0	0	0		0.0	0	0	5	0	1.0
03. Dirty conditions in the work area	0	5	5	5	3.6	0	5	5	0	2.7	0	5	0		0.8	0	5	5		2.5	0	5	10	10	6.0
04. Work involve heavy/high lifts	10	10	5	10	8.6	10	0	5	10	5.9	0	10	5		3.3	0	10	5		3.3	5	5	5	10	6.5
05. Meticulous work (great detail/carefulness required)	5	10	10	10	8.6	5	10	5	10	7.3	10	5	10		9.2	10	0	10		8.3	0	5	5	10	5.0
06. Exhaustive work	5	10	5	10	7.3	5	5	5	10	5.9	5	5	5		5.0	5	5	5		5.0	5	5	10	10	7.5
7. User-Costs & Emissions (U/E)																									
Higher user-costs and emissions due to the following: 01. Road closures required	0	5	0	0	1.4	0	5	0	0	1.4	0	5	5		2.5	0	5	5		2.5	10	10	10	10	10.0
02. Long closure times required for setup & removal	0	5	0	0	1.4	0	0	0	0	0.0	0	5	5		2.5	0	5	5		2.5	10	10	5	10	9.0
03. Night time operations are not performed	10	10	10	10	10.0	5	10	10	10	8.6	0	10	5		3.3	0	10	10		5.0	0	10	5	0	3.0
OVERALL CONCERN RATING (OCR)	3.8	6.6	5.0	6.3	5.1	3.8	5.9	4.8	5.6	4.7	3.0	5.0	5.4		4.1	3.0	4.1	5.6		4.0	4.6	6.6	7.3	7.1	6.6

APPENDIX B

Detailed results of the economic analysis of the Automated Crack Sealer (ACS) System for the state of Texas

ECONOMIC ANALYSIS OF AUTOMATED CRACK SEALER (In-house, hot pour crack sealing)			
GENERAL DATA	SCENARIO 1	SCENARIO 2	SCENARIO 3
WORK UNITS OF THE ARM SYSTEM	Lbs.	Lbs.	Lbs.
ESTIMATED WORK CAPACITY OF THE ARM SYSTEM (UNITS/YEAR)	432,000	432,000	432,000
ESTIMATED YEARLY EFFICIENCY OF THE ARM SYSTEM	90%	90%	90%
ANALYSIS PERIOD OR LIFE OF THE ARM SYSTEM (YEARS)	6	6	6
MINIMUM ATTRACTIVE RATE OF RETURN (MARR)	4.00%	6.00%	8.00%
INITIAL COST OF ARM SYSTEM (PRESENT $)	$70,000	$70,000	$70,000
OPERATING COSTS OF ARM SYSTEM (ANNUAL $)	$4,000	$4,000	$4,000
MAINTENANCE COSTS OF ARM SYSTEM (ANNUAL $)	$3,000	$3,000	$3,000
OVERHEADS OF ARM SYSTEM (ANNUAL $)	$3,500	$3,500	$3,500
SALVAGE VALUE OF ARM SYSTEM (FUTURE $)	$15,000	$15,000	$15,000
LIFE CYCLE COST/UNIT-WORK OF 1 ARM SYSTEM ($/UNIT)	**$0.05**	**$0.05**	**$0.05**
CURRENT TXDOT COSTS/UNIT WORK ($ /UNIT)	$0.73	$0.73	$0.73
" " YEARLY EXPENDITURES FOR THIS ACTIVITY ($/YEAR)	$1,685,600	$1,685,600	$1,685,600
" " EXPENDITURES ON LABOR FOR THIS ACTIVITY (%)	46.14%	46.14%	46.14%
" " TYPICAL CREW SIZE FOR THIS MAINTENANCE ACTIVITY	7	7	7
NUMBER OF CREW MEMBERS TO BE REDUCED BY THE ARM SYSTEM	4	4	4
YEARLY UNIT WORK DONE BY TXDOT (UNITS)	**2,309,041**	**2,309,041**	**2,309,041**
% WORK PERFORMED BY 1 ARM SYSTEM	**18.71%**	**18.71%**	**18.71%**
LIFE CYCLE LABOR SAVING/UNIT-WORK OF1 ARM SYSTEM	**$0.19**	**$0.18**	**$0.16**
TXDOT LIFE-CYCLE SAVINGS (1 ARM SYSTEM)	**$322,680**	**$297,803**	**$275,290**
TXDOT LIFE-CYCLE SAVINGS (ALL WORK BY ARM SYSTEMS)	**$1,613,399**	**$1,489,014**	**$1,376,452**

Note: Output in bold format

Figure B.1a Economic Analysis of ACS for hot pour in-house crack sealing by TxDOT (direct savings)

ECONOMIC ANALYSIS OF AUTOMATED CRACK SEALER (In-house, hot pour crack sealing)			
CASE STUDY	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**
PROJECT	I-35, San Marcos to New Braunfils (20 mile segment)		
ESTIMATED TOTAL UNIT WORK TO BE PERFORMED	4,800	4,800	4,800
NO. OF LANES EACH DIRECTION	2	2	2
ADT EACH DIRECTION	27,500	27500	27500
ESTIMATED LENGTH OF ROAD CLOSURE, MILES (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF LANES CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF DAYS CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
ESTIMATED REDUCTION IN CLOSURE TIME (FROM CONV. TO ARM)*	20%	20%	20%
USER COSTS PER OPERATION, CONV. METHODS *	10,625	10,625	10,625
USER COSTS PER OPERATION, ARM SYSTEM *	8,368	8,368	8,368
NO. OF THESE TYPICAL OPERATIONS PER YEAR	6	6	6
TOTAL USER COSTS, CONVENTIONAL METHODS *	**$334,186**	**$313,479**	**$294,709**
TOTAL USER COSTS, ARM SYSTEM *	**$263,197**	**$246,889**	**$232,106**
TOTAL UNIT COST USING CONV. METHODS (TXDOT+USER COSTS)	**$70.35**	**$66.04**	**$62.13**
TOTAL UNIT COST USING ARM SYSTEM (TXDOT+USER COSTS)	**$55.42**	**$52.04**	**$48.97**
TXDOT SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$664**	**$613**	**$566**
USER-COST SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$70,989**	**$66,590**	**$62,603**
TOTAL SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$71,653**	**$67,203**	**$63,169**

Note: Output in bold format

Figure B.1b Economic Analysis of ACS for hot pour in-house crack sealing by TxDOT (user-costs savings)

ECONOMIC ANALYSIS OF AUTOMATED CRACK SEALER (Contractors, hot pour crack sealing)			
GENERAL DATA	SCENARIO 1	SCENARIO 2	SCENARIO 3
WORK UNITS OF THE ARM SYSTEM	Lbs.	Lbs.	Lbs.
ESTIMATED WORK CAPACITY OF THE ARM SYSTEM (UNITS/YEAR)	432,000	432,000	432,000
ESTIMATED YEARLY EFFICIENCY OF THE ARM SYSTEM	90%	90%	90%
ANALYSIS PERIOD OR LIFE OF THE ARM SYSTEM (YEARS)	6	6	6
MINIMUM ATTRACTIVE RATE OF RETURN (MARR)	20.00%	25.00%	30.00%
INITIAL COST OF ARM SYSTEM (PRESENT $)	$70,000	$70,000	$70,000
OPERATING COSTS OF ARM SYSTEM (ANNUAL $)	$4,000	$4,000	$4,000
MAINTENANCE COSTS OF ARM SYSTEM (ANNUAL $)	$3,000	$3,000	$3,000
OVERHEADS OF ARM SYSTEM (ANNUAL $)	$3,500	$3,500	$3,500
SALVAGE VALUE OF ARM SYSTEM (FUTURE $)	$15,000	$15,000	$15,000
LIFE CYCLE COST/UNIT-WORK OF 1 ARM SYSTEM ($/UNIT)	**$0.04**	**$0.04**	**$0.04**
CURRENT TXDOT COSTS/UNIT WORK ($ /UNIT)	$0.70	$0.70	$0.70
" " YEARLY EXPENDITURES FOR THIS ACTIVITY ($/YEAR)	$4,320,400	$4,320,400	$4,320,400
" " EXPENDITURES ON LABOR FOR THIS ACTIVITY (%)	46.14%	46.14%	46.14%
" " TYPICAL CREW SIZE FOR THIS MAINTENANCE ACTIVITY	7	7	7
NUMBER OF CREW MEMBERS TO BE REDUCED BY THE ARM SYSTEM	4	4	4
YEARLY UNIT WORK DONE BY TXDOT CONTRACTORS (UNITS)	**6,172,000**	**6,172,000**	**6,172,000**
% WORK PERFORMED BY 1 ARM SYSTEM	**7.00%**	**7.00%**	**7.00%**
LIFE CYCLE LABOR SAVING/UNIT-WORK OF1 ARM SYSTEM	**$0.11**	**$0.10**	**$0.09**
CONTRACTORS' LIFE-CYCLE SAVINGS (1 ARM SYSTEM)	**$165,248**	**$138,259**	**$116,065**
CONTRACTORS' LIFE-CYCLE SAVINGS (ALL WORK BY ARM SYSTEMS)	**$2,313,476**	**$1,935,626**	**$1,624,906**

Note: Output in bold format

Figure B.2a Economic Analysis of ACS for hot pour crack sealing by Contractors (direct savings)

ECONOMIC ANALYSIS OF AUTOMATED CRACK SEALER (Contractors, hot pour crack sealing)			
CASE STUDY 1	SCENARIO 1	SCENARIO 2	SCENARIO 3
PROJECT	I-35, San Marcos to New Braunfils (20 mile segment)		
ESTIMATED TOTAL UNIT WORK TO BE PERFORMED	4,800	4,800	4,800
NO. OF LANES EACH DIRECTION	2	2	2
ADT EACH DIRECTION	27,500	27500	27500
ESTIMATED LENGTH OF ROAD CLOSURE, MILES (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF LANES CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF DAYS CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
ESTIMATED REDUCTION IN CLOSURE TIME (FROM CONV. TO ARM)*	20%	20%	20%
USER COSTS PER OPERATION, CONV. METHODS *	10,625	10,625	10,625
USER COSTS PER OPERATION, ARM SYSTEM *	8,368	8,368	8,368
NO. OF THESE TYPICAL OPERATIONS PER YEAR	6	6	6
TOTAL USER COSTS, CONVENTIONAL METHODS *	**$212,001**	**$188,153**	**$168,475**
TOTAL USER COSTS, ARM SYSTEM *	**$166,967**	**$148,185**	**$132,687**
TOTAL UNIT COST USING CONV. METHODS (CONTRACTOR+USER COSTS)	**$44.87**	**$39.90**	**$35.80**
TOTAL UNIT COST USING ARM SYSTEM (CONTRACTOR+USER COSTS)	**$35.41**	**$31.51**	**$28.29**
CONTRACTORS' SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$340**	**$284**	**$239**
USER-COST SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$45,034**	**$39,968**	**$35,788**
TOTAL SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$45,374**	**$40,253**	**$36,027**

Note: Output in bold format

Figure B.2b Economic Analysis of ACS for hot pour crack sealing by Contractors (user-costs savings)

ECONOMIC ANALYSIS OF AUTOMATED CRACK SEALER (In-house, cold pour crack sealing)			
GENERAL DATA	SCENARIO 1	SCENARIO 2	SCENARIO 3
WORK UNITS OF THE ARM SYSTEM	Gallons	Gallons	Gallons
ESTIMATED WORK CAPACITY OF THE ARM SYSTEM (UNITS/YEAR)	44,550	44,550	44,550
ESTIMATED YEARLY EFFICIENCY OF THE ARM SYSTEM	90%	90%	90%
ANALYSIS PERIOD OR LIFE OF THE ARM SYSTEM (YEARS)	6	6	6
MINIMUM ATTRACTIVE RATE OF RETURN (MARR)	4.00%	6.00%	8.00%
INITIAL COST OF ARM SYSTEM (PRESENT $)	$70,000	$70,000	$70,000
OPERATING COSTS OF ARM SYSTEM (ANNUAL $)	$4,000	$4,000	$4,000
MAINTENANCE COSTS OF ARM SYSTEM (ANNUAL $)	$3,000	$3,000	$3,000
OVERHEADS OF ARM SYSTEM (ANNUAL $)	$3,500	$3,500	$3,500
SALVAGE VALUE OF ARM SYSTEM (FUTURE $)	$15,000	$15,000	$15,000
LIFE CYCLE COST/UNIT-WORK OF 1 ARM SYSTEM ($/UNIT)	**$0.47**	**$0.46**	**$0.45**
CURRENT TXDOT COSTS/UNIT WORK ($ /UNIT)	$4.76	$4.76	$4.76
" " YEARLY EXPENDITURES FOR THIS ACTIVITY ($/YEAR)	$688,800	$688,800	$688,800
" " EXPENDITURES ON LABOR FOR THIS ACTIVITY (%)	60.70%	60.70%	60.70%
" " TYPICAL CREW SIZE FOR THIS MAINTENANCE ACTIVITY	7	7	7
NUMBER OF CREW MEMBERS TO BE REDUCED BY THE ARM SYSTEM	4	4	4
YEARLY UNIT WORK DONE BY TXDOT (UNITS)	**144,706**	**144,706**	**144,706**
% WORK PERFORMED BY 1 ARM SYSTEM	**30.79%**	**30.79%**	**30.79%**
LIFE CYCLE LABOR SAVING/UNIT-WORK OF1 ARM SYSTEM	**$1.60**	**$1.50**	**$1.41**
TXDOT LIFE-CYCLE SAVINGS (1 ARM SYSTEM)	**$272,392**	**$250,631**	**$230,943**
TXDOT LIFE-CYCLE SAVINGS (ALL WORK BY ARM SYSTEMS)	**$817,175**	**$751,892**	**$692,828**

Note: Output in bold format

Figure B.3a Economic Analysis of ACS for cold pour in-house crack sealing by TxDOT (direct savings)

ECONOMIC ANALYSIS OF AUTOMATED CRACK SEALER (In-house, cold pour crack sealing)			
CASE STUDY	SCENARIO 1	SCENARIO 2	SCENARIO 3
PROJECT	I-35, San Marcos to New Braunfils (20 mile segment)		
ESTIMATED TOTAL UNIT WORK TO BE PERFORMED	330	330	330
NO. OF LANES EACH DIRECTION	2	2	2
ADT EACH DIRECTION	27,500	27500	27500
ESTIMATED LENGTH OF ROAD CLOSURE, MILES (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF LANES CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF DAYS CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
ESTIMATED REDUCTION IN CLOSURE TIME (FROM CONV. TO ARM)*	20%	20%	20%
USER COSTS PER OPERATION, CONV. METHODS *	10,625	10,625	10,625
USER COSTS PER OPERATION, ARM SYSTEM *	8,368	8,368	8,368
NO. OF THESE TYPICAL OPERATIONS PER YEAR	6	6	6
TOTAL USER COSTS, CONVENTIONAL METHODS *	**$334,186**	**$313,479**	**$294,709**
TOTAL USER COSTS, ARM SYSTEM *	**$263,197**	**$246,889**	**$232,106**
UNIT COST (USER-COSTS) FROM CONV. SYSTEM ($/UNIT)	**$1,012.69**	**$949.94**	**$893.06**
UNIT COST (USER-COSTS) FROM ARM SYSTEM ($/UNIT)	**$797.57**	**$748.15**	**$703.35**
TOTAL UNIT COST USING CONV. METHODS (TXDOT+USER COSTS)	**$1,017.45**	**$954.70**	**$897.82**
TOTAL UNIT COST USING ARM SYSTEM (TXDOT+USER COSTS)	**$801.20**	**$751.87**	**$707.15**
TXDOT SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$374**	**$344**	**$317**
USER-COST SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$70,989**	**$66,590**	**$62,603**
TOTAL SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$71,363**	**$66,934**	**$62,920**

Note: Output in bold format

Figure B.3b Economic Analysis of ACS for cold pour in-house crack sealing by TxDOT (user-cost savings)

ECONOMIC ANALYSIS OF AUTOMATED CRACK SEALER (Contractors, cold pour crack sealing)			
GENERAL DATA	SCENARIO 1	SCENARIO 2	SCENARIO 3
WORK UNITS OF THE ARM SYSTEM	Gallons	Gallons	Gallons
ESTIMATED WORK CAPACITY OF THE ARM SYSTEM (UNITS/YEAR)	44,550	44,550	44,550
ESTIMATED YEARLY EFFICIENCY OF THE ARM SYSTEM	90%	90%	90%
ANALYSIS PERIOD OR LIFE OF THE ARM SYSTEM (YEARS)	6	6	6
MINIMUM ATTRACTIVE RATE OF RETURN (MARR)	20.00%	25.00%	30.00%
INITIAL COST OF ARM SYSTEM (PRESENT $)	$70,000	$70,000	$70,000
OPERATING COSTS OF ARM SYSTEM (ANNUAL $)	$4,000	$4,000	$4,000
MAINTENANCE COSTS OF ARM SYSTEM (ANNUAL $)	$3,000	$3,000	$3,000
OVERHEADS OF ARM SYSTEM (ANNUAL $)	$3,500	$3,500	$3,500
SALVAGE VALUE OF ARM SYSTEM (FUTURE $)	$15,000	$15,000	$15,000
LIFE CYCLE COST/UNIT-WORK OF 1 ARM SYSTEM ($/UNIT)	**$0.42**	**$0.40**	**$0.39**
CURRENT TXDOT COSTS/UNIT WORK ($ /UNIT)	$8.40	$8.40	$8.40
" " YEARLY EXPENDITURES FOR THIS ACTIVITY ($/YEAR)	$305,200	$305,200	$305,200
" " EXPENDITURES ON LABOR FOR THIS ACTIVITY (%)	60.70%	60.70%	60.70%
" " TYPICAL CREW SIZE FOR THIS MAINTENANCE ACTIVITY	7	7	7
NUMBER OF CREW MEMBERS TO BE REDUCED BY THE ARM SYSTEM	4	4	4
YEARLY UNIT WORK DONE BY TXDOT CONTRACTORS (UNITS)	**36,333**	**36,333**	**36,333**
% WORK PERFORMED BY 1 ARM SYSTEM	**122.61%**	**122.61%**	**122.61%**
LIFE CYCLE LABOR SAVING/UNIT-WORK OF1 ARM SYSTEM	**$1.79**	**$1.59**	**$1.43**
CONTRACTORS' LIFE-CYCLE SAVINGS (1 ARM SYSTEM)	**$331,760**	**$286,040**	**$248,390**
CONTRACTORS' LIFE-CYCLE SAVINGS (ALL WORK BY ARM SYSTEMS)	**$331,760**	**$286,040**	**$248,390**

Note: Output in bold format

Figure B.4a Economic Analysis of ACS for cold pour crack sealing by Contractors (direct savings)

ECONOMIC ANALYSIS OF AUTOMATED CRACK SEALER (Contractors, cold pour crack sealing)			
CASE STUDY	SCENARIO 1	SCENARIO 2	SCENARIO 3
PROJECT	I-35, San Marcos to New Braunfils (20 mile segment)		
ESTIMATED TOTAL UNIT WORK TO BE PERFORMED	330	330	330
NO. OF LANES EACH DIRECTION	2	2	2
ADT EACH DIRECTION	27,500	27500	27500
ESTIMATED LENGTH OF ROAD CLOSURE, MILES (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF LANES CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
NO. OF DAYS CLOSED (CONV., ARM)	(1,1)	(1,1)	(1,1)
ESTIMATED REDUCTION IN CLOSURE TIME (FROM CONV. TO ARM)*	20%	20%	20%
USER COSTS PER OPERATION, CONV. METHODS *	10,625	10,625	10,625
USER COSTS PER OPERATION, ARM SYSTEM *	8,368	8,368	8,368
NO. OF THESE TYPICAL OPERATIONS PER YEAR	6	6	6
TOTAL USER COSTS, CONVENTIONAL METHODS *	**$212,001**	**$188,153**	**$168,475**
TOTAL USER COSTS, ARM SYSTEM *	**$166,967**	**$148,185**	**$132,687**
TOTAL UNIT COST USING CONV. METHODS (CONTRACTOR+USER COSTS)	**$650.83**	**$578.56**	**$518.93**
TOTAL UNIT COST USING ARM SYSTEM (CONTRACTOR+USER COSTS)	**$512.98**	**$456.26**	**$409.45**
CONTRACTORS' SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$455**	**$392**	**$341**
USER-COST SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$45,034**	**$39,968**	**$35,788**
TOTAL SAVINGS ON CASE STUDY 1 (LIFE CYCLE OF ARM SYSTEM)	**$45,489**	**$40,361**	**$36,129**

Note: Output in bold format

Figure B.4b Economic Analysis of ACS for cold pour crack sealing by Contractors (user-costs savings)

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