Life Cycle Cost Analysis:
Conventional Versus Asphalt-Rubber Pavements

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INTRODUCTION

The Arizona Department of Transportation (ADOT) has used Asphalt Rubber (AR) as a modified binder since the early 1970's (1). The primary purpose for using AR is to reduce reflective cracking in hot mix asphalt (HMA) rehabilitation overlays (2,3). In addition, AR has been used to reduce maintenance and provide a smooth riding surface with good skid resistance. The AR mixes have also performed well in snow and ice conditions providing a tough surface that stands up well to snow plows. Recently, AR mixes have been recognized as a means of reducing the tire/ pavement interface noise (4).

The AR as used in Arizona is a mixture of approximately 20 percent ground tire rubber (crumb rubber) made from the recycling of used or defective tires. The ground tire rubber is added to hot paving grade asphalt at a high temperature and mixed with a high shear mixer. The mixing time and subsequent time of material interaction is generally 45 to 60 minutes (1). After the interaction the hot AR product has acquired unique elastomeric properties. The hot AR is then pumped into a conventional hot plant and mixed with aggregate and placed like a conventional HMA, except for a few significant differences.

These significant differences relate to the gradation of the mineral aggregate and the percent binder. The AR hot mix is generally either a gap graded or open graded mix. The gap graded mix contains about 7.5 percent AR binder and is placed generally as the final structural course 1.5 to 2 inches in thickness. The open graded contains generally 9 percent binder and is placed as the final wearing course from 0.5 to 1.0 inch thick. The mix designs for these two mixes are typically of a volumetric type. Recently, a research study has been completed at Arizona State University (ASU) to evaluate the binder and the mix engineering properties in terms of the inputs needed for the new AASHTO 2002 Pavement Design Guide (5).

The typical cost of a crumb rubber modified (CRM) mix is 1.5 to 2.0 times more than a conventional mix (6). However, the benefits of using CRM are many, and therefore, a life cycle cost analysis (LCCA) should be performed. LCCA is an engineering economic analysis tool that allows the comparison of different cost options for given projects during a selected analysis periods. In this study, agency and user costs of an asphalt-rubber pavement and a conventional asphalt pavement were calculated and compared. Agency costs such as reconstruction, rehabilitation, and maintenance incurred directly by the agency are easily identified by the agency. However, user costs are difficult to quantify and calculate, and the different models used often provide different solutions. Two models (computer programs) were used in this study. These are the World Bank's Highway Design and Maintenance System (HDM-4), and MicroBENCOST that was developed under NCHRP project 7-12. Both of these are among the known models that can provide useful tools for analyzing life cycle cost analysis.

PAVEMENT SECTIONS SELECTED FOR THIS STUDY

Data for project comparison with and without asphalt rubber modification was provided by the Arizona Department of Transportation (Mr. George Way). The conventional pavement used in this analysis was a reconstruction project on Interstate (I))-40 West Bound (WB) at Mile Post (MP) 191-194. The pavement was built in 1985 to replace the deteriorated concrete pavement. It was a 20 year design and consisted of a very thick asphalt concrete section.. This conventional asphalt pavement system consisted of 4-in. of aggregate base, 6-in. of bituminous treated base, and 11-in. of asphalt concrete. By 1995 it had cracked to such a degree and become rough enough to warrant rehabilitation with asphalt rubber layer. Since then, the asphalt rubber also cracked to some degree, but the ride is still very good. This rehabilitation section was a ten-year design and it appears that the pavement will last over the ten-year period.

The asphalt rubber pavement is immediately adjacent to the above project. It is located on I-40 WB MP 196-204. This asphalt-rubber pavement system had 8-in. of aggregate base with broken old concrete pavement, 3-in. of conventional asphalt concrete, 2-in. of asphalt-rubber gap graded mixture (ARAC), and 0.5-in. of asphalt-rubber open graded friction course (AR-ACFC).

To compare both types of pavements under the same conditions, the length of the project considered was 4 miles. The International Roughness Index (IRI) and Present Serviceability Rating (PSR) were used for the performance index for this study. However, ADOT measured the ride quality index by Mays Meter, and therefore the measurements were converted to IRI using ADOT's regression equation that is presented later in this report. The Average Daily Traffic (ADT) on this pavement is approximately 20,000 with 4% annual growth rate and 20% trucks.

OBJECTIVES

The main objective of this study was to conduct life cycle cost analysis comparison on the selected conventional and asphalt rubber pavements using the HDM-4 and MicroBENCOST computer programs.

REVIEW OF MicroBENCOST AND HDM-4

The computer programs MicronBENCOST and HDM-4 were utilized in evaluating the cost-benefits of using an asphalt-rubber pavement compared to a conventional asphalt pavement. The following is a brief background on each program.

1. MicroBENCOST

MicroBENCOST was developed under NCHRP project 7-12(2) by the Texas Transportation Institute (TTI) (7). This program can analyze benefits and costs of seven general categories of projects: add-capacity, bypass, intersection/interchange, pavement rehabilitation, bridge, safety, and highway-railroad grade crossing. It can be used to compare different alternatives of pavements during the analysis periods. One main disadvantage of this program is that all inputs are entered before the file can be saved because it is a DOS based program. Another disadvantage is related to default values. The default values called up by the program based on user input are not necessarily updated when the user makes a change to the input (8).

2. HDM-4

The Highway Design and Maintenance Standard Model (HDM-4) was developed by the World Bank for evaluating the technical and economic aspects of highway investment projects (9). This program can apply three tools for life cycle costs analysis: Strategy analysis, Program analysis, and Project analysis. The major disadvantage of this program is that it is difficult to compare user costs of different alternative at high quality highway (more than 2 mm/km of IRI) because it was developed for developing countries. Table 1 shows how HDM-4 classifies ride quality at different classes (9).

Table 1. Default Values for Ride Quality - Asphalt and Portland Cement Concrete Roads (9).

Road Class	Ride quality (m/km IRI)			
	Good	Fair	Poor	Bad
Primary or Trunk	2	4	6	8
Secondary or Main	3	5	7	9
Tertiary or Local	4	6	8	10

COMPONENTS OF LIFE CYCLE COST ANALYSIS (LCCA)

The components of LCCA are grouped in two categories as they are used for this study. These are the agency and user costs. Agency costs consist of initial construction, rehabilitation, and maintenance costs. Other costs such as preliminary engineering and right of way were not considered for this study. User costs include travel time delay costs, vehicle operating costs (VOC), accident costs, discomfort costs, etc.., However, this study considered only travel time delay costs and VOC because other user costs are difficult to collect and quantify. Also, the effect on work zone during construction and rehabilitation was ignored.

ANALYSIS APPROACHES

The general approach used in this study involved utilizing MicroBENCOST and HDM-4 to compute and compare life cycle costs over time for an asphalt-rubber pavement and a conventional asphalt pavement subjected to roadway traffic. Actual data related to both pavements over an 11-year period were obtained from ADOT. Based on these data, the prediction of maintenance costs and IRI were made during the analysis period. The procedures for evaluating the life cycle costs used in this study are described below in a 5-step procedure.

Step 1. Analysis Period and Discount Rate

Life cycle cost analysis should be sufficiently long to reflect long-term cost differences associated with reasonable design strategies. FHWA recommended an analysis period of at least 35 years (10). Generally, the life of concrete pavement is more than 20 years, while the life of asphalt pavement is around 10 years. Despite the fact that the data available from ADOT covered only 11 years of performance, a 25-year analysis period was selected because it would be appropriate for reflecting long-term cost effect as one or more rehabilitation strategies should be taken. For the period March 1991 through August 1996, the discount rate ranges between 3 to 5 percent (10). This study selected 4 % as an average discount rate to be used in the analysis.

Step 2. Performance Index

Table 2 shows the performance data for the 11-year period and is also graphically shown in Figure 1. For simplicity, the asphalt rubber pavement is referred to as ARAC, whereas the conventional pavement is referred to as AC. In Table 2, it is noted that the IRI values of the asphalt-rubber pavement are constant along the years, but for the conventional asphalt pavement it is increasing with time.

Based on the actual IRI measurements for the 11-year period for both pavements, predictions of IRI values up to 25-year analysis period were made by fitting the data to an exponential function as shown Figure A-1 and A-2 in the Appendix. The reason of using exponential function was that it best fit IRI trends compared to linear and power functions. These predictions of performance index were used for analyzing and computing user costs of both pavements during the 25-year analysis period. Table A-1 in the Appendix shows the prediction of IRI trends using the exponential functions developed for each pavement.

Table 2. Performance Index of Both Pavements.

Conventional AC					Asphalt Rubber (ARAC)				
Year	Mays Inch/mile	IRI inch/mile	IRI m/km	PSR	Year	Mays Inch/mile	IRI inch/mile	IRI m/km	PSR
1985	56	66.99	1.06	3.88	1991	41	48.66	0.77	4.16
1986	58	69.44	1.10	3.84	1992	47	55.99	0.88	4.04
1987	44	52.33	0.83	4.10	1993	54	64.55	1.02	3.92
1988	40	47.44	0.75	4.18	1994	43	51.11	0.81	4.12
1989	44	52.33	0.83	4.10	1995	49	58.44	0.92	4.01
1990	56	66.99	1.06	3.88	1996	51	60.88	0.96	3.97
1991	58	69.44	1.10	3.84	1997	44	52.33	0.83	4.10
1992	74	88.99	1.40	3.57	1998	45	53.55	0.85	4.08
1993	87	104.87	1.66	3.36	1999	45	53.55	0.85	4.08
1994	67	80.43	1.27	3.69	2000	42	49.88	0.79	4.14
1995	87	104.87	1.66	3.36	2001	44	52.33	0.83	4.10

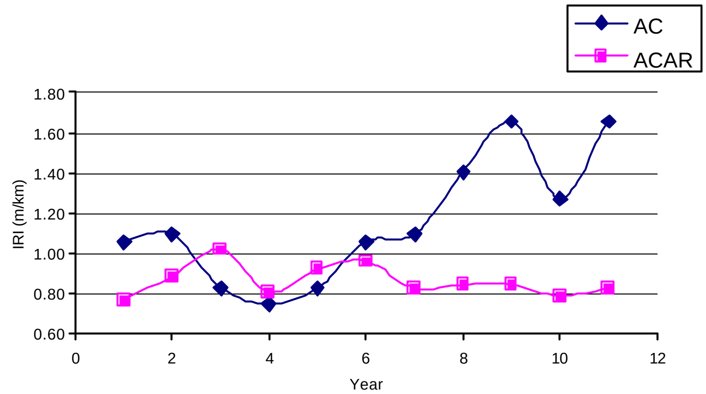


Figure 1. IRI Data for Both Pavements - 11-Year Period.

Step 3. Agency Costs

Agency cost data was also obtained from ADOT. Table 3 shows initial reconstruction and overlay costs for both pavements. The unit costs of a conventional asphalt pavement is less than those for an asphalt-rubber pavement, but the total initial cost is much more for the conventional pavement due to difference in the thickness of each layer (as constructed). The difference in initial cost is $639,232.

Table 3. Initial Reconstruction and Overlay Costs of Both Pavements.

AC Pavement	Thickness (in)	Length (yard)	Width (yard)	Cost ($) /sq_yd_in	Total Cost ($)
AB	4	7040	8	0.55	123904
BTB	6	7040	8	1	337920
AC	11	7040	8	1.7	1053184
Sum					1515008
ARAC Pavement					
AB	8	7040	8	0.55	247808
AC	3	7040	8	1.7	287232
ARAC	2	7040	8	2.4	270336
ARACFC	0.5	7040	8	2.5	70400
Sum					875776

Table 4 shows the maintenance costs for conventional and asphalt-rubber pavements over the years and at Mile Post (MP) number. Because of the difference in the years for the two pavements, a 4 % discount rate was used to adjust the costs to correspond to similar years for the analysis. .

Table 4. Maintenance Costs by Year.

Year	AC Maintenance Costs at MP ($)					Year	ARAC Maintenance Costs at MP ($)				
	MP191	MP192	MP193	MP194	Total		MP196	MP197	MP198	MP199	Total
1985	17294	7800	10131	6943	42168	1991	62	29	29	34	154
1986	128	128	128	128	512	1992	50	1082	50	50	1232
1987	36	1822	36	36	1930	1993	163	1124	163	163	1613
1988	981	346	54	48	1429	1994	450	2667	450	450	4017
1989	846	355	355	217	1773	1995	1122	160	160	160	1602
1990	1	14	25	67	107	1996	425	425	598	340	1788
1991	1872	1734	5485	1036	10127	1997	1213	3240	121	121	4695
1992	2493	172	178	2367	5210	1998	4682	1839	63	63	6647
1993	3701	4344	6406	14225	28676	1999	2372	3659	4036	796	10863
1994	2431	3878	2115	323	8747	2000	1547	1945	1555	1310	6357
1995	3012	3054	5093	739	11898	2001	232	2288	1896	356	4772

Figures 2 and 3 show trends of both pavement maintenance costs over the 11-year period. After reconstruction or overlay, maintenance costs of both pavements increase as years pass. In addition, its costs of both pavements increase as pavement roughness decrease. Trends of maintenance costs on both pavements are made assuming linear function excluding one or two outliers. Based on these trends, maintenance costs of both pavements project until the end of analysis periods. Appendix provides maintenance costs in the table 2 and liner functions of both pavements during analysis periods.

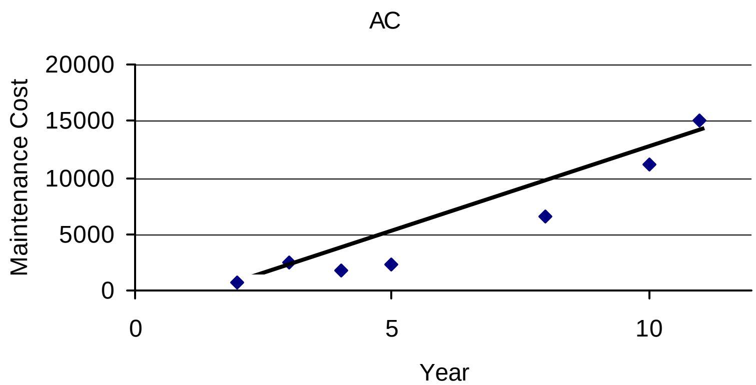


Figure 2. Maintenance Costs Trend for the Conventional AC Pavement.

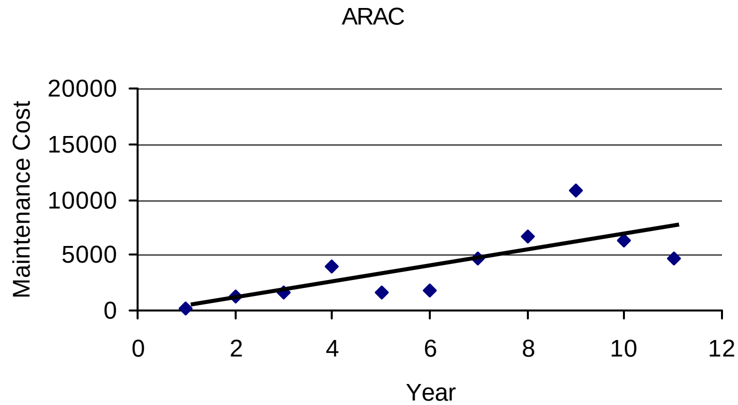


Figure 3. Maintenance Costs Trend for the Asphalt-Rubber (ARAC) Pavement.

Step 4. User Costs

Vehicle Operating Costs (VOC) and delay time costs were also considered. Three broad vehicle classes and weighted average values of time are recommended by FHWA (10). Table 5 shows the three broad vehicle classes and weighted time cost values in US dollars.

Table 5. Recommended values of travel time ($/Vehicle-Hour) - Aug 96 (10).

	Trucks	
Passenger Cars (Average)	Single-Unit (Average)	Combinations (Average)
$ 10 to 13 ($11.58)	$ 17 to 20 ($18.54)	$ 21 to 24 ($22.31)

For MicroBENCOST, the program provided the vehicle unit operating costs for a wide range of vehicle classifications. Table 6 includes a simple modified version for three classifications, which was arrived at by averaging values of similar vehicle classes. Table 6 also shows vehicle unit operating costs for the three vehicles classes. This table was utilized for quantifying VOC for the two pavement types. All user costs were converted to base year costs using the Consumer Price Index (CPI). Estimate of travel time values in Table 5 is based on wages, so the CPI of the city average wages was used. While measured VOC in Table 6 is dependent on policies (for example, public transportation fee and fuel), so the CPI of average transportation was used. The CPIs of travel time values in 1991 (year average) and 1996 (August) are 136.2 and 157.3, while those of the VOC in those years were 123.8 and 139.1, respectively. Multiplying the cost by an escalation factor based on the consumer price index (CPI), the conversion to base year cost can be made. The escalation factor is computed as follows:

Table 6. Vehicle unit Operating Costs (in 1995 dollars).

Vehicle Class	Fuel Cost ($/gal)	Oil Cost ($/qrt)	Tire Cost ($/veh)	Maint & Rep Cost ($/1000 mi)	Deprec. Cost ($/veh)
Passenger Cars	0.86	3.31	277	74.5	12207
Single-Unit Truck	0.84	1.66	3227	207.89	47197
Combinations Truck	0.76	1.66	11349	252.25	95928

$$EscalationFactor = \frac{CPI_{bsse\_year}}{CPI_{stated\_year}} \quad (1)$$

where,

CPI_{base_year} = CPI for base year, e.g. 1991
CPI_{stated_year} = CPI for original year of stated costs, e.g., 1995 and 1996

Step 5. Economic Indicator

Net Present Value (NPV) and Equivalent Uniform Annual Cost (EUAC) were utilized to evaluate the cost effectiveness of the two pavements in this study. NPV is the discounted monetary value of expected net benefit. EUAC expresses present and future costs in terms of an equalized, annual pavement using a selected discount rate. NPV and EUAC were calculated by the following equations:

$$NPV = Initial\_Cost + \sum_{K=1}^{n} future\_\cos ts_k \left[\frac{1}{(1+n)^{nk}} \right] \quad (2)$$

$$EUAC = \sum_{K=1}^{n} NPV \left[\frac{i}{1-(1+i)^{n}} \right] \quad (3)$$

COST-EFFECTIVENESS ANALYSIS

Agency Costs

Agency costs consider reconstruction (or rehabilitation) cost and maintenance cost. Table A-2 in the Appendix shows that initial construction and maintenance costs for both types of pavements during the analysis period. NPV and EUAC for the conventional asphalt pavement are $ 1,788,509 and $26,836, respectively. While those of the asphalt-rubber pavement are $994,750 and $14,926, respectively. The data show that, during the analysis period selected, the asphalt-rubber pavement is more cost-effective compared to a conventional asphalt pavement.

User Costs Using MicroBENCOST

Performance index of MicroBENCOST is based on PSI. Using Al-Omari and Darter's equation, the IRI can be converted into PSR (11). The equation for an asphalt concrete pavement is as follows:

$$PSR = 5 \exp(-0.24\, IRI) \quad (4)$$

Table A-3 and A-4 provides the detailed user costs for the two pavements. Figures 4 through 6 show the VOC, time delay costs, and total user costs for the two pavements during the selected analysis period. Figure 4 shows that the VOC increases over the years, as the pavement roughness increases. The difference of VOC NPV between the two pavements during the analysis period is $9,340,000. Figure 5 shows the time costs trends for the two pavements. Travel time costs are closely related to speed. Table A-3 and A-4 show the speed difference for the two pavements. The speed of an asphalt-rubber pavement is almost constant because its performance index is uniform (good condition); while that of a conventional pavement decreases due to increased pavement roughness. The difference of time cost NPV between the two pavements is $3,288,000.

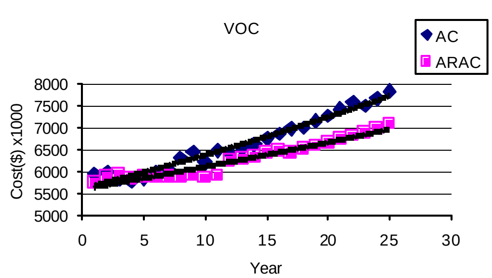


Figure 4. MicroBENCOST VOC.

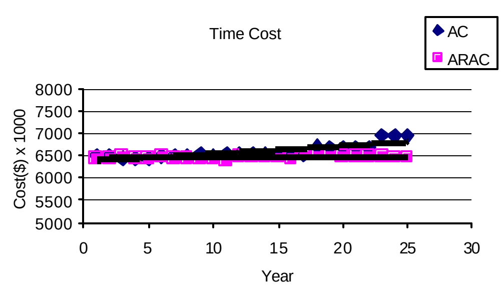


Figure 5. MicroBENCOST Time Delay Costs.

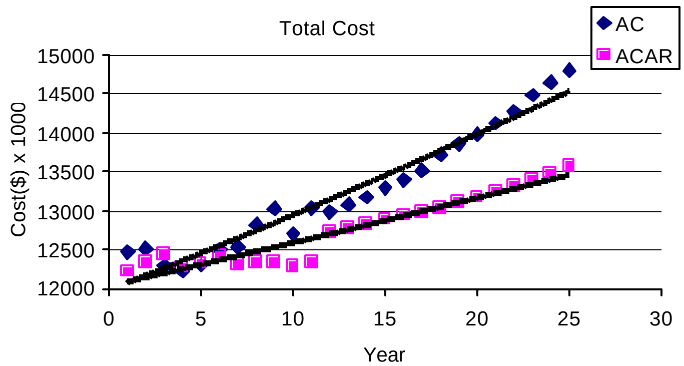


Figure 6. MicroBENCOST Total User Costs.

The total user cost is the sum of VOC and travel time cost. Figure 6 shows trends of total user costs for the two pavements. As pavements get rougher, the total user costs increase. The difference of the total user cost NPV between the two pavements is $12,627,000.

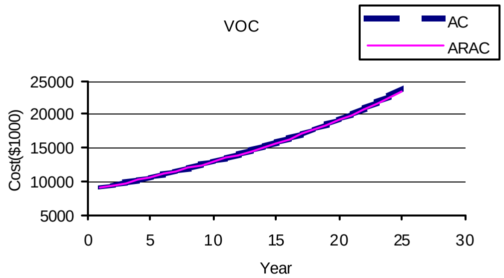
User Costs Using HDM-4

HDM-4 can apply three tools for life cycle costs analysis: Strategy analysis, Program analysis, and Project analysis. This study considered only the Project analysis. Project analysis can be used to estimate the economic or engineering viability of investment projects by considering the structural performance of pavements, life cycle predictions of highway deterioration, effects of highway work and costs, highway user costs and benefits, and economic comparisons of project alternatives. HDM-4 calculates user costs using the IRI. Given that the performance data for the two pavements (provided by ADOT) were measured by Mays Ride Meter (MRM), the following ADOT regression equation was used to convert the MRM to IRI:

$$IRI = 1.222 * MRM - 1.44 \quad (5)$$

Where MRM is in inches per mile.

Several trials were done using the distress model calibration factors in HDM-4 in order to match similar IRI values to the trend observed for each pavement. Table A-5 in the Appendix shows trends of IRI and user costs for the two pavements using HDM-4. Figure 7 through 9 show trends of VOC, travel time costs, and total user costs. The user costs for the two pavements increase as the pavement roughness is increased. However, the difference in user costs for the two pavements are not noticeable. It appears that for high quality highway analysis (IRI less than 2), such as that found in developed countries, the HDM-4 may not be suitable for evaluating user costs. Historically, the HDM-4 was developed for use in developing countries where higher IRI values exist.



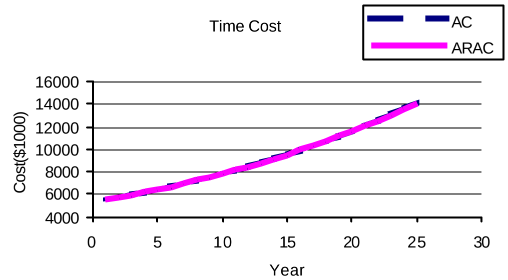


Figure 7. HDM-4 Vehicle Operating Costs.

Figure 8. HDM-4 Time Delay Costs.

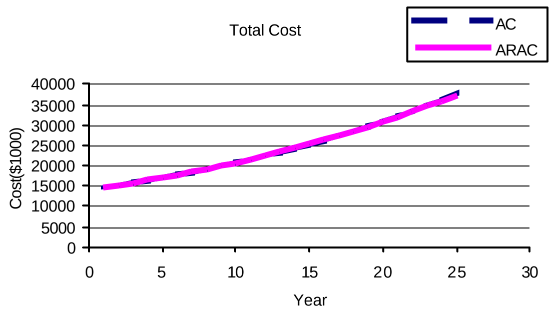


Figure 9. HDM-4 Total User Costs.

Concluding Remarks on MicroBENCOST and HDM-4

MicroBENCOST can be only used for project analysis, whereas the HDM-4 can be used for comprehensive analysis including strategy, programming, and project analysis. On the other hand, StratBENCOST computer program was developed under NCHRP project 2-18(2) to include strategy analysis.

The main difference between the HDM-4 and MicroBENCOST is that MicroBENCOST does not have the performance prediction models, and simply uses the PSR as direct input for each year into the program. On the other hand, the HDM-4 has performance prediction models and predicts IRI based on pavement condition. Therefore, HDM-4 requires much more data detail to run the project analysis.

In addition, it appeared that for high quality highway analysis (IRI less than 2), such as that found in developed countries, the HDM-4 was not able to differentiate differences in user costs. Historically, the HDM-4 was developed for use in developing countries where higher IRI values exist.

SUMMARY AND CONCLUSION

Agency costs include all costs, such as initial construction, rehabilitation, and maintenance costs, incurred directly by the agency over the life of the project, while user costs incurred indirectly by agency. In a survey conducted in the United States, 29 percent indicated that they assess user cost impacts quantitatively in considering major construction projects; while 27 percent asses user cost impacts for major rehabilitation and maintenance projects; 38 percent do so in planning roadwork mitigation strategies for major construction, and 33 percent do so for maintenance projects. (12).

User costs should be included to the extent they might affect the choice of pavement alternatives. This study calculated and evaluated agency costs and user costs for an asphalt-rubber pavement (referred to as ARAC) and a conventional asphalt pavement (referred to as AC) using MicroBENCOST and HDM-4. The asphalt-rubber pavement was shown to be cost-effective for the two pavements selected for this study. Table 7 shows a summary of the difference of costs between the two pavements. This include the initial construction (or overlay), maintenance, and user costs.

Table 7. Construction, Maintenance and User Costs Comparison (MicroBENCOST).

	AC		ARAC		Difference	
Year	MC ($)	UC ($1000)	MC ($)	UC ($1000)	MC($)	UC ($1000)
0	1515008		875776		639232	
5	1844	12296	1317	12325	527	-29
10	7477	12705	4295	12288	3182	417
15	10471	13288	5853	12890	4618	398
20	11998	13981	6471	13172	5527	809
25	12649	14800	6683	13565	5966	1235

0: Initial Construction Cost, MC: Maintenance Cost, UC: User Cost.

Figures 11 and 12 show maintenance and user costs trends for the two pavements, respectively. After 5 years, the maintenance and user costs are not much different. After 10 years, the maintenance cost begins to substantially be different, as higher maintenance costs will be anticipated for the conventional pavement. This difference for user costs starts at about 15 years.

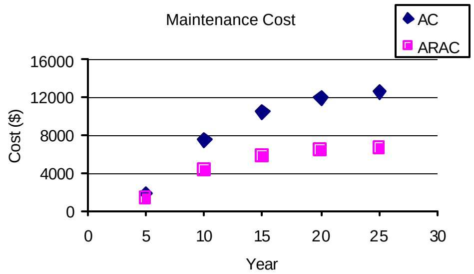


Figure 11. Maintenance Cost Comparison.

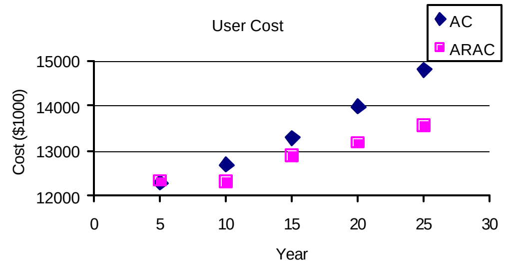


Figure 12. User Costs Comparisons.

Based on the data analysis presented for the two pavements, an asphalt-rubber pavement would be more cost-effective than a conventional pavement with respect to agency costs as well as user costs. In addition, the good performance of the asphalt-rubber pavement would increase its service life, which in turn would have a substantial impact on life cycle cost analysis Furthermore, if one or more rehabilitation is eliminated in a typical analysis period (35 years), it would also have a significant impact on user costs during the work zone periods.

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APPENDIX

DATA USED FOR MicorBENCOST and HDM-4 ANALYSIS

Table A-1. IRI Trends of Both Pavements During the Analysis Period.

AC					ARAC				
Year	Mays Inch/mile	IRI inch/mile	IRI m/km	PSR	Year	Mays Inch/mile	IRI inch/mile	IRI m/km	PSR
1	56	66.99	1.06	3.88	1	41	48.66	0.77	4.16
2	58	69.44	1.10	3.84	2	47	55.99	0.88	4.04
3	44	52.33	0.83	4.10	3	54	64.55	1.02	3.92
4	40	47.44	0.75	4.18	4	43	51.11	0.81	4.12
5	44	52.33	0.83	4.10	5	49	58.44	0.86	4.07
6	56	66.99	1.06	3.88	6	51	60.88	0.96	3.97
7	58	69.44	1.10	3.84	7	44	52.33	0.83	4.10
8	74	88.99	1.40	3.57	8	45	53.55	0.85	4.08
9	87	104.87	1.66	3.36	9	45	53.55	0.85	4.08
10	67	80.43	1.27	3.69	10	42	49.88	0.79	4.14
11	87	104.87	1.66	3.36	11	44	52.33	0.83	4.10
12	83	100.59	1.59	3.42	12	67	80.53	1.27	3.69
13	88	106.67	1.68	3.34	13	70	83.65	1.32	3.64
14	94	113.12	1.79	3.26	14	72	86.89	1.37	3.60
15	99	119.95	1.89	3.17	15	75	90.25	1.42	3.55
16	105	127.21	2.01	3.09	16	78	93.75	1.48	3.51
17	112	134.90	2.13	3.00	17	81	97.38	1.54	3.46
18	118	143.05	2.26	2.91	18	84	101.15	1.60	3.41
19	125	151.70	2.39	2.81	19	87	105.07	1.66	3.36
20	133	160.87	2.54	2.72	20	90	109.14	1.72	3.31
21	141	170.60	2.69	2.62	21	94	113.37	1.79	3.25
22	149	180.91	2.86	2.52	22	98	117.76	1.86	3.20
23	158	191.85	3.03	2.42	23	101	122.32	1.93	3.15
24	168	203.45	3.21	2.31	24	105	127.06	2.01	3.09
25	178	215.75	3.41	2.21	25	109	131.98	2.08	3.03

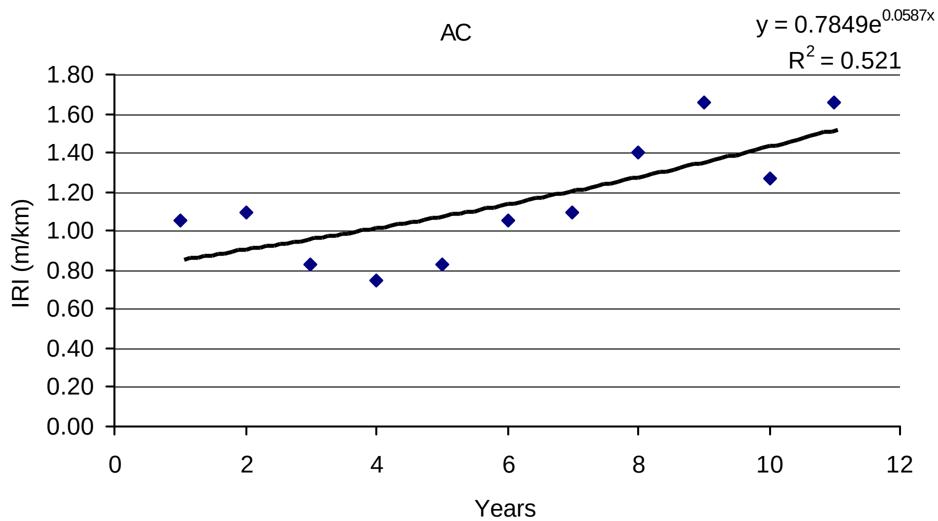

Figure A-1. IRI Trend and Exponential function of AC

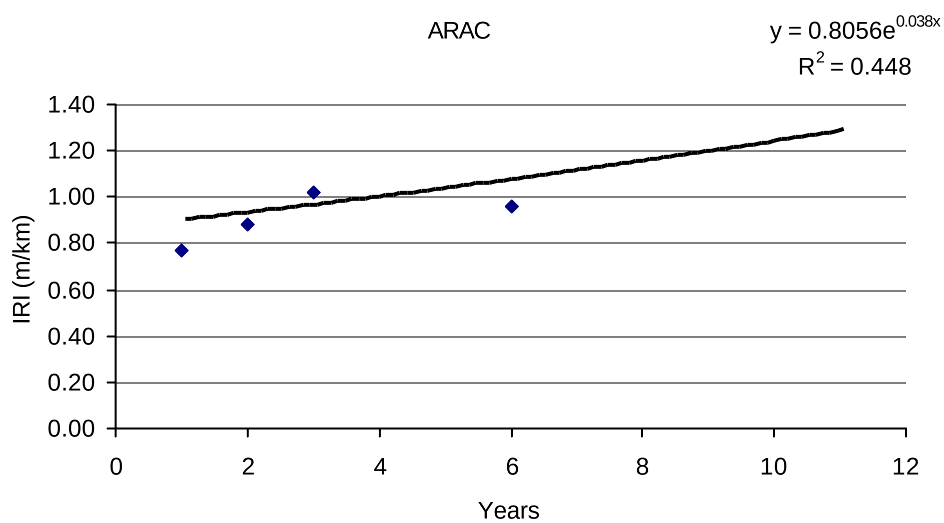

Figure A-2. IRI Trend and Exponential function of ARAC

Table A-2. Maintenance Costs and NPVs for the Two Pavements.

Year	AC	ARAC	NPV_AC($)	NPV_ARAC ($)
1	53356	154	51304	148
2	648	1232	599	1139
3	2442	1613	2171	1434
4	1808	4017	1545	3434
5	2243	1602	1844	1317
6	135	1788	107	1413
7	12814	4695	9738	3568
8	6595	6647	4819	4857
9	36284	10863	25493	7632
10	11068	6357	7477	4295
11	15055	4772	9779	3100
12	14399	8359	8994	5221
13	15886	9087	9541	5457
14	17372	9814	10032	5667
15	18858	10542	10471	5853
16	20345	11269	10862	6017
17	21831	11997	11207	6159
18	23317	12724	11510	6281
19	24804	13452	11773	6385
20	26290	14179	11998	6471
21	27776	14907	12189	6541
22	29262	15634	12347	6597
23	30749	16362	12476	6638
24	32235	17089	12576	6667
25	33721	17816	12649	6683
			273501	118974
Initial construction Cost			1515008	875776
Total NPV			1788509	994750

$$EUAC\_AC = \sum_{K=1}^{n} NPV\left[\frac{i}{1-(1+i)^{n}}\right] = \$26,836$$

$$EUAC\_ARAC = \sum_{K=1}^{n} NPV\left[\frac{i}{1-(1+i)^{n}}\right] = \$14,926$$

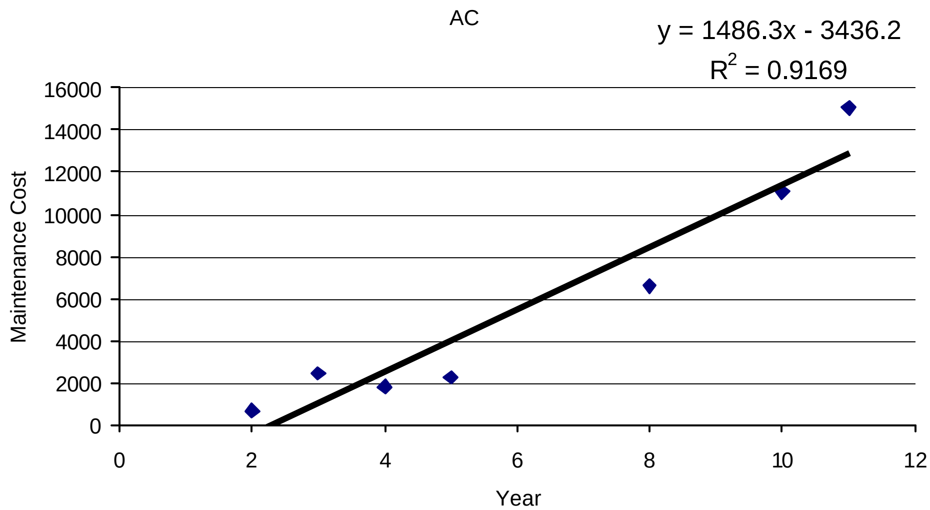

Figure A-3. Maintenance Costs Trend of the Conventional Pavement.

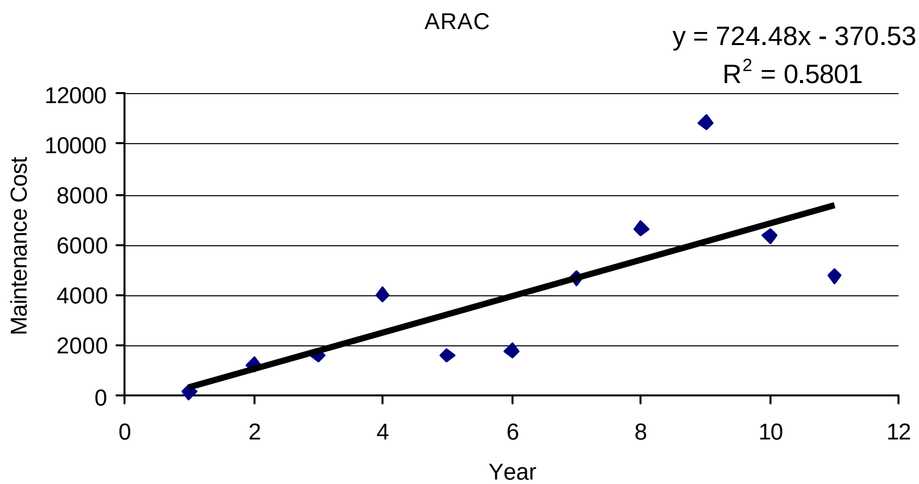

Figure A-4. Maintenance Costs Trend of Asphalt-Rubber Pavement.

Table A-3. User Costs for the Conventional Asphalt Pavement (MicroBENCOST).

Year	Major Average Speed (mph)	Route Num. Veh. 1000	Discounted Moterist Costs (Thous.$) Time Costs	Veh. Oper. Costs	Total Costs	Using CPI (Thous.$) Adj. Time Costs	Adj. VOC	Adj. Total Costs
1	62.5	20	7535	6677	14212	6524	5943	12467
2	62.53	20.8	7532	6729	14261	6522	5989	12511
3	63.2	21.63	7452	6555	14007	6452	5834	12286
4	63.23	22.5	7448	6481	13929	6449	5768	12217
5	63.27	23.4	7444	6574	14018	6445	5851	12296
6	62.66	24.33	7516	6723	14239	6508	5984	12491
7	62.7	25.31	7511	6778	14289	6503	6032	12536
8	62.74	26.32	7507	7098	14605	6500	6317	12817
9	62.14	27.37	7579	7259	14838	6562	6461	13023
10	62.82	28.47	7497	6982	14479	6491	6214	12705
11	62.22	29.61	7569	7284	14853	6554	6483	13037
12	62.27	30.79	7564	7223	14787	6549	6429	12978
13	62.31	32.02	7558	7337	14895	6544	6530	13074
14	62.36	33.3	7552	7454	15006	6539	6634	13173
15	62.41	34.63	7547	7588	15135	6535	6753	13288
16	62.46	36.02	7540	7711	15251	6529	6863	13391
17	62.52	37.46	7534	7851	15385	6523	6987	13511
18	61.93	38.96	7752	7875	15627	6712	7009	13721
19	61.98	40.52	7745	8033	15778	6706	7149	13856
20	62.04	42.14	7738	8181	15919	6700	7281	13981
21	62.09	43.82	7731	8348	16079	6694	7430	14124
22	62.15	45.58	7724	8520	16244	6688	7583	14271
23	60.92	47.4	8053	8440	16493	6973	7512	14484
24	60.98	49.29	8046	8630	16676	6967	7681	14647
25	61.04	51.27	8038	8809	16847	6960	7840	14800
Total			190712	187140	377852	165130	166556	331686

$$VOC\_EscalationFactor = \frac{CPI_{bsse\_year}}{CPI_{stated\_year}} = 0.89 \text{ (Adj. VOC)}$$

$$Time\_Cost\_Escalation\,Factor = \frac{CPI_{bsse\_year}}{CPI_{stated\_year}} = 0.8659 \text{ (Adj. Time Cost)}$$

Table A-4. User Costs of An Asphalt-Rubber Pavement (MicroBENCOST)

Year	Major Average Speed (mph)	Route Num. Veh. 1000	Discounted Moterist Costs (Thous.$) Time Costs	Veh. Oper. Costs	Total Costs	Using CPI (Thous.$) Adj. Time Costs	Adj. VOC	Adj. Total Costs
1	63.14	20	7459	6475	13934	6458	5763	12221
2	63.17	20.8	7456	6610	14066	6456	5883	12339
3	62.56	21.63	7528	6651	14179	6518	5919	12438
4	63.23	22.5	7448	6544	13992	6449	5824	12273
5	63.27	23.4	7444	6606	14050	6445	5879	12325
6	62.66	24.33	7516	6626	14142	6508	5897	12405
7	63.34	25.31	7435	6595	14030	6438	5870	12307
8	63.38	26.32	7431	6628	14059	6434	5899	12333
9	63.42	27.37	7426	6639	14065	6430	5909	12339
10	63.46	28.47	7421	6587	14008	6426	5862	12288
11	63.5	29.61	7416	6642	14058	6421	5911	12333
12	62.91	30.79	7487	7008	14495	6483	6237	12720
13	62.95	32.02	7481	7080	14561	6478	6301	12779
14	63	33.3	7475	7141	14616	6472	6356	12828
15	63.05	34.63	7470	7216	14686	6468	6422	12890
16	63.11	36.02	7463	7281	14744	6462	6480	12942
17	62.52	37.46	7534	7249	14783	6523	6452	12975
18	62.57	38.96	7527	7327	14854	6517	6521	13038
19	62.63	40.52	7521	7407	14928	6512	6592	13104
20	62.68	42.14	7514	7490	15004	6506	6666	13172
21	62.74	43.82	7507	7586	15093	6500	6752	13252
22	62.8	45.58	7500	7672	15172	6494	6828	13322
23	62.86	47.4	7493	7759	15252	6488	6906	13393
24	62.92	49.29	7485	7861	15346	6481	6996	13477
25	62.99	51.27	7478	7966	15444	6475	7090	13565
Total			186915	176646	363561	161842	157216	319059

$$VOC\_EscalationFactor = \frac{CPI_{bsse\_year}}{CPI_{stated\_year}} = 0.89 \text{ (Adj. VOC)}$$

$$Time\_Cost\_EscalationFactor = \frac{CPI_{bsse\_year}}{CPI_{stated\_year}} = 0.8659 \text{ (Adj. Time Cost)}$$

Table A-5. User Costs of Two Pavements by HDM-4.

Year	AC($1000)				ARAC($1000)			
	IRI m/km	VOC	Time	Total	IRI m/km	VOC	Time	Total
1	0.78	9050	5494	14544	0.80	9050	5494	14544
2	1.06	9420	5716	15136	0.80	9412	5714	15126
3	1.07	9797	5945	15741	0.80	9789	5943	15731
4	1.07	10189	6183	16371	0.81	10180	6180	16361
5	1.09	10597	6430	17026	0.82	10588	6428	17015
6	1.10	11021	6687	17708	0.83	11012	6685	17697
7	1.12	11463	6955	18417	0.85	11453	6952	18406
8	1.13	11922	7233	19155	0.88	11912	7231	19143
9	1.15	12399	7523	19922	0.92	12390	7520	19911
10	1.18	12896	7824	20720	0.96	12887	7822	20709
11	1.23	13414	8137	21552	1.02	13406	8135	21541
12	1.34	13956	8464	22420	1.09	13945	8461	22406
13	1.45	14519	8804	23322	1.17	14506	8801	23306
14	1.57	15106	9157	24263	1.25	15090	9154	24243
15	1.70	15717	9525	25242	1.33	15697	9521	25218
16	1.84	16352	9908	26260	1.40	16330	9902	26232
17	1.98	17014	10307	27320	1.48	16987	10299	27286
18	2.13	17703	10721	28424	1.56	17671	10712	28384
19	2.28	18421	11152	29574	1.63	18382	11142	29524
20	2.44	19172	11602	30774	1.70	19122	11589	30710
21	2.60	19957	12071	32027	1.78	19891	12054	31945
22	2.77	20787	12559	33345	1.85	20692	12537	33229
23	2.94	21676	13069	34745	1.92	21524	13040	34563
24	3.12	22657	13601	36258	1.98	22389	13563	35952
25	3.31	23787	14159	37946	2.05	23290	14107	37397
Sum		378988	229224	608212		377594	228985	606579